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5 APRIL 1984

MILITARY HANDBOOK

DESIGN GUIDANCE
FOR
PRODUCIBILITY

DEPARTMENT OF DEFENSE
UNITED STATES OF AMERICA

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DEPARTMENT OF DEFENSE
WASHINGTON, DC 20301

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1. This handbook was developed by the Army Materials and Mechanics Research Center in accordance with established procedures.

2. This publication was approved on 5 April 1984 for printing and inclusion in the military standardization handbook series.

3. This document provides the design engineer with information to assist him in reducing or eliminating design features that would make producibility difficult to achieve.

4. Beneficial comments (recommendations, additions, or deletions) and any pertinent data that may be of use in improving this document should be addressed to: Commander, Army Materials and Mechanics Research Center, ATTN: DRXMR-LS, Watertown, MA 02172 by using the self-addressed Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

FOREWORD

Basically the task of the design engineer is to design a product that satisfies the requirements for functioning, i.e., insure that it works. Implicit in this design is the fact that the technology and materials exist to fabricate the design. Onlv later—during production engineering—is thought given to modifying the basic design m permit ease and efficiency in production. This sequential approach is at best a "band-aid" approach, i.e., curing problems that were unconsciously designed into the product initially. The consideration of producibility in the initial design would reduce the possibility of altering its functional characteristics as a result of a change to satisfy producibility and would eliminate, or reduce, the incorporation of a design feature making producibility difficult to achieve.

The importance and impact of producibility surfaced with the industrial mobilization occasioned by World War II. The need to re-engineer a particular design to permit ease of manufacture by multiple producers gave testimony that problems existed. Also, the emergence of new skills, technologies, and materials emphasized the need to consider producibility in the initial design phase and thereby avoid or eliminate frequently encountered design problems. In order to keep abreast of rapidly changing technologies that impact producibility, Appendix A, "Information Sources", is presented. Appendix A provides extensive references, data sources, and other sources of information—each broadly categorized by the technical sources that they cover.

Comments relative to the detail associated with data in the handbook follow:

a. Product brand names are used only as illustrations or examples; their use does not constitute an endorsement by the US Government.

b. The display of a dual dimensional system, i.e., the conversion of English to metric units, indicates "soft metric", a single dimensional unit, "hard metric".

c. Rounding off of units—except for approximate temperatures—was made in accordance with the procedures in pat-. 4-2.4, Engineering Design Handbook, DARCOM-P 706-470, Metric Conversion Guide. Approximate temperature conversions were rounded to the nearest 5 degrees.

Except for Chapters 5 and 6, this handbook was prepared by IIT Research Institute. Chapters 5 and 6 were prepared by the Plastics Technical Evaluation Center (PLASTEC), the Defense Department's specialized information center on plastics.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABS = acrylonitrile-butadiene-styrene
AC = ‘acquisition cost
AISI = American Iron and Steel Institute
AMI = American Microsystems, Inc.
AMD = Advanced Micro Devices, Inc.
AMS = Aerospace Materials Specifications
AMS = Army Management Structure
ANSI = American National Standards Institute
AOQ = average outgoing quality
AP = arbour press
AQL = acceptable quality level
ASARC = Army Systems Acquisition Review Council
ASTM = American Society for Testing and Materials
AWG = American Wire Gage
AMS = American Welding Society
BIT = built-in test
BITE = built-in test equipment
BDSA = Business and Defense Services Administration
BMC = bulk molding compounds
Bet-sic = silicon-carbide-coated boron
CAM = computer aided manufacturing
CDR = critical design review
CEI = configuration end item
CI = configuration item
CMOS = complimentary metal oxide semiconductor
CNC = computer numerical control
COMPAT = computer program for retrieving data on the compatibility of polymers with explosives and propellants
CON = cobalt napthanate
CP = continuous path
CPM = critical path method
CRT = cathode ray tube
CSOS = complimentary silicon sapphire semiconductor
DART = daily automatic rescheduling technique
DCP = decision coordinating paper
DESC = Defense Electronics Supply Center
DCEBA = diglycidyl ether of bisphenol-A
DIP = dual-in-line packagc
DMS = Defense Materials System
DNC = direct numerical control
DoD = Department of Defense
DP = drill press
DSARC = Defense Systems Acquisition Review Council
DT = development test
DTO = digital testing oscilloscope
DTUPC = design to unit production cost
EA = Electronic Associates
E-BEAM = electron beam
ECL = emitter coupled logic
ECM = electrochemical machining
EDM = electrical discharge machining
EIA = environmental impact assessments
EIA = Electronic Industries Association
EIS = environmental impact statements
EMC = Electromagnetic Compatibility
ENGR = engineering
EP = epoxy
EPROM = erasable programmable read only memory
ESR = equivalent series resistance
ETT = elevated temperature testing
FCA = functional configuration audit
FEP = fluorinated ethylene propylene
FET = field effect transistor
FQR = formal qualification review
FSD = full-scale development
GALS = general assembly line simulator
GASP = general activity simulation program
GFE = Government-furnished equipment
GI = General Instruments
GPSS = general purpose simulation system
GSA = General Services Administration
M = molecular weight
HDPE = high-density polyethylene
HM = high modulus
HMX = cyclotetramethvlene-tetranitramine
HMOS = scaled down silicon-gate metal-oxide semiconductor

LIST OF ABBREVIATIONS AND ACRONYMS (cont'd)

IC = integrated circuits
ICBT = in-circuit board tester
ID = inside diameter
I^2L = integrated injection logic, bipolar product
PL = integrated injection logic, tripolar product
IM = intermediate modulus
INTEL = Intel Corporation
IPR = in-process review
IPRR = initial production readiness review
JANTX = high reliability diode or transistor
J-FET = J-type field effect transistors
JMSNS = justification of major system new starts
L = lathe
LCC = life cycle cost
L/D = length-to-diameter ratio
LDD = low dislocation density
LDPE = low-density polyethylene
LED = luminous electronic diode
LHS = low-cost, high-strength
LIF = low insertion force
LOA = letter of agreement
LQ = limiting quality
LR = letter requirement
LRU = line replaceable unit
LSC = logistic support cost
LSI = large-scale integration
MEKP = methyl ethyl ketone peroxide
MGT = management
MIL-HDBK = military handbook
MIL-SPEC = military specification
MIL-STD = military standard
MMI = Magnetic Memories, Inc.
MMT = manufacturing methods and technology
MNT = mononitrotoluene
MOS = Mostek
MOS = metal oxide semiconductor
MOSFET = metal oxide silicon field effect transistors
MPDA = metaphenylene diamine
MSI = medium-scale integrated
MTBF = mean time between failures
MTD = manufacturing technology development
MTM = methods-time-measurement
MTTR = mean time to repair
NA = not applicable
NC = nitrocellulose
NC = numerical control
NCM = numerical control machines
NDT = nondestructive testing
NEMA = National Electrical Manufacturers Association
NG = nitroglycerin
NMA = nadic methylanhydride
NMOS = N-type metal oxide semiconductor
NPN-PNP = NPN-type and PNP-type transistor
NPO = zero temperature coefficient
NQ = nitroguanidine
NS/MMC = net shape or machined metal components
NY = nylon
OC = operating characteristic
OD = outside diameter
O&S = operating and support
OSHA = Occupational Safety and Health Administration
OT = operational test
PA = procurement appropriation
PAN = polyacrylonitrile
PB-RDX = mixture of RDX, polystyrene, and dioctylphthalate
PC = printed circuit
PCA = physical configuration audit
PCB = printed circuit board
PDM = program decision memorandum
PDR = preliminary design review
PE = polyester
PED = plastic encapsulation devices
PEP = producibility engineering and planning
PERT = program evaluation review technique
PET = polyethylene terephthalate
PETN = pentaerythritol tetranitrate
PH = phenolic
PI = polyimide
PLASTEC = Plastics Technical Evaluation Center
PM = program manager
PMOS = P-type metal oxide semiconductor
PN = junction
POS = point of sale
P to P = point to point
PP = polypropylene
PPM = parts per million
PR = program reviews

LIST OF ABBREVIATIONS AND ACRONYMS (cont'd)

prepregs = preimpregnated materials
PROM = programmable read only memory
PRR = production readiness review
PS = polysulfone
PTFE = polytetrafluoroethylene
PVC = polyvinyl chloride
Q = heat of explosion
QA = quality assurance
QC1 = quality control inspection
QPL = qualified product list
RAC = Reliability Analysis Center
RADC = Rome Air Development Center, Griffis Air Force Base, New York
RAM = reliability. availability, and maintainability
RAM = random access memory
R&M = reliability and maintainability
RCA = Radio Corporation of America
R&D = research and development
RDT&E = research, development, test, and evaluation
RDX = cyclotrimethylene trinitramine
RF = radio frequency
RFI = radio frequency interference
RIM = reaction injection molding
RISKA = risk analysis
rms = root mean square
ROC = required operational capability
ROM = read only memory
RT = room temperature
RTM = resin transfer molding
SAE = Society of Automotive Engineers
SAN = styrene-acrylonitrile
SDR = system design review
SIP = single-in-line package
SMC = sheet molding compounds
SMS = Standard Microsystems Corporation
SOS = silicon-on-sapphire process
SPI = Society of the Plastics Industry
SRR = systems requirement review
SSI = small-scale integrated
SSR = solid-state relay
SSR = system requirement review
SSS = Solid-State Scientific
STWR = strength-to-weight ratio
TDP = technical data package
TI = Texas Instruments
TIIC = Texas Instruments integrated circuits
TL = turret lathe
TMC = thick molding compounds
TNT = trinitrotoluene
T-P = thermoplastic
T-S = thermosetting
TTL or T^2L = transistor-transistor logic
TX = suffix denoting high reliability semiconductor, e.g., JAN TX 2n222
UHF = ultra high frequency
UNS = Unified Numbering System
UV = ultraviolet
VCD = variable center distance
VE = value engineering
VE = vinyl ester
VHF = very high frequency
VMOS = anisotropically etched, double-diffused process
W.DIG = Western Digital
ZIF = zero insertion force

CHAPTER 1

BASIC CONCEPTS OF PRODUCIBILITY

in this chapter the subject of producibility is introduced and defined, and the factors that determine whether or not an item is acceptable from a producibility point of view are described in general terms. Producibility is further defined by actual examples of good and poor producibility. The relationship of Producibility to other elements and junctions of the design process is discussed also. This chapter concludes with an overview of this entire handbook that includes insight into the types of data and information contained in each chapter.

1-1 INTRODUCTION

In the era preceding World War II, a designer's only concern with production was to determine whether the designed product could be manufactured. The ensuing technological explosion of materials and manufacturing processes coupled with the sophistication of the products to be produced have changed that situation. Today, the designer is concerned not only with determining whether an item can be produced but also with the degree to which it can be effectively produced. For example, a design that describes an equipment item that is required for issue to every soldier and can be manufactured by only one producer on a proprietary process at a cost of $50,000 each from a scarce or difficult to obtain material would have a very low degree of producibility. Conversely, the same item that could be produced by any manufacturer at a cost of a few cents each from readily available material would have a very high degree of producibility.

To contribute to the development of a new item of military hardware, the design engineer must operate within a controlled environment and conform to a set of prescribed standards. This environment is determined by the life cycle of the product, which consists of the conceptual, validation, full-scale development, production and deployment, and operating and support phases. The prescribed standards applicable to each phase of the life cycle (Ref. 1) provide the designer with descriptions of the various required characteristics of the product.

During each stage of acquisition an organized and systematic pattern of events must take place if a design is to meet fully all of its objectives. Implicit in these objectives is the requirement that the product of a design achieve the highest possible degree of producibility. However, producibility goals are rarely defined in documents-such as the required operational capability (ROC) or letter requirement (LR)—describing the end item.

Since the design effort has often been conducted to satisfy a description that includes no reference to producibility, the design engineer may easily neglect it as an element of his responsibility or overlook the effects of it on the total design. This handbook is intended to assist the designer in recognizing producibility implications and to provide guidance in designing to maximize producibility benefits.

Checklist approaches can be developed to spot-check the producibility features of a specific design. However, the development of sound design practices that promote producibility objectives is best accomplished as (1) the product of individual knowledge, experience, and a continua] effort to keep abreast of development in a specific field or (2) an investigation into those developments in fields in which there is infrequent involvement. This handbook is devoted to the latter objective, i.e., to assist the design engineer in investigating those fields or disciplines that are infrequently encountered.

1-2 DEFINITION OF PRODUCIBILITY

Producibility has been defined in many ways. The most desirable producible design is one that could be made by any reasonably skilled worker out of a wide variety of material in a short time. Department of Defense (DoD) Directive 5000.34 (Ref. 2) defines producibility as the relative ease of producing an item or system that is governed by the characteristics and features of a design that enable economical fabrication, assembly, inspection, and testing using available production technology. Military Standard (MIL-STD) 1528 (Ref. 3) defines producibility as the composite of characteristics, which, when applied to equipment design and production planning, leads to the most effective and economic means of fabrication, assembly, inspection, test, installation, checkout, and acceptance of systems and equipment.

For the purposes of this handbook, producibility is defined as the combined effect of those elements or characteristics of a design and the production planning for it that enables the item, described by the design, to be produced and inspected in the quantity required and that permits a series of trade-offs to achieve the optimum of the least possible cost and the minimum time, while still meeting the necessary quality and performance requirements. The key elements of this definition, analyzed independently in the paragraphs that follow, provide the fundamental factors having the greatest impact on producibility.

1-2.1 ELEMENTS OR CHARACTERISTICS OF A DESIGN

This phrase in the definition refers to the fundamental design elements that describe form, fit, and function to include useful life and to the elements or characteristics of a design that affect producibility. These latter elements or characteristics are the specified materials, simplicity of design, flexibility in production alternatives, tolerance requirements, and the accuracy and clarity of the technical data package (TDP).

1-2.1.1 Specified Materials

Mechanical, physical, and chemical properties usually constitute the primary decision criteria for selecting a material to satisfy the requirements of a design objective. These properties may facilitate or limit the selection of a manufacturing process because of their interrelationship with the factors of formability, machinability, joining, and heat or surface treatment. For example, some materials are extremely limited in their ability to be configured to desired shapes. A design specifying only one material is constrained to the manufacturing processes compatible with that material. The design should specify as many alternate materials as possible to broaden the number of potential manufacturing processes and to allow for the substitution of nonscarce or nonstrategic materials.

1-2.1.2 Simplicity of Design

A complex approach to satisfying the design objective can result in extreme cost increases. Typically, such a design may exceed the functional requirements, thereby adding weight, increasing the cost to manufacture, and raising the cost of reliability, availability, and maintainability (RAM). It is even more likely that a complex design will require additional cost and delivery time because of increased manufacturing and assembly costs.

1-2.1.3 Flexibility in Production Alternatives

Only in rare instances will just one material or manufacturing process satisfy the requirements of the design objective. More frequently any one of several materials or processes will result in an acceptable product. The identification of alternative materials and processes will greatly enhance producibility by anticipating bottlenecks caused by a potential lack of material or process availability. Rarely does a design or a TDP directly specify a manufacturing process. However, indirectly there are many ways for this to occur. Materials, tolerances, draft lines (castings), relief angles (forgings), and bend radii all are part of the TDP, and all have a direct impact on the selection of a manufacturing process. These are all factors of significant importance to producibility and should receive explicit attention during the design process through a review of the TDP by a manufacturing engineer.

1-2.1.4 Tolerance Requirements

The specification of unnecessarily tight tolerances and surface roughness has a very detrimental effect on producibility. As tolerances and surface roughness become tighter, more specialized and expensive manufacturing operations are required, The intensity of the labor content of manufacturing processes rises concurrently as the tightness of tolerances and surface roughness requirements increase. These should be specified only to the minimum quality level absolutely essential to the design objective.

1-2.1.5 Clarity and Simplicity of the Technical Data Package

Reliability of the information conveyed by the TDP is of vital importance to the successful production of the design objective. Unclear or vague design information can be as detrimental to producibility as inaccurate information.

1-2.2 ELEMENTS OR CHARACTERISTICS OF PRODUCTION PLANNING

This phrase, as used in the definition of producibility, implies the total assessment of the total available resources to accomplish the production requirements of a given design. This includes the availability of other resources through subcontracting. Typically, the factors of production rate and quantity, special tooling requirements, manpower and facilities, and availability of materials should be considered.

1-22.1 Production Rate and Quantity

Planned production rates and quantities are the decision criteria for the establishment and sizing of secondary facilities for subassembly and final assembly. Errors in judgment here can have a snowballing effect that can result in extremely high losses of time and money. For example, the establishment of an automatic assembly plant generally requires large investments in special purpose tooling, which is justified by the production rate and quantity of components to be manufactured. If sufficient components are unavailable due to errors in judgment of the production rate in the component plant, justification for automatic assembly costs is futile.

1-2.2.2 Special Tooling Requirements

Special purpose tools are those tools required to adapt a general purpose machine to a special purpose requirement. They are required in support of high-rate production and may be required in low-rate production. Generally, the quality and cost of the tooling are in direct proportion to the production rate. Failure to plan for tooling requirements can idle an entire facility and have disastrous effects on producibility.

1-2.2.3 Manpower

Availability of unique labor skills is vitally important to any planned production. For example, availability of manpower uniquely trained to perform a highly skilled production operation, such as grinding optical components, is vital to the producibility of any component requiring that operation.

1-2.2.4 Facilities

Availability of unique facilities, such as a five-axis numerical control machine, when they are the only manufacturing facilities capable of producing the component, is vital to the producibility of the component.

1-2.2.5 Availability of Materials

This is an obviously critical element to the successful production of any component or product. The time phasing of deliveries of material to coincide with the production schedule is a producibility-determining element. Good producibility planning would also assure that the material is not critical or geographically sensitive without specification of an appropriate alternate material.

1-2.3 PRODUCTION OR INSPECTION IN QUANTITY REQUIRED

High-rate production and inspection carry with them complete sets of criteria that are quite different from those of low-rate production and inspection. However, they both share the common interrelationships among the design elements of form, fit, and function, material selection, and manufacturing process selection.

1-2.3.1 High-Rate Production and Inspection

A design planned for high-rate production must be configured, dimensioned, and tolerance in a manner consistent with the capabilities of high-rate production processes. Not all materials are compatible with high-rate production processes; consequently, care must be exercised to assure that the material selected is compatible with both high-rate production processes and the properties required by the design objective. During production planning, consideration of production rate compatible inspection processes is also vital to producibility. For example, the automation of composite component manufacturing processes can make significant improvements in delivery times. However, unless corresponding improvements can be made in the inspection processes, there is no appreciable gain.

1-2.3.2 Low-Rate Production and Inspection

The ability to amortize production cost in high-rate production over a large number of parts provides many opportunities for producibility improvements. Low-rate production does not offer the same opportunities. However, the cost savings per improvement are usually greater in low-rate production due to its inherent labor intensive nature. Manufacturing technology developments in recent years have tended to be more concerned with this area—witness the development of numerical control (NC) and the typical 3:1 cost reduction when NC machining techniques are used in lieu of conventional machining techniques. Interestingly, the cost reduction tends to decrease as production volume increases. Most inspection at this level is performed manually. The designer must guard against specifying quality requirements that can be measured only by specially developed inspection processes that can be justified only by high-rate production.

1-2.4 OPTIMAL COST AND TIME THROUGH TRADE-OFFS

Each step in the execution of a producibility plan has as its objective the acquisition of a product at the least possible cost and in the minimum time. However, in the final result these items are traded off to achieve the optimum balance of time and cost and still satisfy the performance requirements for the product.

1-2.4.1 Least Cost

Some general rules leading to designs with intrinsic producibility are simplicity and standardization in components and manufacturing processes. However, the large number of demands involved in the cost of ownership of a system—such as RAM, safety, and obsolescence—heavily interact with each other to create the need for cost trade-offs throughout the acquisition process from conception to production and deployment. These are all aspects of designing for producibility.

1-2.4.2 Least Time

A design that satisfies all of the performance characteristics and that can be produced for the least possible cost but cannot be available in the required time is not producible. As a result, continuous attention must be given throughout the acquisition process to assure that the required materials, manpower, manufacturing processes, and inspection aids will in fact be available when needed to assure that the product reaches the user in the minimum time.

1-2.5 NECESSARY QUALITY AND PERFORMANCE REQUIREMENTS

In the process of achieving all of the previously discussed elements of producibility, it is essential that the performance objectives of the design not be compromised or adversely affected by factors introduced to maximize producibility. The objective of producibility is a design that meets the performance objectives and yet can be produced in the simplest and most economical manner.

1-3 EXAMPLES OF GOOD AND POOR PRODUCIBILITY

The examples in the paragraphs [hat follow come from a variety of sources and provide meaningful data on the value of a producibility program. Additionally, they graphically demonstrate a few elements that further define the term producibility.

1-3.1 PROJECTILE BODY

This item, originally designed as shown in Fig. 1-1, required the body to be machined from H41400 steel and subsequently heat treated. The slot requires a secondary milling machine setup and operation. This steel is difficult to machine. Further, this is a material and process combination that is not conducive to the high production requirements of the item. A subsequent producibility review made minor design comfiguration changes as shown in Fig 1-2 to permit it to be compatible with a more production oriented process The material was changed to C1141 free-macining steel, and the internal configuration of the body was modified with no detrimental impact on the functional intent or performance characteristics. Elimination of the slot permits the entire process to be performed in one machine setup. The one-year net savings resulting from this producibility effort were $88,000.

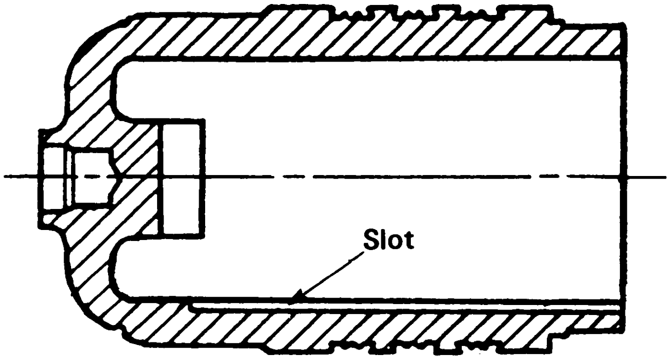


Figure 1-1. Projectile Body—Before

Figure 1-2. Projectile Body—After

1-3.2 AIRCRAFT DISPENSER HOUSING

This device, shown in Fig/ 1-3, was originally designed for fabrication by forming and riveting from sheet metal with a dip brazed cover and a cast frame. Following a producibility analysis, it was agreed that the housing could be fabricated in a one or two-piece casting process. The process was evaluated to assure compatibility of the final product with the necessary design characteristics and functional intent. Subsequently, it was learned that this component would be used on numerous aircraft and thus would effect further savings as a result of the 50% per item cost reduction.

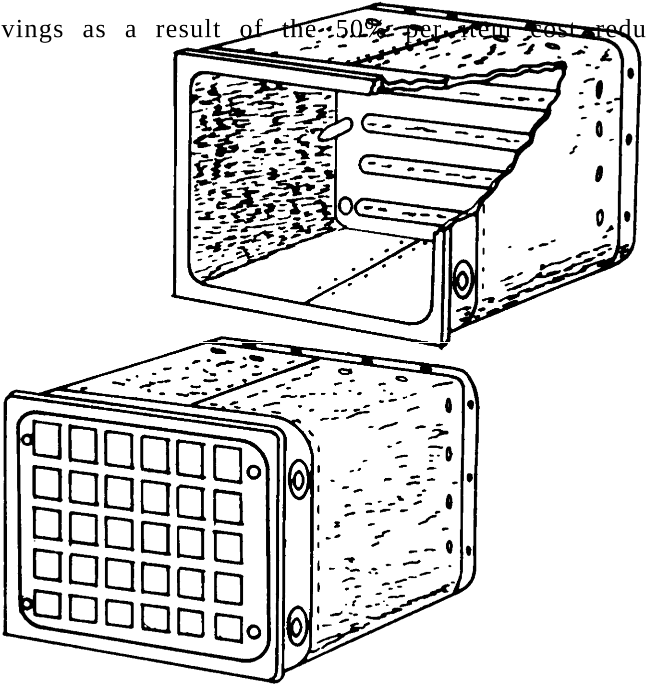


Figure 1-3. Aircraft Dispenser Housing

1-3.3 WARHEAD BODY

The warhead body shown in Fig. 1-1 was originally designed with a wall thickness dimtension of 6.60-0.50 mm (0.26 — 0.02 in.) and a cocentricity requirement of 0.10-mm (0.004-in.) total indicator reading. Subsequent producibility analysis revealed that these dinensional and tolerance requirements were difficult to maintain with the manufacturing process being used. Further analysis revealed that the tolerances could be changed to the more compatible tolerances shown in

Figure 1-4. Warhead Body

Fig. 1-4 without affecting the performance characteristics of the item. It should be noted that in this instance the tolerances on the tube thickness are tightened to allow more liberal tolerance for the concentricity while the tolerance on the outside diameter remains unchanged. This redistribution of the tolerances increased the acceptable output using the same manufacturing methods and thus reduced the production man-hours. The one-year savings resulting from this producibility analysis were in excess of $100,000.

1-3.4 ADAPTER

This example demonstrates the efficiency of using standard materials and design simplicity to gain producibility. The adapter shown in Fig. 1-5 was machined from bar stock because of its irregular wall. Subsequent analysis revealed the potential of reducing the size of the wall irregularity and machining the part from seamless tubing. The irregularity was not required, and the entire part could be made from standard seamless tubing, which would eliminate all machining. The adapter, a mass production item, was subsequently manufactured with savings in excess of $500,000.

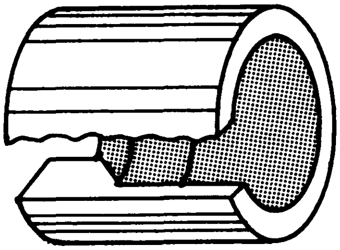


Figure 1-5. Adapter

1-3.5 SPIDER AND NUT ASSEMBLY

In this example the use of standard components and production oriented manufacturing processes resulted in significant improvements in producibility. The spider and nut assembly shown in Fig. 1-6 required the fabrication of the spider and the subsequent welding of a common machine nut to achieve a finished assembly.

Subsequent producibility analysis showed the same end results could be achieved if the nut were roll crimped rather than welded as shown in Fig. 1-7. Tests revealed that this new process would satisfy the design requirements and concurrently improve producibility.

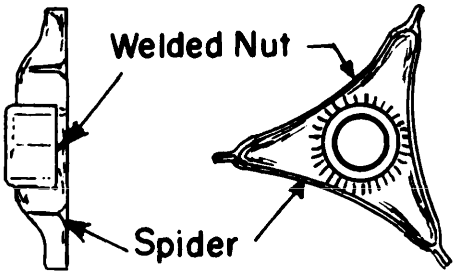


Figure 1-6. Welded Spider and Nut Assembly

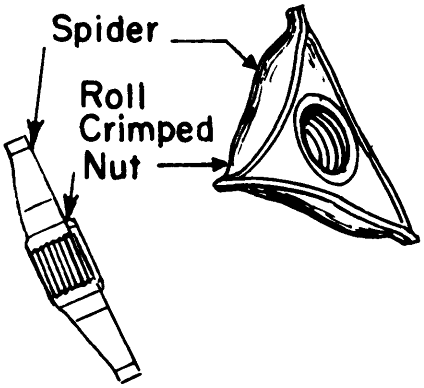


Figure 1-7. Roll Crimped Spider and Nut Assembly

1-3.6 SELF-CENTERING GASKETS

Simplicity of assembly was the objective of the producibility improvement shown in Fig. 1-8. The original design had a raised face on the flange for the gasket contact and a flat gasket that had to be centered manually and held in place while the flanges were being bolted. Redesign of the gasket added a countersink that matched the raised face on the flange, This permitted automatic centering and held the gasket temporarily in place while the flanges were bolted. The extra cost of countersinking the gasket was more than offset by the savings in assembly time. Additionally, reliability was improved because the gasket was always centered. This is a good example of achieving producibility by designing for assembly.

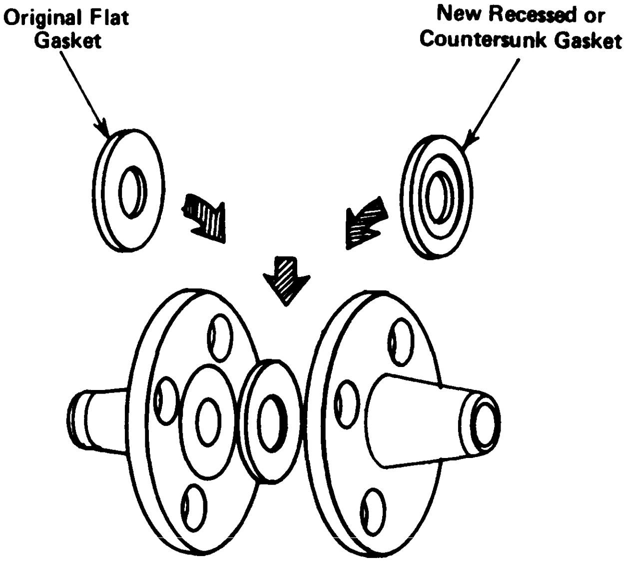


Figure 1-8. Self-Centering Gasket

1-3.7 THREADED INSERTS

A mechanical device was designed with 12 threaded holes in the body for the attachment of a cover plate. A large number of these bodies were being rejected because of stripped threads in a number of the holes. In many cases these were being field repaired by drilling out the stripped thread and using a standard threaded insert. Subsequent investigations revealed that the use of the threaded insert was less expensive than tapping the holes. The basic design was changed to specify the threaded insert, and the tapping operation was eliminated, which resulted in improved producibility.

1-3.8 SWITCH HOUSING

A 50.8-mm (2-in.) square steel box, 25.4 mm (1 in.) deep was required for a switch housing (see Fig. 1-9). The maximum tolerance for these dimensions was 0.38 mm (0.015 in.), and cadmium plating was required for corrosion resistance. The housing was originally designed to be a fabricated sheet metal box with welded seams and was to be subsequent> cadmium plated. Investigations revealed that an aluminum box could be used that would eliminate the need for the cadmium plating. Further investigation showed that the housing could be made by investment casting rather than by fabricating and welding. This producibility analysis resulted in cost savings of 50% over the original design.

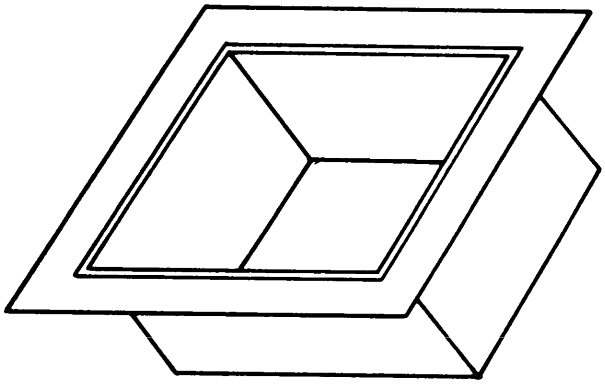


Figure 1-9. Switch Housing

1-3.9 PRODUCIBILITY IN THE FABRICATION PROCESS

A metal part was being formed in the shop in a series of successive operations. Each operation was set up in a different press brake. The first operation formed a flat strip of metal into an angle section; a subsequent operation punched three notches in one leg of that angle. Review of these operations revealed that the two tools, one for bending and one for notching, could be set up side by side in the press brake. This would permit one operator on one press brake to do both operations simultaneously; the operator would simply move the piece from the bending tool to the notching tool, place a new piece of material in the bending tool, and then actuate the press. This is a unique example of improving producibility by changing the material flow through the shop.

1-4 PRODUCIBILITY AND THE DESIGN PROCESS

Most programs, regardless of their position in the acquisition process and regardless of the type of program, can benefit from producibility considerations. The type of program, major or otherwise, will determine the depth of producibility considerations to be employed. Its progress through the program milestones will determine the areas of emphasis for producibility studies. Producibility considerations should be introduced as early as possible in the acquisition process for maximum benefit as depicted in Fig. 1-10, and the designer must keep producibility in mind from the first moment he puts pencil to paper. It must then be addressed at every stage of breadboarding, brass boarding, and pilot production. A major program in the conceptual stage of the acquisition process will emphasize broad areas of producibility}' on a general scale. Comparably, a major program in the full-scale development phase will emphasize specific producibility studies in far greater depth.

Major programs are defined by DoD Directive 5000.1 (Ref. 4) as systems involving an anticipated cost of $200 million (FY80 dollars) in research, development, test, and evaluation (RDT&E) or $1 billion (FY80 dollars) in production cost, or both. The management of systems other than major programs will be guided by the provisions of the same directive.

Designated programs proceed through the acquisition process as follows:

1. DoD Component Head submits a Justification of Major System New Starts (JMSNS) to the Secretary of Defense.
2. The Secretary of Defense provides appropriate program guidance in the Program Decision Memorandum (PDM). This action provides official sanction for a new program start and authorizes the Military Service to initiate the first acquisition phase when funds are available.
3. When selected alternative concepts warrant system demonstration, approval to proceed is requested. This request is reviewed by the Defense System Acquisition Review Council (DSARC) prior to a decision by the Secretary of Defense.
4. The Secretary of Defense reaffirms the need and approves one or more alternatives for entry into the demonstration and validation phase. When this phase is complete, the Military Service recommends the preferred system. This recommendation is reviewed by the DSARC prior to a decision by the Secretary of Defense.
5. The Secretary of Defense again reaffirms the need and approves the selection of a system to enter full-scale development. At this decision point the Secretary of Defense establishes thresholds of performance, reliability, availability, and maintainability (RAM) logistical support requirements, cost, and schedule of

the system. The decision to start production of a system is delegated to the Military Service, provided these thresholds are met.

6. If an Army system is within the thresholds established by the Secretary of Defense, the decision to start production is made by the Army Acquisition Executive (AAE). The status of the system is reviewed by the Army System Acquisition Review Council (ASARC) prior to the decision by the AAE.

Throughout the acquisition process, producibility is and must be a continuing effort closely integrated with the acquisition phases to be an effective tool. This integration of producibility into the acquisition process is shown graphically on Fig. 1-10 and is discussed in more detail in the paragraphs that follow:

1. ***Concept Exploration Phase.*** Early implementation of a producibility effort is a must if a successful program is to be conducted. Producibility considerations should begin immediately after the JMSNS is approved. An initial producibility estimate is prepared by using previous production experience and data from contract studies and advanced technology programs. Based on the requirements (e.g., performance, need dates), the initial estimate includes, but is not limited to

a, Critical material data such as material properties, availability, lead times, and processing constraints

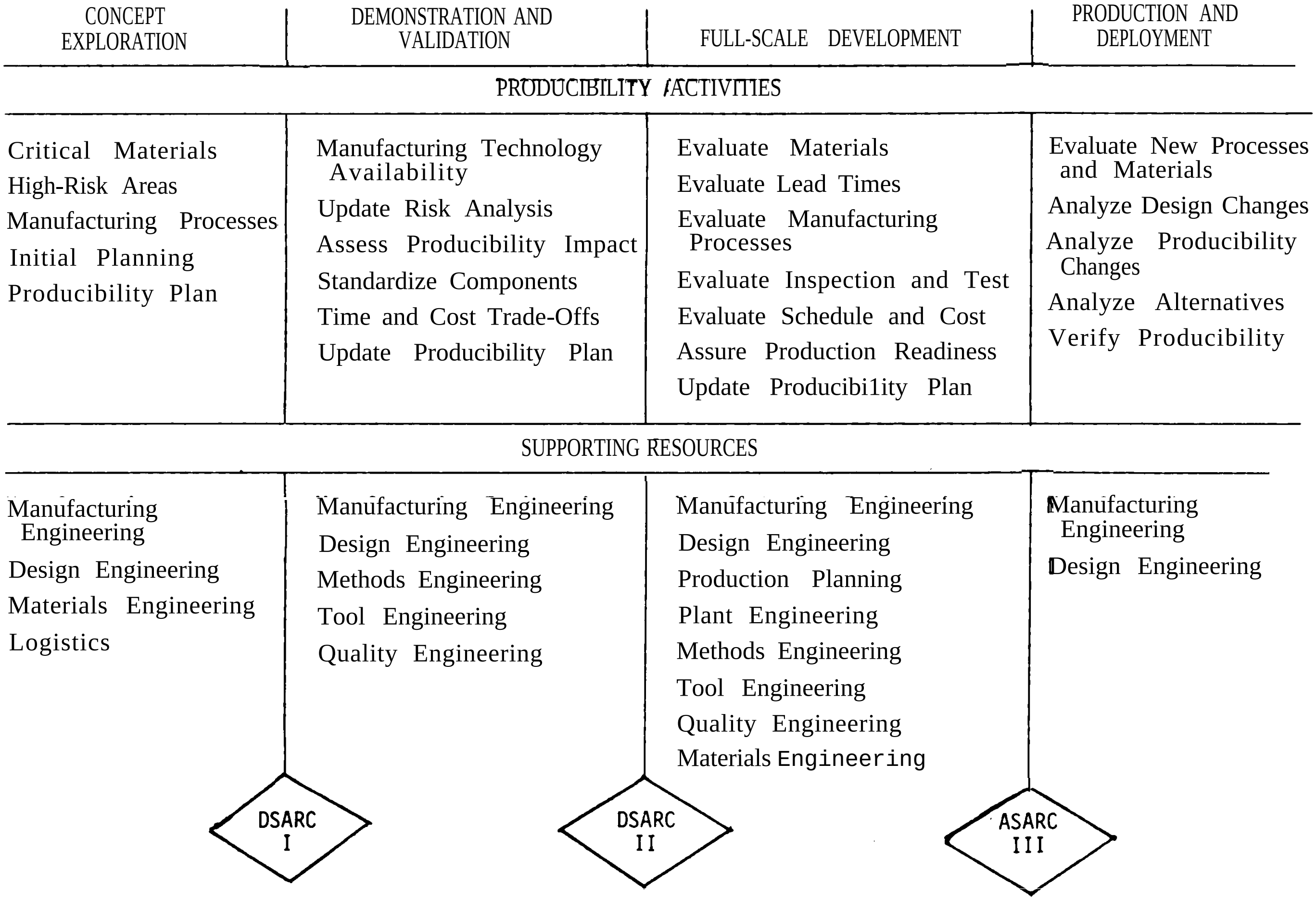
b. High-risk areas introduced by new manufacturing processes and materials as related to each design alternative considered, including estimates of time required to resolve identified risks

c. State of the art producibility criteria, e.g., manufacturing tooling and test capability by location and quantity (Government and industry).

The initial producibility estimate is essentially an assessment of current and projected production capacity and capability. This is essential to system trade-offs so that the need for new development can be separated from existing state of the art technology. Producibility considerations in system feasibility studies require that design/support/production trade-offs be performed and consider such things as

a. Alternative fabrication and assembly methods and capabilities/capacities—e.g., casting, forging, riveting, welding

b. Alternative machine capabilities



CONCEPT EXPLORATION	DEMONSTRATION AND VALIDATION	FULL-SCALE DEVELOPMENT	PRODUCTION AND DEPLOYMENT
PRODUCIBILITY ACTIVITIES			
Critical Materials High-Risk Areas Manufacturing Processes Initial Planning Producibility Plan	Manufacturing Technology Availability Update Risk Analysis Assess Producibility Impact Standardize Components Time and Cost Trade-Offs Update Producibility Plan	Evaluate Materials Evaluate Lead Times Evaluate Manufacturing Processes Evaluate Inspection and Test Evaluate Schedule and Cost Assure Production Readiness Update Producibility Plan	Evaluate New Processes and Materials Analyze Design Changes Analyze Producibility Changes Analyze Alternatives Verify Producibility
SUPPORTING RESOURCES			
Manufacturing Engineering Design Engineering Materials Engineering Logistics	Manufacturing Engineering Design Engineering Methods Engineering Tool Engineering Quality Engineering	Manufacturing Engineering Design Engineering Production Planning Plant Engineering Methods Engineering Tool Engineering Quality Engineering Materials Engineering	Manufacturing Engineering Design Engineering

Figure 1-10. Producibility in the Acquisition Process

c. Available versus required techniques and controls for installation, inspection, test, quality, and cost and schedule balance

d. Critical material status and forecast

e. Available versus required expertise to resolve risk areas

f. Preliminary manufacturing cost estimates

g. Available versus required real property, production equipment, tools, and test equipment

h. Risks associated with production planning based on proposed and projected capabilities, especially when state of the art advances are required.

It is not reasonable to expect that all necessary producibility studies can be conducted by a single individual charged with managing the producibility function. Successful promotion of producibility during the concept exploration phase is dependent upon the availability and use of experts in the areas of design, state of the art materials and fabrication methods, and present/planned development programs in related areas. During this phase, manufacturing personnel will identify current and required industry capabilities/capacities and assure that planning for follow-on phases includes sufficient time for scheduling the required development and manufacturing activities within schedule constraints. One way to achieve the desired interfaces during the concept exploration phase is through participation in system/subsystem\component technical reviews. One such review, the system requirement review (SRR), may be levied by the program manager in accordance with guidance provided in Ref. 5. The SRR is a formal program review conducted during either the concept exploration phase or early in the demonstration and validation phase. This review is to determine the appropriateness of the initial direction and progress of the engineering management effort and the approach taken to achieve an optimum configuration. The total engineering management activity and its output are reviewed for responsiveness to the statement of work and system requirements. Early producibility analysis will provide a valuable source of information required to meet the objectives of DSARCI.

2. ***Demonstration and Validation Phase.*** The objective of this phase is to prove the design concept. This includes validation of performance, cost, and schedule by study, hardware development, and/or prototype testing. The results of this phase will be the basis for reaching a decision on whether or not to proceed into full-scale development. The demonstrat ion and validation phase affords engineering and manufacturing personnel the opportunity to conduct trade-off studies. Producibility considerations, which are narrower in scope and greater in number than during the concept exploration phase, create opportunities to achieve significant benefit as the hardware design evolves and before it becomes too fixed to be altered economically. The producibility of a system must be examined thoroughly prior to the DSARC II decision. This examination includes

a. Insuring that all manufacturing technology that pertains to the producibility of the system is available or adequately planned and that this technology will fully support the development of specific methods applicable to the design

b. Updating the production feasibility and risk analyses

c. Assessing impacts on producibility by performance requirements/design constraints as the design evolves into the detail parts

d. Standardizing components and material to the maximum extent practicable during design

e. Assessing the effects that the continuing tradeoff studies have had on the producibility of the system

f. Evaluating the adequacy of plans for proofing critical production processes, tooling, and test equipment

g. Evaluating and updating the overall producibility plan. The producibility effort required during this phase will require extensive coordination and support from other disciplines. Manufacturing engineering personnel will be required to validate the adequacy and availability of manufacturing processes. Methods engineering will be required to validate the adequacy of specific methods of manufacturing. Tool engineering should validate the adequacy of planned tooling requirements. Quality engineering should validate the reasonableness of planned test and evaluation procedures. All of these members of the producibility team should work closely with product design engineering to maximize the producibility aspects of a product in relationship to each member's particular specialty.

h. Considering the significant producibility factors that are visible this early in the program, e.g., critical materials, tooling, manufacturing methods and processes, and facilities. Producibility analysis during this phase of the program will assist in identification of risks, preliminary cost and schedule estimates, and issues that must be resolved prior to the DSARC II program justification.

3. ***Full-.Scale Development Phase.*** The intended output of this phase is a preproduction system that closely approximates the final production product, written documentation, actual practices necessary to enter the production phase, and test results that meet requirements. During this phase all production and support equipment must be designed and proven capable, and these actions must be accomplished at an acceptable cost. An important aspect of producibility during this phase is to identify all key characteristics for hardware components that reduce production flow time, minimize material and labor costs, establish optimum schedule requirements for the production

phase, improve inspection and test routines, and minimize special production tooling and test equipment. During the manufacture of full-scale development units, evaluations of these characteristics must be accomplished to assure compliance with producibility requirements. The producibility plan will be maintained, implemented, and updated on a continuing basis until a production readiness posture is achieved. The fruits of producibility efforts will be realized in

a. Facilitating the readiness of the system for entrance into the production process

b. Assuring that the system can be acquired on schedule at minimum cost

c. Assuring that producibility plans are realistic. The program situation may require additional decisions, such as release of funds for long lead time material or effort and additional hardware for test and evaluation. Producibility efforts will minimize long lead time requirements.

This phase in the program continues to require support from many disciplines and organizations. The emphasis is on the verification that the final design evolves with maximum producibility employed. Manufacturing engineering skills are now a predominant factor in achieving a smooth transition to the production and deployment phase. Producibility efforts must consider such activities as production planning and scheduling, manufacturing flow, plant layout, material handling, manufacturing methods and processes, tooling, and inspection and test equipment. Use of technical consultants will often be required.

A production readiness review (PRR) should be completed prior to the release of the system for initial production. Each PRR subteam that deals with areas related to producibility should have at least one member identified as the producibility focal point; thus considerable man-hours will be saved both in planning and conducting these reviews. Since producibility reviews consider most of the same information, there will be less data duplication.

The culmination of producibility efforts during this phase to achieve an optimized production schedule and cost should strongly support the program manager's presentation on production readiness at ASARC III.

4. ***Production and Deployment Phase.*** The initiation of this phase does not mark the end of producibility efforts. Often design and production are concurrent efforts especially with long lead time items, such as tooling, materials, and purchased parts. Emphasis on producibility is a must during production. Although the impact of producibility will be less dramatic than during the previous phases, producibility can achieve significant cost reductions by striving for use of emerging manufacturing technology and by insuring that design changes are producible. Potential producibility, design, or process changes, especially late in the production phase, should be analyzed for the benefits to accrue both to the present program and to possible follow-on procurements. Since production and deployment normally have considerable overlap, the producibility studies conducted can be viewed for their impact on the operational activities, such as reliability and maintainability. The producibility plan—developed during the concept exploration phase and implemented and updated throughout demonstration and validation and the full-scale development phases-furnishes program management a continuous thread of documentation to evaluate and verify the achievement of producibility during the fabrication, assembly, installation, acceptance tests, and final checkout of equipment. The experience and related information documented in the early phases are useful in achieving more efficient use of manufacturing resources during production. The specific producibility activities include, but are not limited to

a. Process/methods analysis to minimize the manufacturing costs and lead times and maximize quality

b. Application of alternative materials

c. Investigation of manufacturing design changes for cost reduction

d. Evaluation of engineering change proposals to insure producibility

e. Application of new manufacturing technology.

The supporting resources required during this phase are primarily manufacturing engineering and product design engineering.

1-4.1 INTERFACE WITH OTHER FUNCTIONAL AREAS

Producibility has significant interface with a number of other functional areas in the acquisition process. The relationship of the key elements in the definition of producibility to other functional areas is shown in Table 1-1, and the interface with production functions is shown in Table 1-2. How each of the other functional areas interfaces with producibility is discussed in subsequent paragraphs.

1-4.1.1 Reliability, Availability, and Maintainability

Reliability, as a discipline, was born in the late 1940's from concern that hardware being delivered was not performing as it should for as long as it should. Reliability engineering thus developed as a tool not only of design but also of prediction, i.e., "the probability that an item will perform its intended function for a specified interval under 'stated' conditions". Availability, as a function of this program, is the assurance that the item will be available to perform its function at a given time. Maintainability engineering inherently recognizes that complete reliability at all times is an impossible goal and thus addresses itself to "the probability

TABLE 1-1. INTERFACE OF FUNCTIONAL AREAS WITH PRODUCIBILITY KEY ELEMENTS

OTHER FUNCTIONAL AREAS	KEY PRODUCIBILITY ELEMENTS													
	Least Cost	Minimum Time	Materials Selection	Manufacturing Simplicity	Manufacturing Flexibility	Clarity of Data	Tolerances	Production Planning	Production Rate and Quantity	Special Tooling	Manpower Availability	Machine Availability	Materials Availability	Performance Requirements
Reliability, availability, and maintainability}	X	X	X	X	X								X	X
Safety engineering			X											X
Standardization	X	X	X		X		X			X			X	X
Design/cost techniques	X		X						X	X				
Manufacturing technology)'	X	X	X		X		X	X	X	X	X	X	X	
Life cycle costing	X		X	X					X		X	X		
Systems engineering			X				X		X					X
Quality assurance and testing						X	X	X	X		X	X		X
Technical data management	X	X				X				X				X
Value engineering	X	X	X	X										X
Product engineering	X	X	X			X	X		X					X

TABLE 1-2. INTERFACE OF PRODUCTION DISCIPLINES WITH PRODUCIBILITY KEY ELEMENTS

PRODUCTION DISCIPLINES	KEY PRODUCIBILITY ELEMENTS													
	Least Cost	Minimum Time	Materials Selection	Manufacturing Simplicity	Manufacturing Flexibility	Clarity of Data	Tolerances	Production Planning	Production Rate and Quantity	Special Tooling	Manpower Availability	Machine Availability	Materials Availability	Performance Requirements
Production or manufacturing engineering	X	X		X	X	X	X	X	X	X	X	X	X	
Industrial engineering	X	X		X	X	X		X	X		X	X		X
Production control	X	X				X		X	X	X	X	X	X	
Material control	X	X	X			X		X	X				X	
Quality control	X	X		X		X	X	X	X					X
Packaging	X	X				X		X	X					
Tool engineering	X	X	X	X		X	X		X	X	X	X	X	
Process planning	X	X	X	X	X	X	X		X	X	X	X	X	
Plant engineering	X	X				X		X	X			X		

that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources”. For example, if a fuel tank has a built-in pump or valve that is subject to failure, does the tank have an access port through which it can be reached, and can the pump be repaired (or replaced) readily through the port? For more information on maintainability see Ref. 6.

The predictability aspects of the RAM program, the general overall concern with life cycle cost, and how the basic design criteria can be influenced to enhance these characteristics are all elements of concern to producibility.

1-4.1.2 Safety Engineering

Safety engineering is concerned with the conservation of human life and its effectiveness and the prevention of damage to items consistent with mission requirements. Thus it is obvious that reliability, maintainability, and safety engineering are concerned with failure, but from different standpoints:

1. Reliability—to predict failures
2. Maintainability-to correct failures
3. Safety—to minimize the effects of unforeseen hazards.

Therefore, it is concluded that the interface between safety engineering and producibility is the same as that between the RAM program and producibility. Further, it is important to note that producibility enhancements can have an impact on safety engineering and vice versa. For more information see Ref. 7.

1-4.1.3 Standardization

Standardization is defined in Ref. 8 as the “adaptation and use of engineering criteria to:

1. Improve operational readiness by increasing efficiency of design, development, material acquisition, and logistic support.
2. Conserve money, manpower, time, facilities, and natural resources.
3. Minimize the variety of items, processes, and practices which are associated with the design, development, production, and logistic support of equipment and supplies.
4. Enhance interchangeability, reliability, and maintainability of military equipment and supplies.”.

Standardization is thus both a tool and an objective of all the preceding elements, and it is a cog in both the cost and the performance effectiveness wheels. Fundamentally, this program has as its objective the producibility of an item through the use of standard, “off-the-shelf” parts. For more information see Ref. 8.

1-4.1.4 Design/Cost Techniques

Cost-effectiveness, not cost, is the criterion with respect to producibility goals; cost-effectiveness is a function of time and dollars. A process should not be selected that entails a production time exceeding that set forth in the producibility objectives. In his efforts to establish a cost for a processed material, the designer will be in a position to examine this time aspect of the problem as well. As an initial step, he should pinpoint the projected lot size or sizes, the projected unit cost, and the maximum allowable production time. After defining all operations in the production of the design in question, the cost/time analysis for each of these can be plotted as shown in Fig. 1-11. If consideration involves a number of different situations, e.g., a wide range of projected lot sizes, there will probably be several end points, which will provide the basis for plotting a cost/time curve such as the one in Fig. 1-11.

Cost/time trade-offs, which can also be plotted, should also be considered as in Fig. 1-12. Frequently, such a relationship may exist between producibility objectives and constraints, or the developing project may produce areas wherein time, performance, and cost involve trade-offs. When a chart, similar to Fig. 1-12, can be drawn to depict the situation, a forceful tool for cost-effectiveness analysis is available. From the end points so plotted the cost-effective candidate can be determined. Processes that result in time and cost combinations in the shaded area are unacceptable; processes that are below the cost-time curve are acceptable.

This effectiveness is graphically delineated by the distance from the end points to the cost/time curve. The candidate process end point with the greatest distance outside the cost/time curve is the most cost-effective when trade-offs are involved. In the illustration $a < c < d < b$. Process E is excluded since it lies in the unacceptable area of the plot. Process B, then, is the most suitable since it lies farther outside the cost/time curve than the other processes considered. Therefore, it will provide the greatest cost/time benefits.

Frequently, the relationship between time and unit cost is not defined. Only a target for each is given. This approach, with its emphasis on the producibility goal of cost-effectiveness, has a great advantage over techniques that consider performance or material cost alone. However, the question concerning which candidates are selected for analysis is still unanswered; large numbers cannot easily be subjected to this process. For more information see Ref. 9.

1-4.1.5 Manufacturing Technology

This program has as its objective the timely establishment or improvement of the manufacturing processes, techniques, or equipment required to support current and projected programs. To the producibility program, technology is the source of new manufacturing processes as they are needed and of state of the art information on available processes.

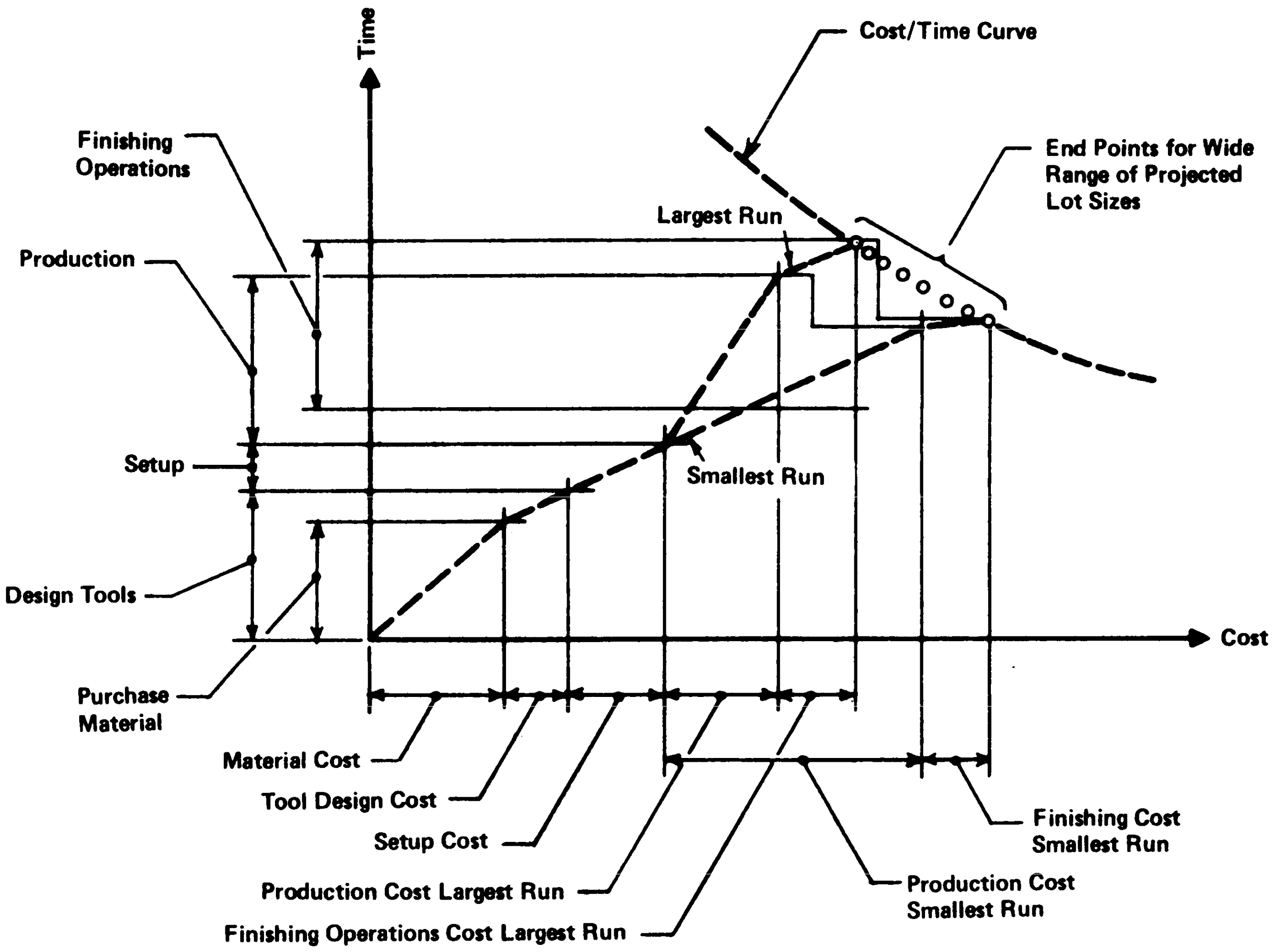


Figure 1-11. Cost/Time Analysis for Theoretical Production Operation

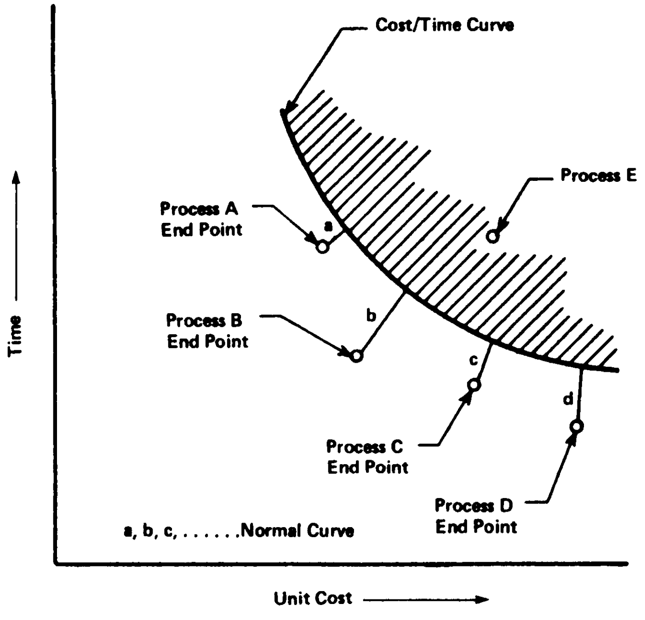


Figure 1-12. Cost/Time Curve for Candidate Selection

1-4.1.6 Life Cycle Costing

Life cycle cost (LCC) represents all costs incurred from the point at which the decision is made to acquire a system through operational life to eventual disposal of the system. A variety of analytical approaches can be used as input to the establishment of an optimum LCC model. The total LCC model is thus composed of subsets of cost models, which are then exercised during trade-off studies. These cost models and cost estimating relationships range from simple informal relationships to complex mathematical statements derived from empirical data.

A total LCC is represented by costs collected in two areas: (1) system acquisition costs and (2) logistics and support costs. In simple mathematical terms this relationship can be stated by

$$LCC = AC + LSC \qquad (1\text{-}1)$$

where

LCC = life cycle cost
AC = acquisition cost
LSC = logistic support cost.

Some of the major elements comprising these cost categories, i.e., design and development, and manufacturing and quality engineering, are, for the most part, the primary targets of a good producibility program. These elements are further broken down:

1. Design and Development:
    - a. Basic engineering
    - b. Test and evaluation
    - c. Experimental tooling
    - d. System management
2. Manufacturing and Quality Engineering:
    - a. Fabrication
    - b. Production tooling
    - c. Quality control
    - d. Test equipment
    - e. Facilities
    - f. Initial spares
    - g. Training.

Fig. 1-13 illustrates the relationship among objectives of a design program. In the past (Fig, 1-13(A)), the emphasis on performance would often become overriding to the detriment of all other factors. Design engineers must now (Fig. 1-1,3(B)) balance performance, reliability, unit production goals, and many other parameters equally against the overall objective of minimizing LCC. For example, it maybe more economical to replace periodically a part, module, or complete system with a relatively inexpensive new one rather than to design and build a very expensive unit with a guaranteed long, trouble-free operational life.

1-4.1.7 Systems Engineering

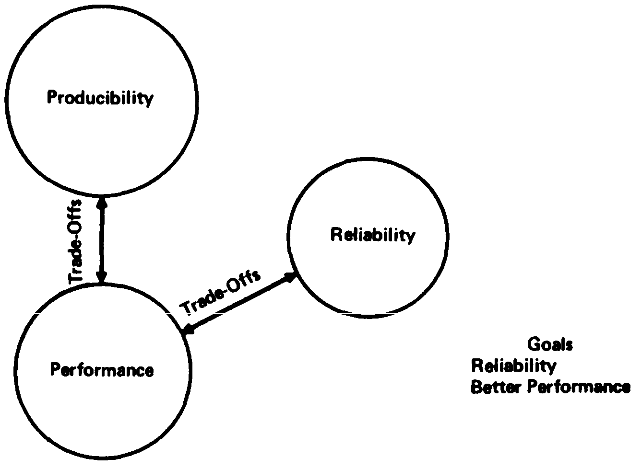
Systems engineering details the intended performance of the system together with its physical and functional characteristics down to the primary functional level.

All elements of the system description are interactive. Modification of any one element of the description almost inevitably affects others. Their combined influence on producibility is equally interactive. Whether viewed from a total system standpoint or from that of individual primary functional areas, the composite requirements set the limits of producibility.

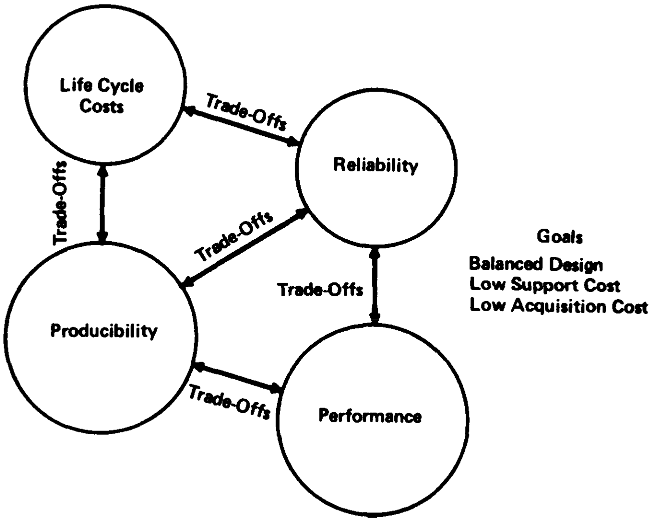
Prior to the start of the design effort, a thorough evaluation of the system description must be made to determine potential problems and complexities in developing the design. This review, while primarily directed toward an evaluation of the design requirements, serves as an indicator of the degree to which producibility aspects may be actively considered in the design. Design problems may vary significantly from one primary functional area to another as may the influence of the design constraints. As a result, separate evaluations must be conducted in each area.

1-4.1.8 Quality Assurance and Testing

Quality assurance is a planned and systematic pattern of all actions necessary to provide adequate confidence that the product will perform satisfactorily y in service. An obvious, inherent element of quality assurance is quality control, which is a management function whereby control of material is exercised for the purpose of preventing production of defective material. Quality control, therefore, verifies that the required standards of quality have been achieved.



(A) Old



(B) New

Figure 1-13. Trade-Off Relationships Between Program Objectives (balanced design)

Quality control normally is thought of as a function of the production program, but not always as an element of the design and development program. However, if the production contractor built the article to conform to the TDP and if it has been inspected for conformance to drawing, the likelihood of achieving the prescribed standards of quality is slim unless there was some form of quality control imposed upon the development of the TDP.

The likelihood of achieving any standard of producibility is even slimmer if the standards have not been defined, planned for, implemented, and verified through inspection and testing. The need for an integrated test program is readily apparent. Any test has as its purpose some element of verification from the earliest stages of a program (when it may be a feasibility verification) to the production stage (when it may be a conformance verification and is an element of quality control).

1-4.1.9 Technical Data Management

Technical data are the key elements in acquiring material either through in-house facilities or contractors' facilities. Their accuracy, completeness, currency, clarity, and adequacy can only be assured with proper technical data management. These are major factors in determining the capability of a manufacturer to produce materiel of the required quality and reliability within the most optimum time and cost. The objectives of a good technical data management system, which are imperative to and an integral part of a good producibility y program, are to

1. Provide the level of identification, control, and status reporting for systems and equipment necessary to assist management in achieving logistic support, weapon readiness, visibility, and traceability
2. Provide managers at all levels with sufficient information for making appropriate and timely decisions during the development, production, and operational periods
3. Attain maximum economical consistency in configuration management data, forms, and reports within the US Army Materiel Development and Readiness Command and at all interfaces with other DoD elements and industry
4. Provide a system for use in the control of project design and engineering that will support optimum competitive procurement and breakout, make contract administration more uniform, increase the effectiveness of standardization and item entry control, and support project definition
5. Assure that a proposed configuration change is timely and includes a thorough consideration of its total impact on cost, operational capability, and support to both hardware and documentation
6. Assure the efficient and timely implementation of all aspects of approved changes.

In fact, unless the configuration is effectively controlled, it is likely that one or all of the other objectives of the system description may be lost. Because of this, application of configuration management to systems of equipment is mandatory continuously during all applicable life cycle periods and must be applied to all materials, parts, components, subassemblies, equipments, accessories, and attachments.

1-4.1.10 Value Engineering

This program is an organized effort directed at analyzing the function of systems, equipment, facilities, procedures, and supplies. The intended purpose is to achieve the required function at the lowest cost of effective ownership consistent with requirements for performance, reliability, quality, and maintainability. The program at the objective level is quite similar to the producibility program with one major difference. Under value engineering, functional analysis is, by necessity, performed after the design has been completed. Conversely, producibility is effective only if accomplished concurrently with the design. However, it should be emphasized that value engineering is a vital element in achieving good producibility. For more information see Ref. 10.

1-4.1.11 Product Engineering

This function is primarily concerned with the engineering aspects of the final product to be produced by a given program. The concentration here is on satisfying the basic requirements document. Other functions must work through product engineering to achieve their goals. All other functions—safety engineering, value engineering, production engineering, producibility engineering, etc.—must achieve their objectives without degrading the minimum functional characteristics of the item being produced. The product engineer is responsible for assuring that the supporting functions do not violate the basic integrity of the product.

1-4.2 INTERFACE BETWEEN PRODUCTION DISCIPLINES

The producibility engineer cannot possibly have an intimate awareness of all the production disciplines necessary to the performance of his assigned mission. It is therefore necessary that the producibility engineer interface with other production disciplines to assure the attainment of necessary objectives. The other production disciplines most critical to producibility and how they can contribute to the producibility engineer are discussed in succeeding paragraphs.

1-4.2.1 Production/Manufacturing Engineering

This discipline is devoted primarily to planning and establishing the processes of economic manufacture. It embraces participation in the refinement of product design, manufacturing methods, selection of equipment, gages, special tooling and test equipment, labor standard manufacturing cost estimating, and economic utilization of materials and manufacturing resources.

Through effective interfacing with design engineering, producibility of a functional design is achieved. The producibility of any product implies the total assessment by a manufacturer of his present, planned, and available resources in terms of capability and capacity. Careful investigations should be made to identify new/alternative methods whereby producibility could be better achieved. New economical processes, available by subcontracting with other manufacturers, should be given appropriate consideration.

1-4.2.2 Industrial Engineering

The application of engineering principles and training and the techniques of scientific management to the maintenance of a high level of industrial production efficiency is a critical element of a successful producibility program. Industrial engineering in its total context includes many of the disciplines discussed in these paragraphs. Good producibility is dependent to a large degree on close and early coordination with this discipline. The quantification of the work force and the work stations within a facility to provide a balanced work flow with minimum production bottlenecks is only one of the many functions of industrial engineering on which producibility is dependent. Other functions include risk analysis, plant simulation, scheduling, and machine loading.

1-4.2.3 Production Control

The actual scheduling of work and control of work commitments by a manufacturer are performed by personnel in this discipline. Of particular importance to producibility is the commitment of manpower and machines to assure delivery of completed products within a specified time and the issuance of progress reports against those commitments. Through effective interfacing with requirements personnel, the necessary resources are identified and production plans are completed. The producibility of any item is dependent on the total assessment by production control of the planned and available resources to satisfy the capacity and capability requirements.

1-4.2.4 Material Control

Everyone has experienced, at one time or another, the inconvenience of a material shortage. In the shop the shortage of an insignificant item of raw material, part, or subassembly can lead to overtime operations, delays in the final completion of the work, extensive revisions in the plan, and, of course, degradation of producibility. The problems that create material shortages may be identified with three types of inventories. The first, raw materials and purchased parts inventory, is the stock of items going directly into the end product. In-process inventory is the second type and includes material that has already been worked on by the operating organization. The level of in-process inventory is a direct reflection of the production schedule and its execution, rather than a result of independent control decisions. The third type is the inventory of finished goods, The items involved are completely processed and are awaiting eventual shipment. The control is accomplished in much the same manner as it is for raw materials.

The first task of sound material control is adequate physical control. To perform this task, it is important to establish an effective requisitioning procedure, provide proper storage conditions, and maintain adequate stockroom security. The second task of material control is recordkeeping. The actual movement of material flowing in and out of the stockroom must be known. Material control can make significant contributions to an effective producibility program.

1-4.2.5 Quality Control

Quality control verifies that the required standards of quality have been achieved. Quality control is normally thought of as a function of the production program, but not always as an element of the design and development program. However, since the production contractor has built the article to conform to the TDP and it has been inspected for conformance to drawing, it most likely has achieved the prescribed standards of quality control imposed upon the development of the TDP.

The likelihood of achieving any degree of producibility is slimmer if standards have not been defined, planned for, implemented, and verified through inspection and testing. The need for an integrated test program is readily apparent. Any test has as its purpose some element of verification from the earliest stages of a program (when it may be a feasibility verification) to the production stage (when it may be a conformance verification and is an element of quality control). The interaction of quality control with producibility is continuous throughout all phases of the material acquisition process.

1-4.2.6 Packaging

The selection of a suitable packaging method requires consideration of many trade-off factors. Characteristics that influence the choice of a packaging method include cost, size, producibility, maintainability, repairability, and reliability. In many cases the system requirements are conflicting, and the selection process becomes one of identifying the packaging approach offering the best compromise of the many divergent requirements.

In military systems the factors of anticipated rough handling, size, weight, and reliability are prime considerations, and the choice of packaging methods must reflect the priority of these factors. It is often mandatory to provide protection of the system against dust, dirt, contamination, humidity, salt spray, and other environments. Although trade-off situations generally do not exist in terms of potential reliability improvements, this protection does significantly impact the operational and reliability levels of the equipment. Packaging should always receive producibility considerations in the same context as tolerancing. Overpackaging, as well as underpackaging, is a primary contributor to poor producibility.

1-4.2.7 Tool Engineering

In almost every form of manufacturing some special purpose tooling is required. Generally, the higher the production quantity the more tooling is required and the more tool engineering is involved. Tooling required for the fabrication and assembly of some configured products demands the use of production tooling regardless of the quantity to be produced. As a consequence, tool engineering is a discipline that can make significant contributions to the producibility of any design.

1-4.2.8 Process Planning

Manufacturing is comprised of numerous, diverse operations and processes. In assessing the producibility of items or systems, the contractor should relate to the following manufacturing process planning considerations:

1. Compatibility of the raw material form with the selected process
2. Shape and size (dimensional) restrictions for the process
3. The production rate of the process (some convenient time base, i.e., pieces/hour)
4. Process tolerance limitations
5. Process surface finish obtainable
6. Tooling requirements
7. Labor skills and man-hour requirements
8. Process yield/waste rates
9. Process optimum lot sizes
10. Primary use of the process.

The process chosen should be the one best able to produce the desired items, and it should not be selected merely due to the availability of plant equipment.

1-4.2.9 Plant Engineering

The engineering of the physical facilities that will produce a planned design is a critical element in determining the producibility of that design. Material and process flow through a plant can be a significant contributor to the efficiency of the plant and ultimately to the producibility of a product. Particular characteristics of a product requirement, such as machining beryllium or magnesium, carry with them specific requirements for environmental controls that have a significant impact on plant engineering and ultimately producibility.

1-5 PRODUCIBILITY HANDBOOK OVERVIEW

This handbook has been structured to provide the user with direct access to the material being sought. The content and intended purposes of the individual chapters are outlined in the paragraphs that follow.

1-5.1 CHAPTER 1, BASIC CONCEPTS OF PRODUCIBILITY

As an executive overview of the handbook, Chapter 1 provides an introduction to the subject of producibility and how producibility interacts with other functional areas and production disciplines. The structure and content of the chapter are described in Fig. 1-14.

1-5.2 CHAPTER 2, PRODUCIBILITY ENGINEERING

This chapter is intended primarily as a guide to the manager of the producibility function. Whether the producibility function is assigned as an explicit discipline or is assigned as a functional discipline to another functional area, this chapter is equally applicable. Chapter 2 describes how the function of producibility interacts specifically with the design process and the entire development process as described in DoD Directive 5000.1 (Ref. 4). The tools and techniques of producibility engineering are also described. For the chapter structure and content refer to Fig. 1-14.

1-5.3 CHAPTER 3, COMMON PRODUCIBILITY CONSIDERATIONS

This and all subsequent chapters are intended for managers of the producibility function and personnel assigned to perform the function. As with any function that spans as many different disciplines and technologies as this one, there area number of guidelines that are equally applicable across all disciplines and functions and a number that are directed toward specific disciplines or technologies. Chapter 3 includes these broad guidelines. The structure and content are graphically described in Fig. 1-14.

1-5.4 CHAPTERS 4 THROUGH 9, SPECIFIC PRODUCIBILITY CONSIDERATIONS

All of these chapters address the subject of achieving producibility in specific disciplines or technologies. As an aid to the user of the handbook, the chapters are identified by their applicability to specific types of components (i.e., metal components, plastic components, composite components, mechanical assembly, electronics, propellant and explosive components, optical components, ceramic components, and textile components). The user can go directly to the chapter that addresses the type of component being considered and acquire either the direct information or a reference source for additional information. These chapters each contain specific information on materials, manufacturing processes, and test and evaluation of specific concern to the achievement of good producibility. The structure and content of these chapters are presented in Figs. 1-15 through 1-23.

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6. AMCP 706-133, Engineering Design Handbook, Maintainability Engineering Theory and Practice, January 1976.
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*Under preparation at this time,

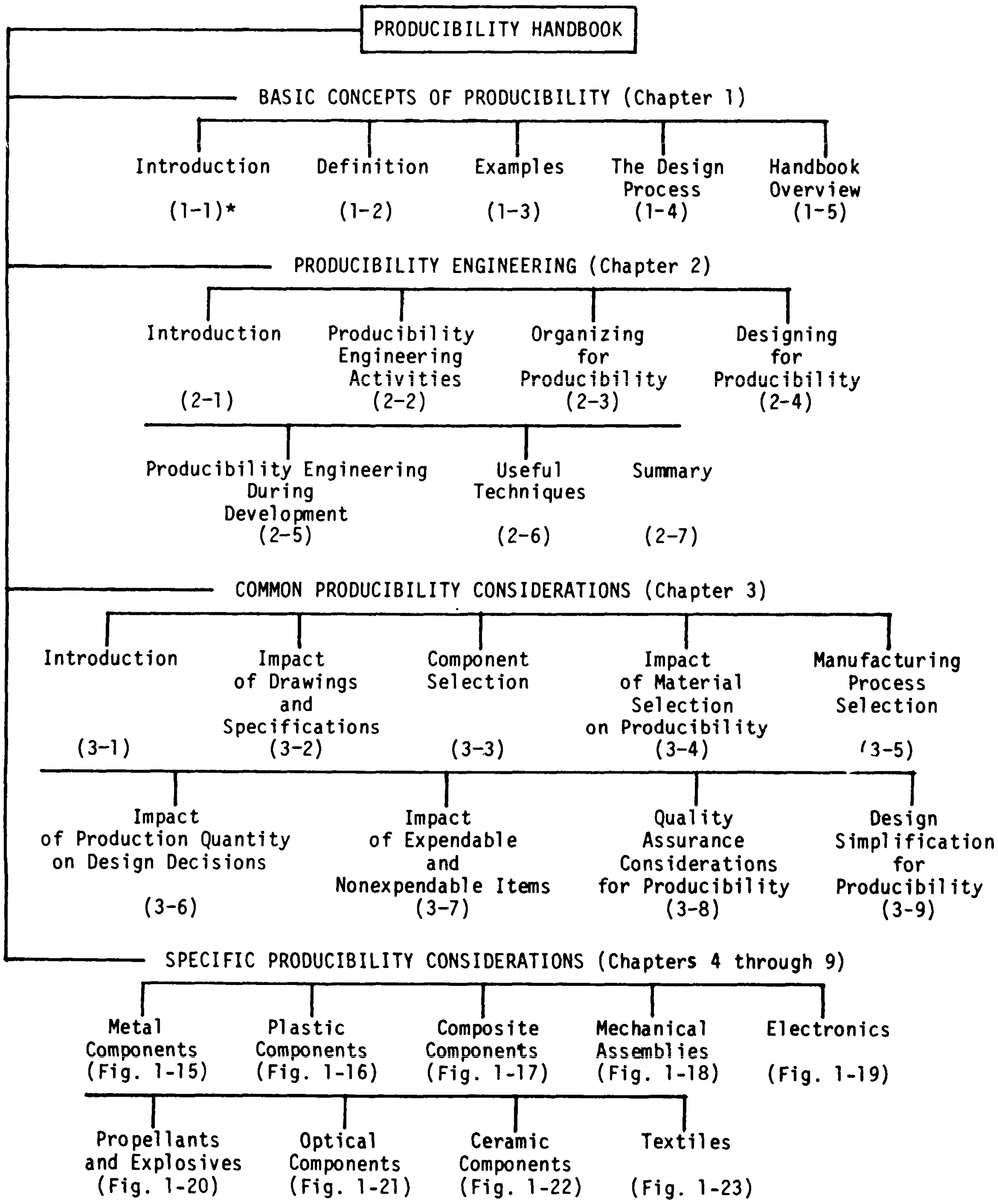

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Figure 1-14. Producibility Handbook Generic Tree

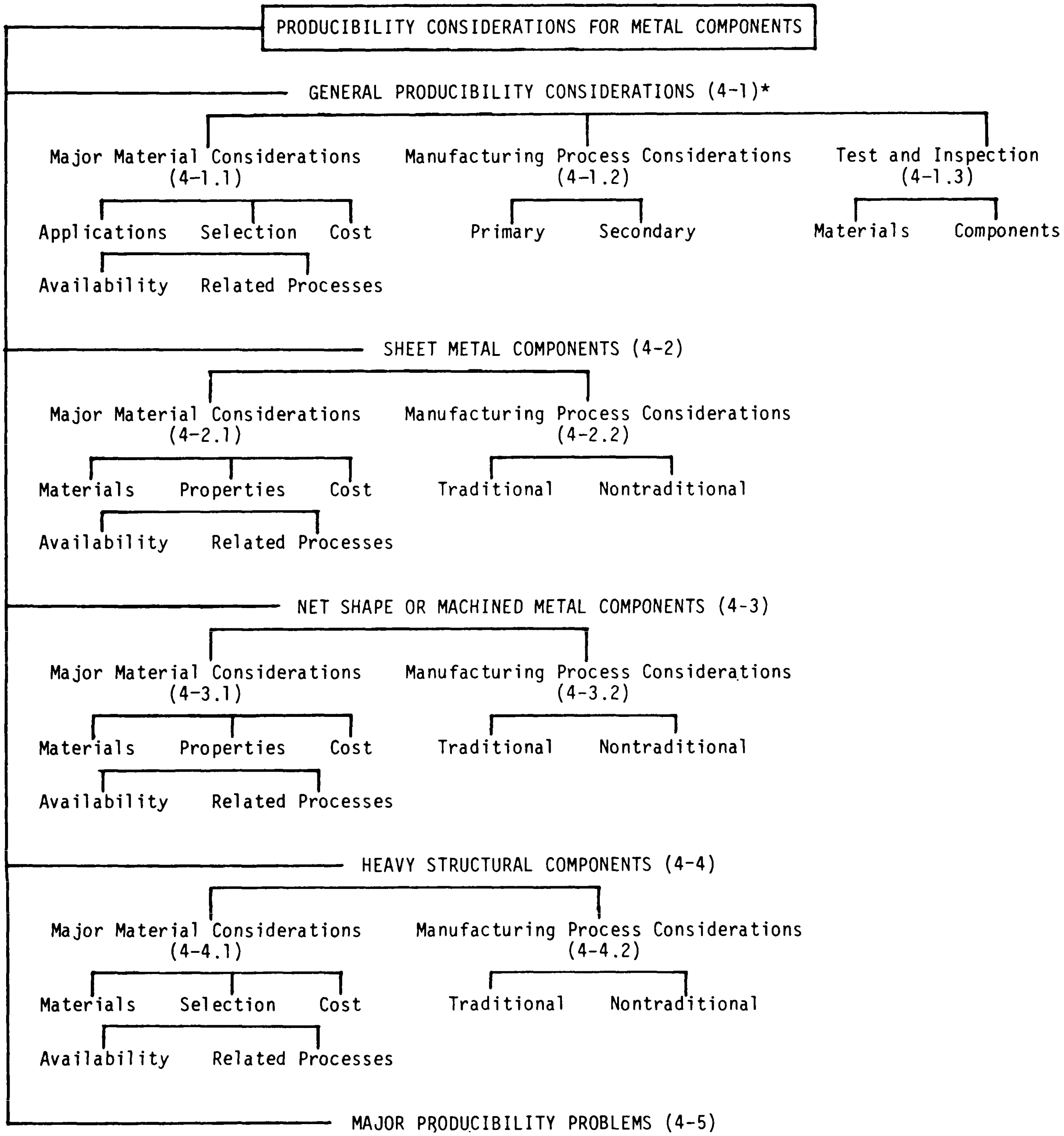

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Figure 1-15. Metal Components Generic Tree

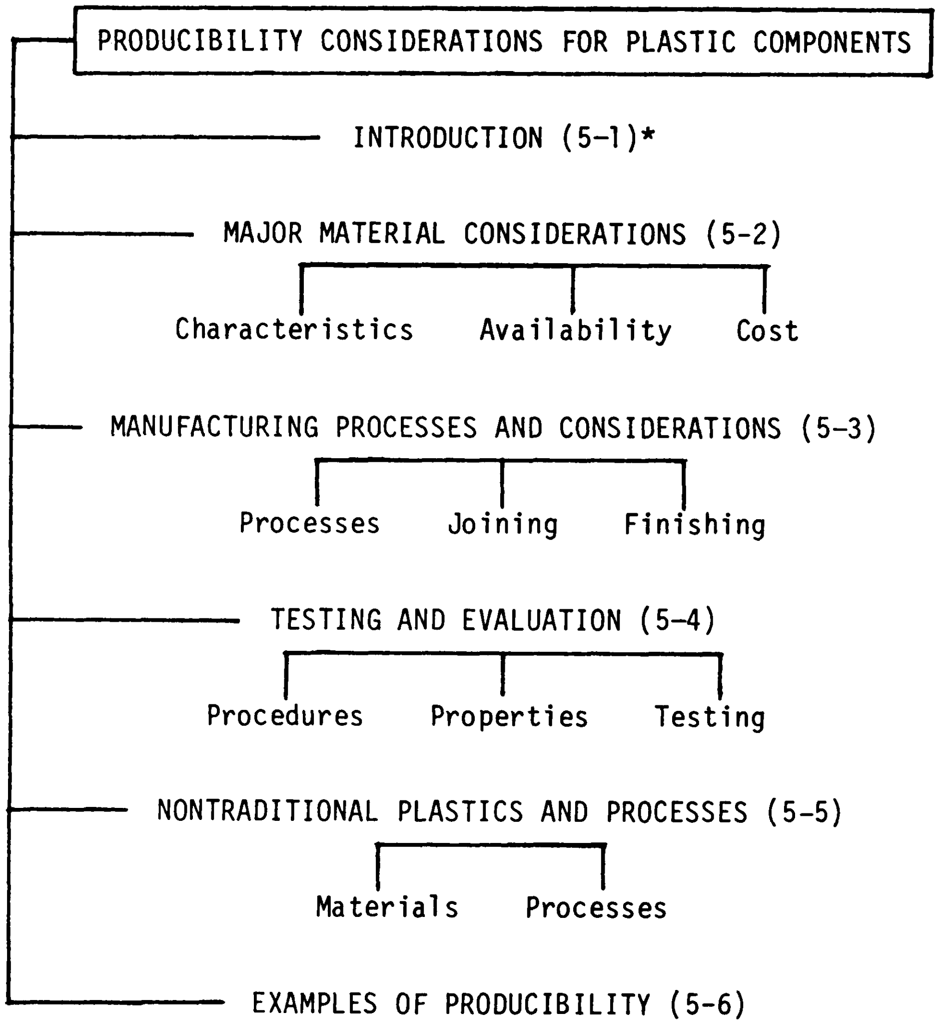

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Figure 1-16. Plastic Components Generic Tree

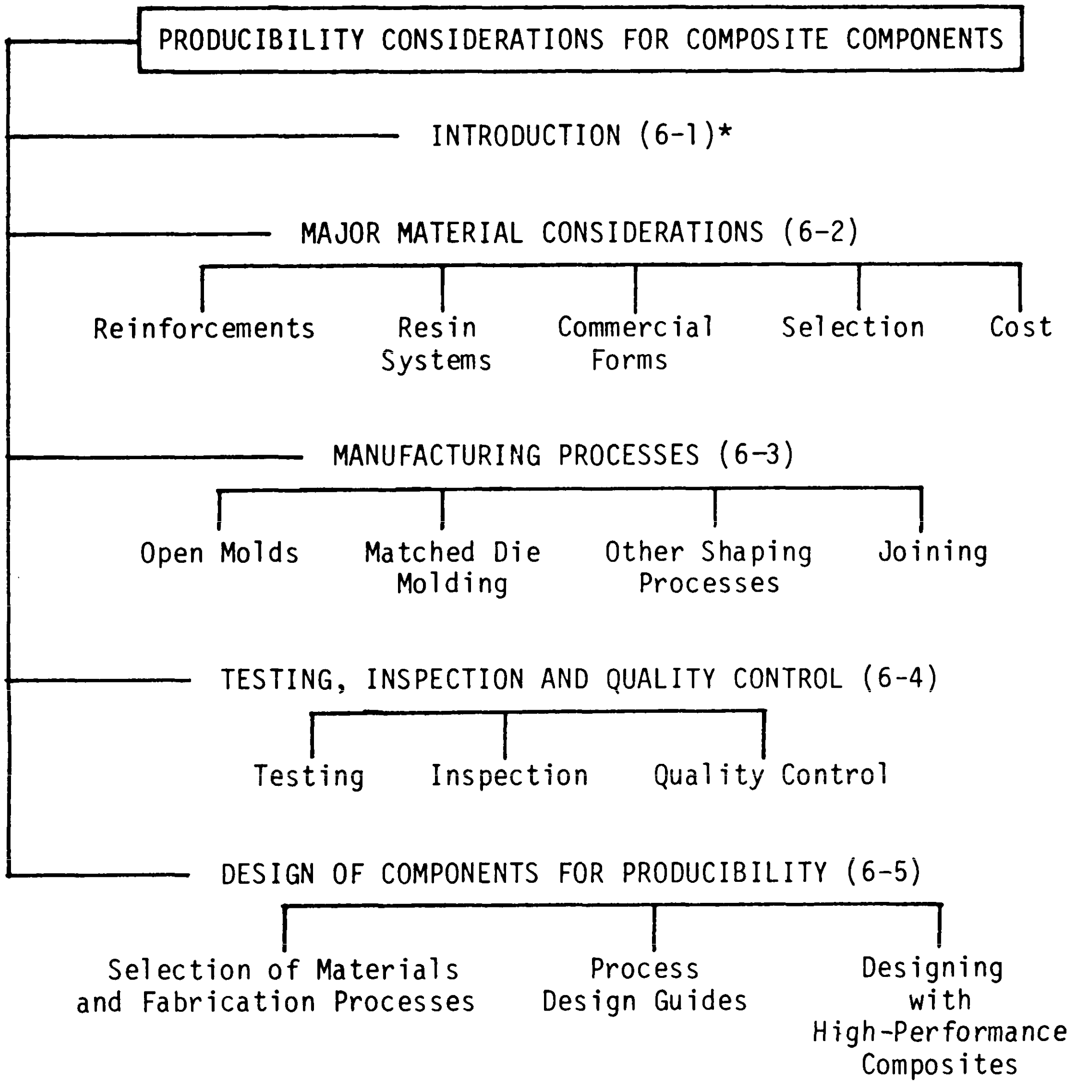

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Figure 1-17. Composite Components Generic Tree

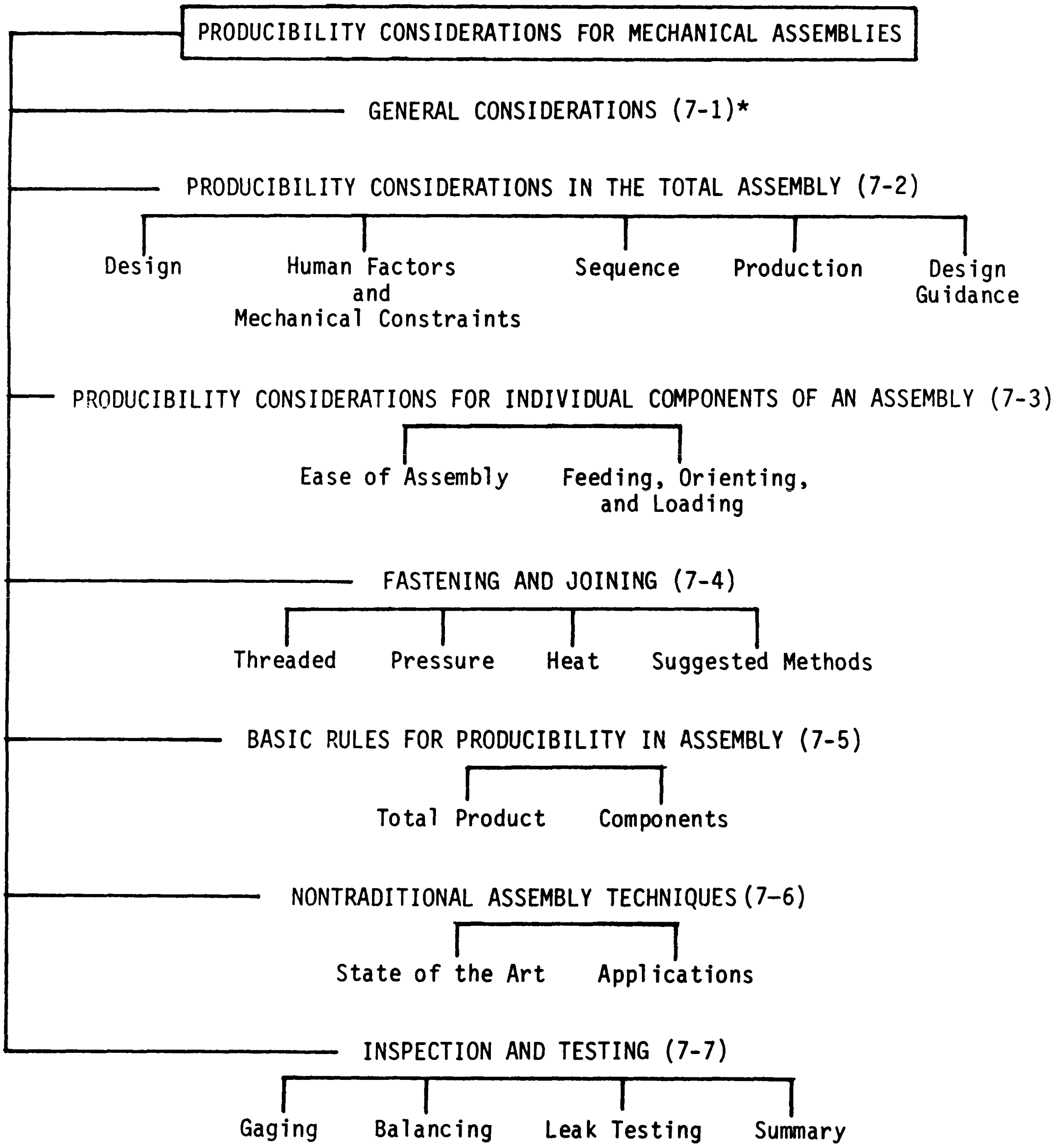

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Figure 1-18. Mechanical Assemblies Generic Tree

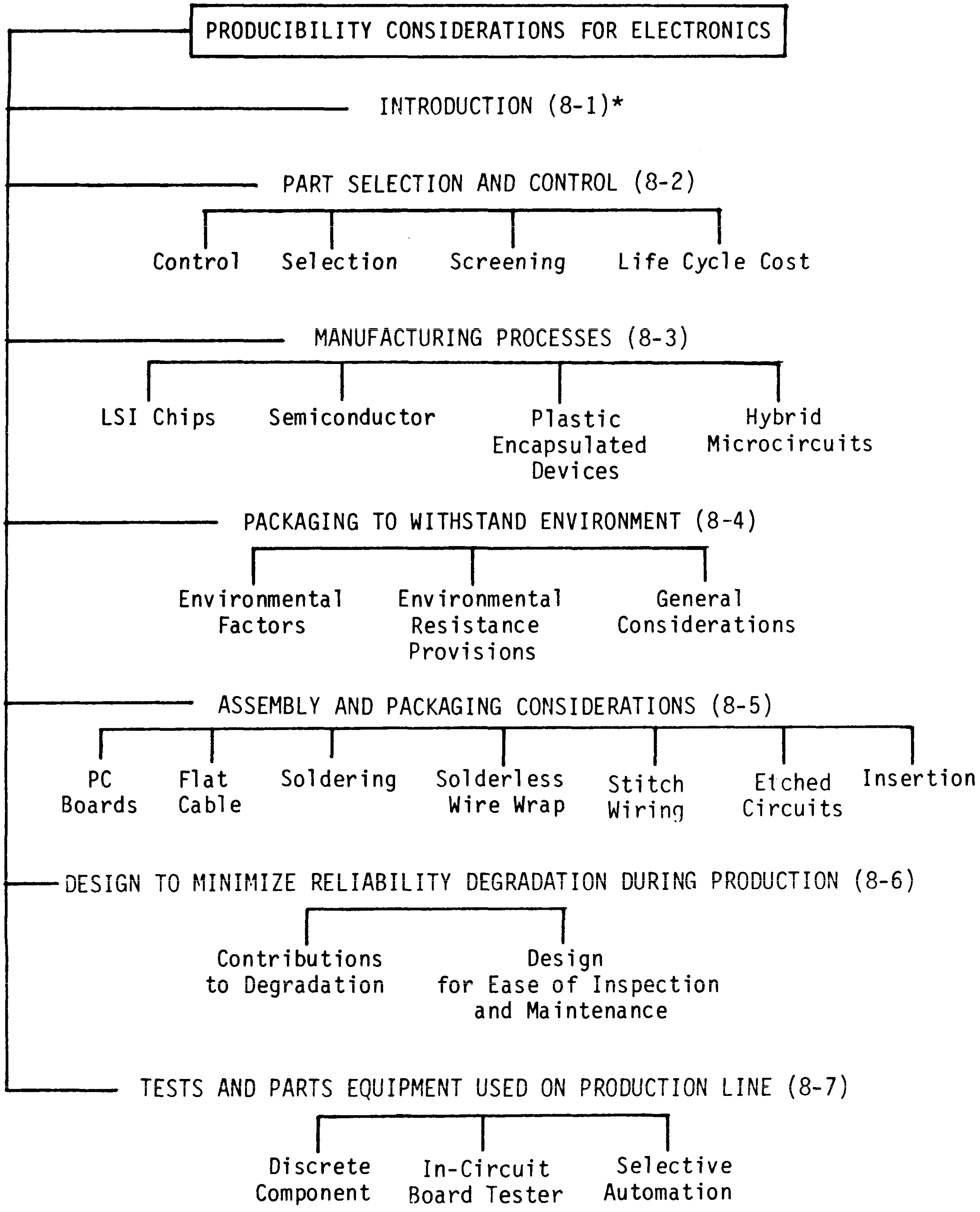

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Figure 1-19. Electronics Generic Tree

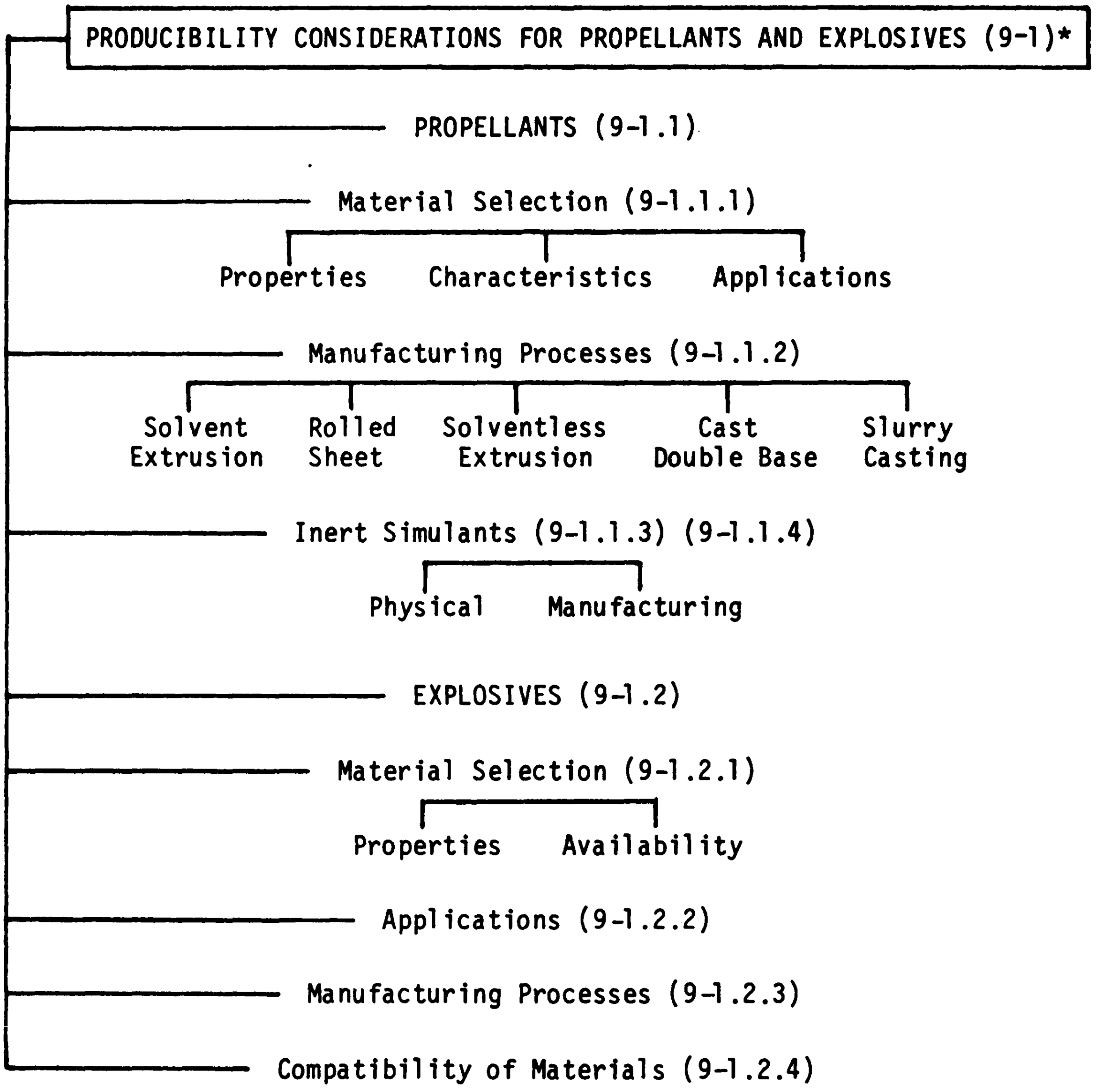

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Figure 1-20. Propellants and Explosives Generic Tree

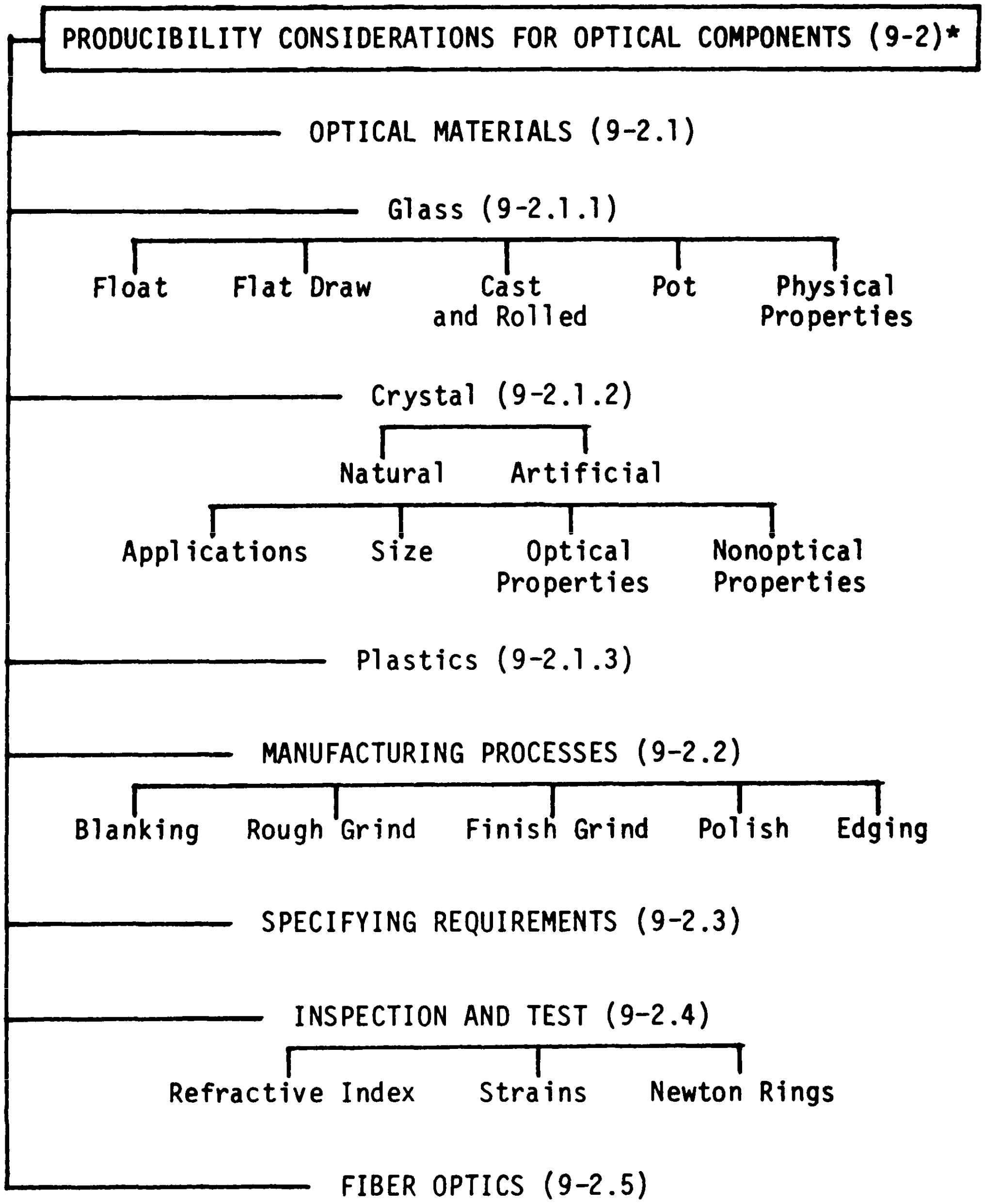

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Figure 1-21. Optical Components Generic Tree

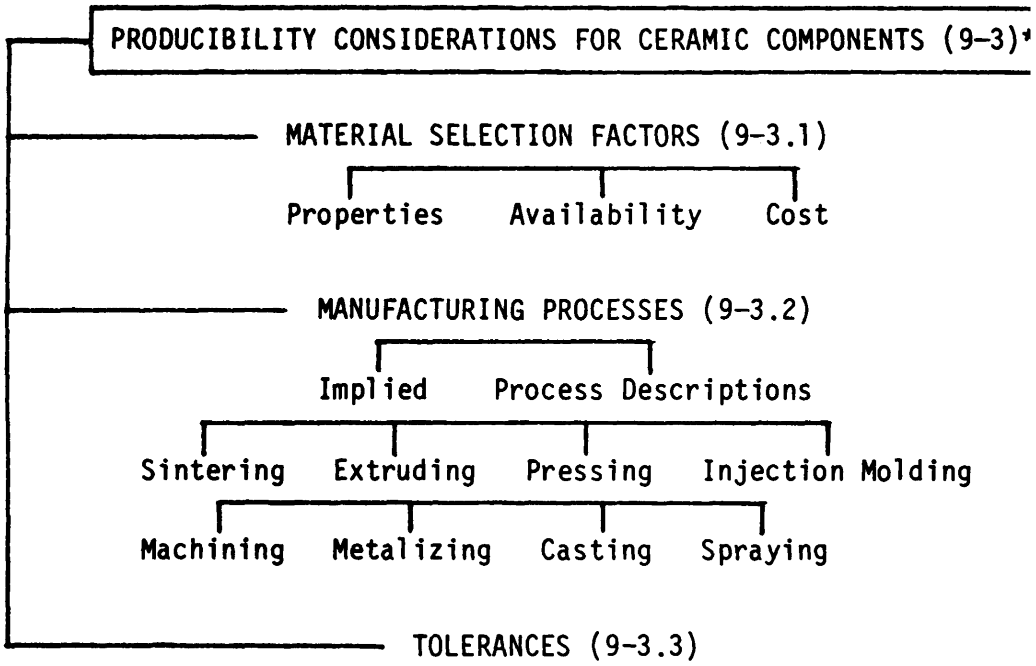

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Figure 1-22. Ceramic Components Generic Tree

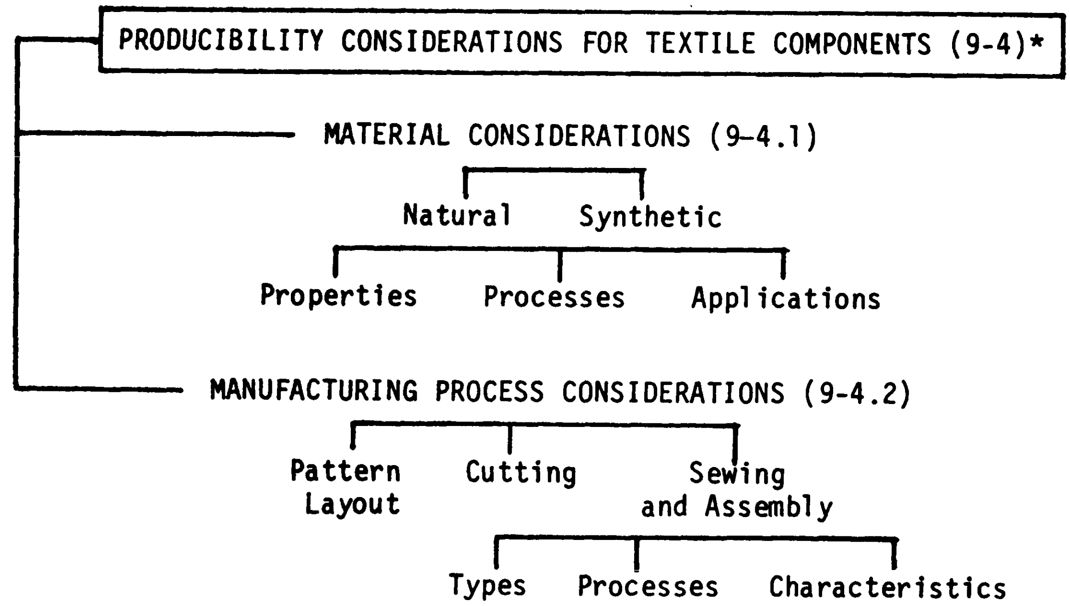

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Figure 1-23. Textiles Generic Tree

CHAPTER 2

PRODUCIBILITY ENGINEERING

Producibility engineering is discussed as an independent and an organizational junction. The interrelationships of the producibility junctions with the design process and development process junctions, as described in Department of Defense (DoD) Directive 5000.1, are included in the discussion. The development of checklists and a producibility plan for each phase of the life cycle of an item are pertinent subjects covered. Tools and techniques useful in the producibility junction and used by the producibility engineer are described and illustrated.

2-1 INTRODUCTION

Most fields of engineering are recognized disciplines (mechanical, industrial, electronic, chemical, etc.), and these disciplines have recognized curriculums of study, position titles, and job duties. Producibility engineering is not a recognized engineering discipline per se. It is, however, an inherent job element of each of the recognized disciplines. More recently, producibility as a function has been receiving greater attention both in civilian industry and in Govrernment. Department of Defense DoD Directive 5000.1, on major system acquisitions, makes producibility considerations a requirement prior to the release of a system for initial or limited production. Additionally, a growing number of industrial firms have initiated formal producibility functions. Originally, the primary emphasis was on obtaining systems with a shorter production cycle at a reduced acquisition cost. Producibility considerations now strive to obtain a system at a lower cost with shorter lead times while not adversely impacting on other design requirements, such as performance, reliability, and maintainability. Producibility engineering is valid only if it reduces the acquisition cost without increasing the operating costs.

Systems development, planning, and acquisition must all incorporate producibility considerations. History has demonstrated that as the complexity of systems increases, so does the acquisition cost. Therefore, producibility programs are imperative as a management means for assuring that practicality is addressed and that the high cost associated with the increasing complexity of systems is scrutinized and warranted. It is recognized that the functions of producibility must be performed by a team of specialists assembled from other functional areas. One individual cannot possibly perform all of the requirements of producibility without assistance from other functional areas. Consequently, organizing for producibility is of prime importance to a successful function, and understanding the activities of producibility engineering is of prime importance in organizing for producibility.

2-2 PRODUCIBILITY ENGINEERING ACTIVITIES

During the creation of a design, the primary objective is to satisfy all of the specific functional and physical objectives, i.e., performance requirements. Concurrently, the producibility engineer, working within those design constraints, is attempting to achieve a design that is the most producible. A thorough understanding of the interaction between the designers' activities and objectives and the forces and activities directed toward producibility engineering is imperative.

2-2.1 SPECIFIED PERFORMANCE CHARACTERISTICS

The performance statements in the system description provide a detailed description of the intended performance of the system. They will generally include:

1. Performance characteristics:
   a. Operational
   b. Employment
   c. Deployment
2. Operability:
   a. Reliability
   b. Maintainability
   c. Useful life
   d. Environmental conditions
   e. Transportability
   f. Human performance
   g. Safety
   h. Dangerous materials and components
   i. Life support.

In the performance statements, the designer is told what the system must accomplish. These statements are the performance objectives for the system. Subsequent statements in the requirements section describe the physical, functional, and support frameworks for the system and place substantial constraints on the design. The relationships between the performance objectives and the constraints establish the potential standards of producibility for the design. If the statements giving constraints rigidly specify the system, subsystem, component, materials, and manufacturing or production processes, the producibility level of the design is largely predetermined (even though it may not have been a primary consideration in establishing the specification). As the degree of latitude expressed in the constraint statements increases, the producibility potential of the system becomes greater, and the direct influence of the design engineer upon eventual producibility increases proportionally,

2-2.2 PHYSICAL CHARACTERISTICS

The statements of physical characteristics for the system reflect the first constraints placed upon the designer. These statements generally include:

1. Required physical limitations of the proposed system:
   a. Dimensions
   b. Weight
   c. Major assemblies
2. Requirements for operator station layout
3. Intended means of transport
4, Degree of ruggedness required (environmental conditions):
   a. Storage
   b. Transportation
   c. Use
5. Potential effects of explosives
6. Hazards:
   a. Biological
   b. Mechanical
   c. Radiation
   d. Other.

These statements will place some constraints upon producibility. (The system might, for example, be more simply designed and more cheaply and easily fabricated if the weight limitations could be increased by 5%) At the same time, the requirements that they impose furnish additional producibility objectives since they describe physical characteristics toward which considerations of producibility can be directed.

2-2.3 PRODUCIBILITY ENGINEERING ACTIVITIES

Regardless of the degree of complexity of an item, the objective of the design is to create an item that will satisfy all of the specified performance and physical objectives and concurrently maximize producibility. However, several influences of the performance and physical objectives will complicate achievement of the producibility engineering activities described in the subsequent paragraphs.

2-2.3.1 Simplicity of Design

In this activity the producibility engineer is seeking to eliminate components of an assembly by building their function into other components or joining separate components into integral components through application of unique manufacturing processes. In one case the producibility engineer is working with the design engineer to identify and eliminate excess components; in the other case he is working with a manufacturing engineer investigating net shape processes to combine components.

2-2.3.2 Standardization of Materials and Components

A wide variety of off-the-shelf materials and components is available; depending on their availability and cost, they can constrain or greatly assist the producibility engineer. The producibility engineer must always verify these factors during the analysis.

2-2.3.3 Production Capability

Determination of the available production capacity and its capability to produce the desired end item is a critical activity of the producibility analysis. In this endeavor the producibility engineer will work closely with manufacturing engineers in applying the principles of the Army's manufacturing technology program.

2-2.3.4 Design Flexibility

This producibility objective requires the producibility engineer to interact with design engineers, materials engineers, and manufacturing engineers to assure that the design offers the maximum number of alternative materials and manufacturing processes to produce an acceptable end item. Unwarranted limitations of materials or processes seriously constrain the producibility analysis.

2-2.3.5 Test and Evaluation

There are two basic activities of the producibility engineer in test and evaluation. The first is the determination— through the design engineer, quality assurance engineers, and the requirements documentation— that the specified quality levels are necessary. The second is the determination, with quality engineers, that the most economical and available methods for controlling the quality levels are used.

2-2.3.6 General Activities

Conducting the major activities requires a close interaction with a large variety of disciplines. While it is not necessary that the producibility engineer be intimately familiar with all the techniques of these disciplines, a reasonable familiarity with the various techniques and tools is imperative. Simulation, risk analysis, scheduling, and break-even analyses are just a few of the techniques or tools. However, in general, most are tools for conducting trade-off studies, which are the foundation of almost all producibility engineering activities.

2-3 ORGANIZING FOR PRODUCIBILITY

There are four alternatives to consider when determining how to organize to achieve producibility:

1. Do nothing and leave the achievement of producibility to those dedicated personnel in the various existing functions to concern themselves with achieving producibility by whatever means possible.
2. Assign responsibility for producibility engineering to the personnel of the existing product engineering function. They already have responsibility for product design and, consequently, are in the best position to effect producibility in the design.
3. Assign responsibility for producibility to the personnel of the production engineering function. They are already in the best position to understand the production processes and their effect on producibility.
4. Establish a new function of producibility engineering and staff it with personnel of product engineering and production engineering background with emphasis on the latter.

Adoption of any of these alternatives will entail an educational process and a dedication to the principles of producibility as set forth herein.

Before considering each of these alternatives, there is a summary of some sound research development test and evaluation management philosophy which was voiced by the Assistant Secretary of the Army for Research and Development (Ref. 1).

"Capable people are the 'Sine Qua Non'." Without capable people, there is no management philosophy whatsoever that can assure the success of research and development endeavors.

"A fundamental principle of research and development fund allocation is return on investment." Organizations as well as individuals need to be monitored continually to measure their long-term return and investment. These organizations should grow or contract in accordance with this return and investment. The "bottom line" in this case is measured in terms of improvement in the fighting capability of our forces in the field.

"Split responsibilities are the spawning ground of management indecisiveness." A split of responsibilities for the achievement of a specific task not only impedes the ability to address the task as a whole but at the same time undermines the assignment of accountability.

"Controversy sharpens." In dealing with technology-related matters, flaws in decision-making nearly. always surface sooner or later simply through the inexorable power of the laws of nature. It is, therefore, preferable to be aware of all sides of an issue before making decisions rather than to learn new facts after decisions have been made.

"Time is often not of the essence." The preponderance of evidence regarding the conduct of major development programs in peacetime indicates that it is better to "do it right" than to "do it fast". There is simply not time enough to hurry.

"The generation of requirements is a closely knit iterative process involving both users and technologists." Many, if not most, items of new military hardware have been a consequence of growth in technology. That is, the "requirement" was always there; the ability to satisfy it was lacking. Accordingly, sound requirements cannot, in general, be created through negotiations at arm's length between the user (who knows what he needs) and the technologist (who knows what can be provided).

"Requirements for new systems should demand only that handful of key characteristics which are essential to the item utility." Features that do not contribute measurably to these few key characteristics should not become a part of the item in question.

"The scrutiny required in rejecting a new idea should be commensurate with the scrutiny involved in accepting it." No organization is immune to the atrophying affects of NIH (not invented here) with the result that safeguards need to be established to protect innovation.

"Cost analysis is not separable from the requirements generation process." All too often requirements have been written in a vacuum with respect to the cost implications; the true quantity and quality trade-offs are addressed only after the fact.

"The most perishable asset in our research, development, test, and evaluation activity is the technological base." The item with the longest lead time to replace, if lost, is the technological base; it must be carefully guarded in times of budget austerity. Similarly, it should enjoy a minimum amount of external management except for the approval of goals and the assessment of return on investment as measured against those goals.

"The technologist works best when directly exposed to the user." A close coupling of the user and the technologist generates significant synergistic effects with regard to assuring the exploitation of new ideas, focusing idea generation in areas of significant payoff, and simply in motivating the efforts of the technologist.

"No change is a small change." Changes to hardware should be made only for the most compelling of reasons—the perpetuation of an engineering effort is not one of them.

2-3.1 DO-NOTHING PHILOSOPHY

Acceptance of this "business as usual" philosophy would be to deny the great wealth of examples of poor producibility, many of which are cited throughout this handbook. If one accepts the philosophy that producibility engineering is neded, the only remaining question is the degree and value of the need. However, one point is very clear: Any program without a focal point and an assignment of direct responsibility is doomed to failure.

2-3.2 ASSIGN RESPONSIBILITY TO PRODUCT ENGINEERING

As pointed out previously and elsewhere in this handbook, the product or design engineer is already in the position to have the greatest impact on determining the producibility of an item. However, it must be remembered that the primary objective of design is to meet the requirement specifications of functional and physical characteristics. This is not to say that there is no concern for producibility; to the contrary, there is great concern. One of the primary considerations of design is the constraint of materials and manufacturing processes. To add these to the responsibility for producibility engineering would be to the detriment of producibility engineering or design engineering; neither of which is a desirable outcome.

2-3.3 ASSIGN RESPONSIBILITY TO PRODUCITON ENGINEERING

This action is the diametrical opposite of that discussed in par. 2-3.2. The situation that must be avoided is the one in which the organizational assignment is to one of two organizations whose respective objectives are diverging rather than converging. The age-old barriers between production and design do not become any less visible with time. Certainly production engineering is in the best position to understand fully all of the constraints and capabilities of the manufacturing processes. However, without truly capable people highly skilled in producibility and in its coordination with production, the outcome would be questionable. Further, by the time production engineering sees the design, it is usually frozen,

2-3.4 ESTABLISH NEW FUNCTION

The establishment of a new function with prime responsibility for producibility engineering can take many forms. It can be a completely new organization; it can be a review team made up of personnel from currently assigned project functions, or it "can be a permanently assigned committee made up of personnel currently assigned to functional areas. Whether the organization is a permanent staff or a part-time staff is not significant for both will function similarly. There is also a need, because of the accelerating advances being made on materials and processes, for an organization that allows for a close interaction between design and manufacturing.

In addition to the important interaction between design and manufacturing engineers, there is also an important interaction among design, manufacturing, quality control, and marketing as shown in Fig. 2-1.

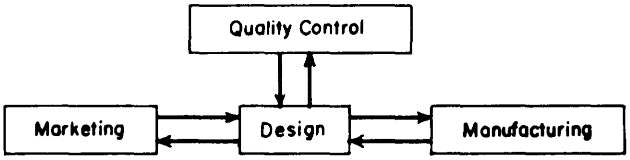

Figure 2-1. Producibility Interactions

Considering the technology explosion of recent years and the number of new processes and materials that are currently being developed, it would seem wise to be able to bring specialists in the areas of materials, manufacturing, and test and evaluation as well as specialty vendors into the design process at an early stage. This can be done in various ways and might involve process engineers, cost analysts, tool engineers, industrial engineers, quality engineers, and metallurgists. Consequently, the form of the new organization is not important to this discussion. The main point is that detailed interaction should be possible between the product design engineer and the previously mentioned personnel.

The material covered in this handbook is, therefore, important not only to the product designer as a supplement to his design knowledge, but also to the process engineers and manufacturing engineers of the future who must be ready to fulfill their responsibilities with respect to their roles in product design. Without recommending or endorsing any particular organization, two approaches are discussed in subsequent paragraphs that seem particularly conducive to achieving producibility. Both of these have been observed in use in industrial organizations and appear to be working quite well.

2-3.4.1 Producibility Review Team

In this concept personnel are assigned to the team from the various functional areas (design, product engineering, manufacturing engineering, industrial engineering, materials engineering, etc.). The team captain is assigned by management or selected by the team; selection depends on individual needs. A team is assigned to only one product program; new teams are assigned for each new product program. Normally, the team captain is the only one on full-time assignment except in the case of very large programs for which additional, competent manufacturing engineers are assigned full-time. The team meets on a regular basis to discussant to analyze the producibility of selected product components. Additionally, the team conducts specifically identified technological searches. The searches are directed toward finding the solution to a particular production problem or toward investigating areas of new manufacturing technology for general use or application by this or other producibility review teams,

2-3.4.2 Producibility Committee

In this organization the chairman of the committee is assigned to the function full-time. All other members are drawn from the various functional organizations and serve as part-time members much like those on the review teams. One significant difference, though, is that the committee assignment is permanent rather than on a project-by-project basis. This adds a degree of professionalism and continuity, which is quite valuable. The group has the power to accept or reject new designs based on the producibility factor. The signatures of the group members are required prior to approval of all new designs. This signature approval is not just a “rubber stamp”, but it carries with it responsibility for assuring producibility in all new designs. The group members work with the designer during the initial design phases and thereafter serve as coordinators between design and manufacturing.

2-4 DESIGNING FOR PRODUCIBILITY

This paragraph provides a general description of the design process, the iterative nature of the process, and the interrelationships of the various functions involved. Subsequent paragraphs address the relationship between the design and the producibility of an item and how producibility can be enhanced through proper considerations during development. This will include producibility engineering and planning (PEP) measures, technical data items, and trade-offs with other systems analysis areas.

2-4.1 INTRODUCTION

During each stage of development, an organized and systematic pattern of events must take place if a design is to meet fully all of its objectives. Implicit in these objectives is the requirement that a design achieve the highest possible degree of producibility. However, producibility goals are rarely defined in documents describing the end item, such as letter of agreement (LOA), required operational capability (ROC), or the letter requirement (LR) (Ref. 2).

Since the design effort has often been conducted to satisfy a description that includes no reference to producibility, the responsibility for producibility may easily be relegated to an unimportant position.

2-4.2 THE DESIGN PROCESS

No fixed pattern of activity applicable to all design programs exists. The sequence and nature of events must be governed by factors such as system complexity, the extent to which new processes and techniques are employed, the structure of the design organization, program schedule, and other variables. Even with an effective approach the design effort must remain an iterative process in which all the principal steps must be followed if an optimized design is to be achieved.

As conditions depart from ideal, increasing consultation among the various specialists contributing to the design is needed. Regardless of the design structure, it is imperative that all of its special aspects be considered simultaneously throughout the entire design cycle. Only with such recurring attention can optimum results be achieved.

Initiation of the development project represents the establishment of the first configuration baseline, the functional baseline (Fig. 2-2), consisting of the LOA and the system specification describing the technical characteristics, and the test and evaluation requirements. The functional baseline also represents the point of transition between investigatory research and development and design engineering. It is at this point in the life cycle that the efforts of the design engineer are introduced and emphasized.

In the case of a major system, a formal validation phase follows. This consists of the initial design work, with any associated developmental hardware fabrication and testing, performed to expand the system specification into a complete series of development specifications for equipment items or major components, minor items, critical components, facilities, and inventory items. This phase does not result in a detailed design but establishes the detailed parameters and specifications from which detailed design engineering can proceed.

The baselines shown in Fig. 2-2 are integral elements of the configuration management system. They would be equally essential whether the formal requirements (Ref. 3) for configuration management did or did not exist. Each baseline represents a datum line, or reference point, from which the design effort must progress. The system specification is the first formally established baseline and the point at which a system design effort begins. Each step in the design effort represents an evaluation through which the system is converted from a raw outline to a detailed, producible description. Thus each step also represents another internal baseline that can be evaluated and measured for conformity to the system specification.

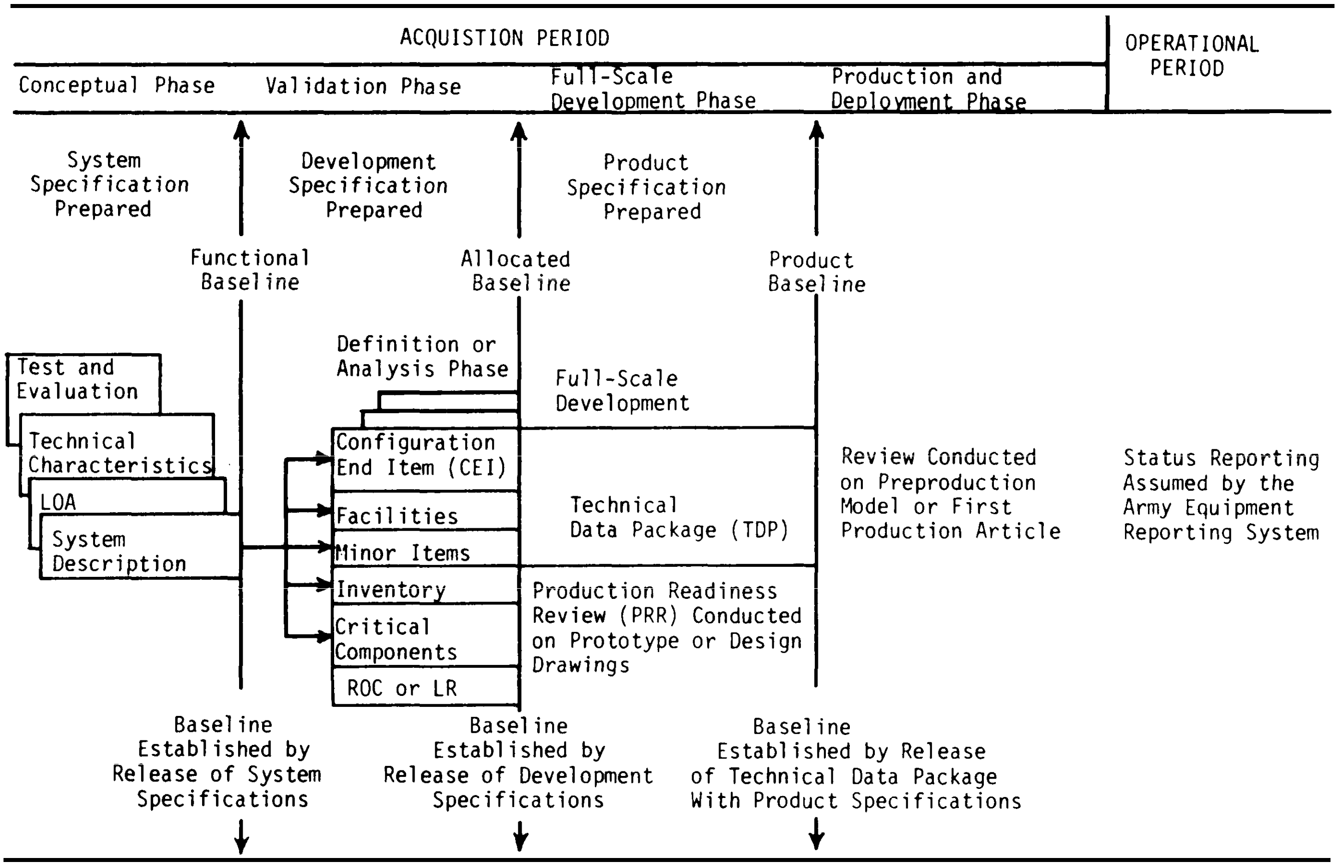

Figure 2-2. Life Cycle Baselines

The design process can be shown in a series of sequential steps (Fig. 2-3). As can be seen, this is not a one-pass operation but is a chain of iterative loops and interactions. The basic design process may be broken down into four basic subdivisions: evaluation, analysis, refinement, and documentation.

2-4.2.1 Evaluation (Steps One, Two, and Three)

As can be seen from Fig. 2-3, the first step of the evaluation is are view of the requirements. The importance of this step cannot be overemphasized. It has been said that a problem properly defined is virtually solved. While this may be optimistic, the fact remains that an improperly defined problem is likely to yield the wrong solution.

The system specifications should define the performance objectives, design constraints, and producibility objectives. However, performance objectives and design constraints often appear to be contradictory, and the producibility objectives are not mentioned. The designer must describe an end product that can be made by many manufacturers as long as they possess the necessary basic machinery and appropriately skilled operators. For this reason, it is especially important that the design requirements be complete and that the trade-offs among the input (performance objectives, design constraints, and producibility objectives) be accomplished in order to design a system that can be procured and reprocured through competitive bidding without recourse to the original design agency.

It is essential to review all design requirements for completeness and clarity and to seek clarification from the responsible activity when these qualities are lacking. If this is not feasible, the parameters that give the designer the greatest number of options should be adopted.

The second step of evaluation is the formulation of ideas on how to meet the cited requirements. This is an indispensable part of any design process. Four suggestions for formulating ideas are

1. Be prolific. Look for many diverse ideas. Do not concentrate on petty design details.

2. Do not avoid wild ideas. An idea may be patently impossible, but statement of it may trigger a related idea that is entirely feasible.

3. Explore new concepts. The tendency to repeat . old approaches and methods can result in design stagnation.

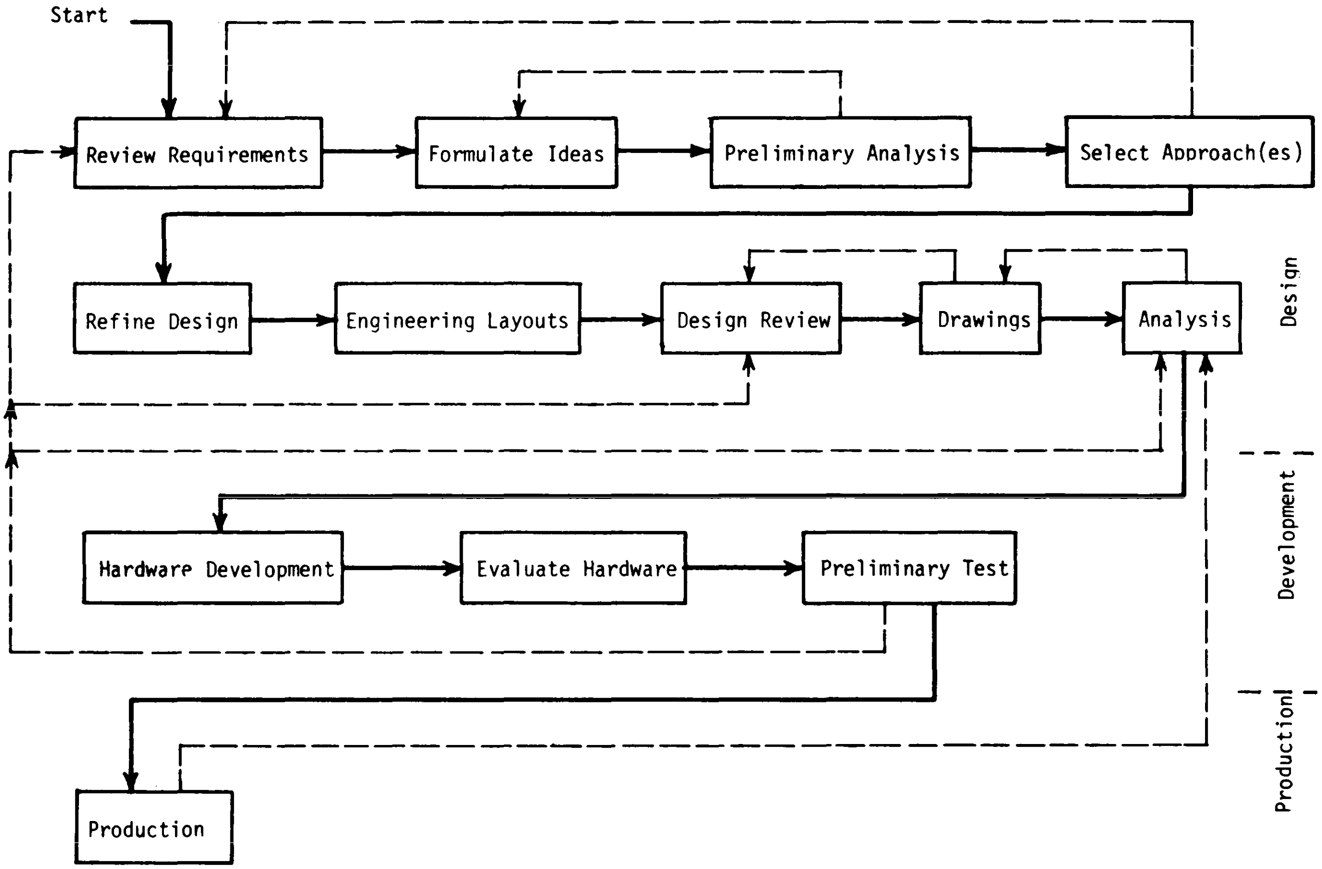

Figure 2-3. The Design Process

4. Avoid limiting generalizations. "It is not practical to use die casting for lots of less than 5000'' may have been true once, but recent developments unknown to the designer may have changed the picture.

The golden rule is to be open-minded. Design is a creative process, and it cannot take place in an atmosphere of needless restrictions, narrowmindedness, and reliance on old concepts. The end product of such an atmosphere is imitation, not creation.

The third step of evaluation is a preliminary analysis of the concepts generated. Here producibility becomes a primary design criteria. The design should be evaluated for cost-effectiveness and ease of production versus the degree of compliance with the functional requirements. Cost-effectiveness and producibility cannot be applied independently at this stage. Each must be evaluated for producibility within the framework of performance objectives and design constraints. Preliminary analyses must be made to select tentatively components, configurations, materials, processes, etc., without locking onto the design of any tentative selections. This selection merely allows the designers to facilitate their evaluation. In fact, if an approach seems to be confined to only one material, process, etc., it should serve to notify the designer that another approach doing less damage to producibility objectives may be a more economical means of achieving the performance objectives.

As shown in Fig. 2-3, this third step is part of an iterative loop. The approaches are analyzed and either are rejected or tentatively accepted. This loop may be traveled a number of times.

2-4.2.2 Selecting Design Approaches (Step Four)

With a number of possibilities to consider, analysis is required to choose the approach that shows the greatest promise. The nature of the particular problem may dictate that several approaches be developed in parallel; however, the steps remain the same. This phase requires, as a minimum, the analysis of four items: risk involved in design alternatives, function versus cost, schedule versus cost, and components versus manufacturing capability. Scheduling is very much a producibility factor. An end item that must go into production in 6 mo cannot use a manufacturing technique that will not be available for 1 yr. However, a possible trade-off of a potential manufacturing development with substantial cost savings may justify rescheduling.

In analyzing components relative to manufacturing capability, the following factors must be considered:

1. Will the item be manufactured in the United States or overseas?
2. Will a commercial component be available several years from now, or does the design specification greatly limit future off-the-shelf procurement, which reduces its cost-effectiveness?
3. Is the component material on the critical list?
4. Are special tools or skills needed?
5. Have unnecessary functions and costs been eliminated?

When these preliminary analyses have been made and the approaches have been given a relative cost-effectiveness rating, the approach to be developed can be selected. The relative ratings and the peculiarities of the specific problem, schedule, funds, etc., will determine whether one or more approaches should be carried into the refinement phase.

2-4.2.3 Refinement (Step Five)

The design approach must evolve into a working, functional assemblage of detail parts and must move from the concept to the specific as shown in Fig. 2-3. Detail parts and areas of design should be sketched to provide a temporary record. Size, weight, possibility of modular construction, reliability, and maintainability objectives should all be examined to determine whether further investigation is warranted. A refined analysis of loads, pressure drops, flows, heating rates, deflections, stresses, and fit should also be made.

2-4.2.4 Documentation (Step Six)

The design bridges the gap between the conceptual and the physical development of the product, i.e.,

1. It serves to define the result of the myriad analyses, investigations, iterations, and refinements that have gone before.
2. It is the vehicle of communication among the designer and management (to whom the approach must be sold), the draftsman (to whom it must be clearly defined), and the many other groups (who are responsible for quality control, prototype production, etc.).
3. It is the working paper used to provide preliminary cost estimates for material, labor, and manufacturing. Sufficient information must be given to provide an understanding of the intent.

The responsibility to make ideas clearly understood cannot be overemphasized.

Orderliness of presentation will facilitate the systematic review for producibility. Descriptive notes may be used to explain more fully processes, materials, functions, and alternates. The combined package must communicate the reasoning behind this approach, the conformance of the approach with objectives and constraints, and the relative cost-effectiveness of it to the approving agency. Layout clarity will greatly influence the acceptance of the design as it proceeds through the remaining steps in Fig. 2-3, which are self-explanatory.

2-4.3 PRODUCIBILITY IN THE DESIGN PROCESS

Concern for producibility must be exercised at the start of the conceptual phase and will influence the entire design effort from that point on in every item of the life cycle. Inherent producibility limitations must be recognized and addressed at each stage of the life cycle process. For example, broad producibility considerations might include the selection of materials and manufacturing processes (Fig. 2-4). This is a highly iteratite process filled with decision points, each of which permits a potential trade-off against some other requirement. Howtever, all demands upon the system-such as reliability, availability, maintainability, safety, or producibility—heavily interact with each other throughout the design process and create the need for trade-offs. The steps in Fig. 2-4 are self-explanatory.

2-4.3.1 Producibility Engineering and Planning (PEP) Measures

Producibility engineering and planning (PEP) measures are funded as part of the research, development, test, and evaluation program. These measures are used for the development of technical data packages, designing, and in some cases proving, special purpose production equipment and tooling, and computer modeling or simulation of production processes to better assess producibility. This is shown graphically in Fig. 2-5.

2-4.3.1.1 Purpose of PEP Measures

The purpose of PEP measures is to insure that materiel designs reflect good producibility prior to release for production. PEP measures include the engineering tasks undertaken to insure a timely and economic transition from development to production. They also include the confirmation of producibility during the latter stages of development. The objective of the PEP effort includes, but is not necessarily limited [o, the following:

1. Develop technical data packages
2. Design and prove out special purpose production equipment and tooling
3. Computer modeling simulation
4. Engineering drawings
5. Engineering, manufacturing, and quality support information
6. Details of unique processes

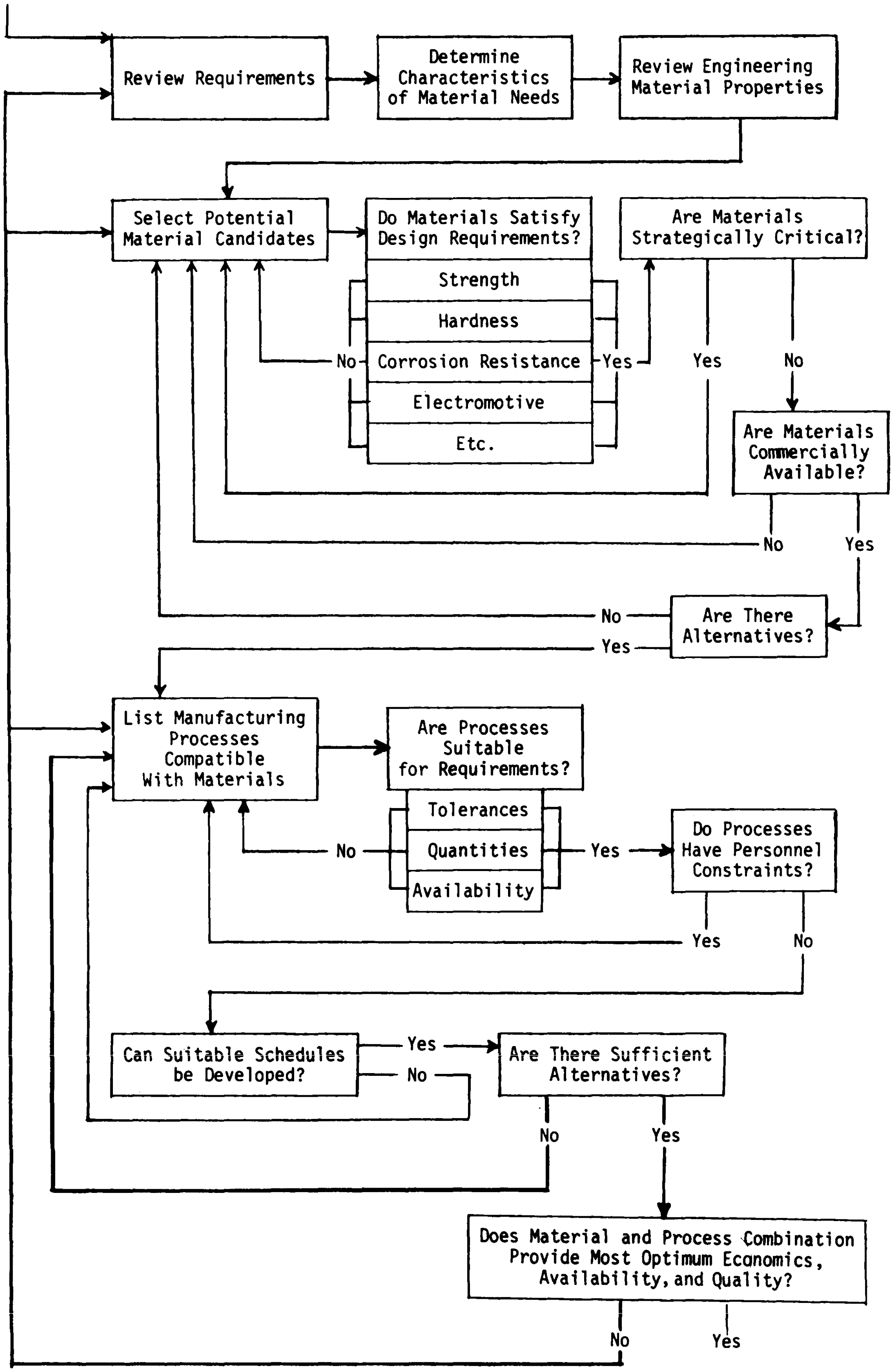

Figure 2-4. Producibility in the Design Process

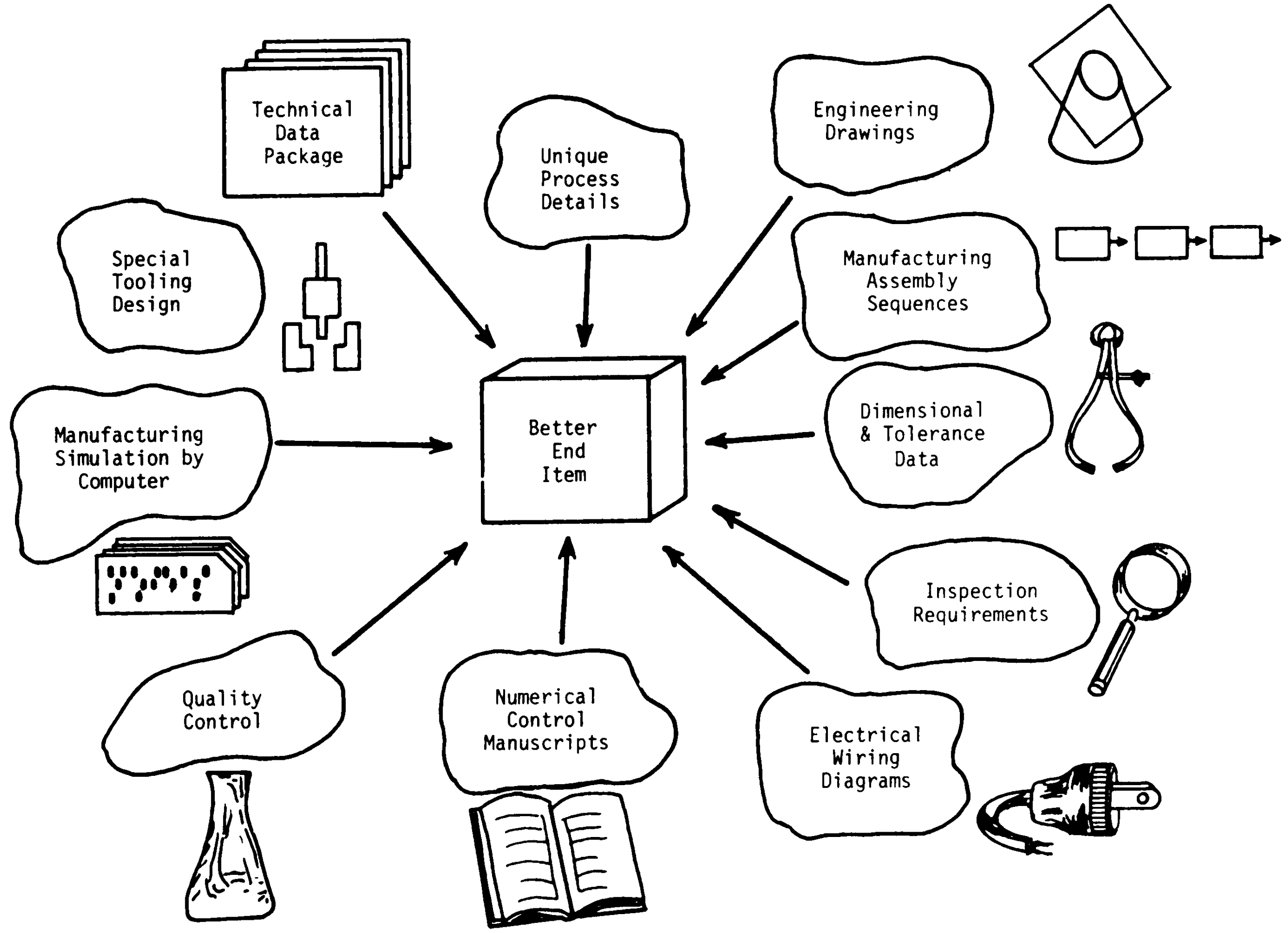

Figure 2-5. Producibility Considerations

7. Details of performance ratings, and dimensional and tolerance data

8. Manufacturing assembly sequence method sheet schematics

9. Mechanical and electrical connections wiring diagram

10. Material and finishing information

11. Inspection, test, and evaluation requirements

12. Calibration information

13. Quality control data.

PEP measures are mostly software oriented and in general include, but are not necessarily limited to, the following:

1. Examining the total technical and procurement data packages for:

a. All dimensions and associated tolerances, parallelism, perpendicularity, etc.

b. Appropriateness and availability of material selected

c. Unique or peculiar processes and process specifications

d. Special handling

e. Special tooling

f. Packaging and packing information

g. Quality control data and procedures

h. Adequacy of surface and protective finishes

i. Inspection, test, and evaluation requirements

j. Maintenance engineering/integrated logistics support

k. Requirements for in-line production test equipment and end item test equipment

1. Manufacturing assembly sequences

m. Suitability for second source identification

n. Cost-effectiveness analysis

o. Calibration equipment and information

p. Adequacy of mechanical and electrical connections.

2. Exploitation of foreign manufacturing tech-

nologies for enhanced producibility

3. Performing risk analysis of new manufacturing processes
4. Computer modeling or simulation of manufacturing processes to assess producibility
5. Planning for plant layouts
6. Applying value engineering principles and methodology throughout development
7. Examining processes (as created by the combination of equipment and operation) to determine hazards to man and the environment; preparing environmental impact assessments (EIA) and environmental impact statements (EIS) as appropriate
8. Determining the need for a manufacturing technology development (MTD) or manufacturing methods and technology (MMT) effort
9. Numerical control part program manuscripts
10. Group technology considerations in part design and fabrication plan
11. Computer-aided manufacturing planning
12. Producibility plan supportive of initial production facilities requirements.

Although PEP is concerned primarily with software, it does permit fabrication of pilot lots to assure producibility of the design, materials, tools, and processes selected. This is not to be construed as authority to use PEP funds for the listed elements in their entirety. There are certain limits and constraints that must be observed.

2-4.3.1.2 PEP Limits and Constraints

Limits and constraints on PEP funding are

1. Tooling and Equipment. The only tooling and equipment that can be built and proven by fabricating pilot lots under a PEP measure are those that are high-risk items and could be considered to have a detrimental effect on achieving the producibility objective.
2. Mobilization Rate Production. PEP is undertaken by the materiel developer prior to quantity procurement to insure optimum producibility and a smooth transition from development into production. If the normal, low-rate peacetime production process is significantly different from the high-rate mobilization production process, it should be anticipated by the producibility engineer by providing adequate alternative processes and materials to assure the producibility of the item under any reasonably expected condition. Normally, the design should specify the materials and processes to provide the best producibility for a high-rate mobilization condition. Peacetime or low-rate production would use an alternate processor material to best optimize the producibility for that rate.

2-4.3.1.3 PEP Measures in the Acquisition Process

PEP in the acquisition process is shown in Fig. 2-6. These efforts are funded by research, development, test, and evaluation (RDTE) and will take place during the advanced development (6.3)* and engineering development (6.4)* phases. PEP should be started as early in the acquisition process as possible to preclude reiterations of designs resulting from changes brought about by producibility analyses. The efforts accomplished during advanced development will primarily address the producibility of critical components. The efforts accomplished during engineering development will extend sufficiently into the low-rate initial production phase’ to insure producibility analysis of the total end item and simultaneously assure the adequacy of the technical data package. This includes changes resulting from low-rate initial production and assuring adequacy of the design for full-scale production. PEP measures should be treated as a separate task in the research, development, test, and evaluation project and should have complete visibility and traceability during the project. They are funded under Army Management Structure (AMS) Code 49 in the RDTE budget. To insure this visibility, the subject of producibility is an agenda item at all program reviews (PR) and production readiness reviews (PRR).

2-4.3.1.4 Responsibility

PEP measures are the responsibility of the materiel developer or project manager (PM). The developer is responsible for validation of producibility when requesting type classification. In providing validation the developer has numerous tools available to him; however, none are more important than a well-engineered and well-executed producibility plan.

2-4.3.2 Producibility Program Plan

This is the program plan under which the producibility analysis will be conducted; it is not to be confused with the actual producibility analysis. The program plan details the organizational structure, authority, and responsibilities of the personnel that will be used to monitor producibility and perform the required analyses. This plan, normally prepared by the developer for the purchaser, outlines the organizational functions, methodology, objectives, and reporting procedures that will be used to insure producibility in the design of an item. The importance of the program plan as a contractual clause cannot be overemphasized. A producibility analysis will often involve data that will require a predetermination of rights to proprietary data. Many manufacturers classify their manufacturing process information as proprietary, and it is advisable to clarify this point with a contract clause on the predetermination of rights. However, it must be recognized that some processes are proprietary and will

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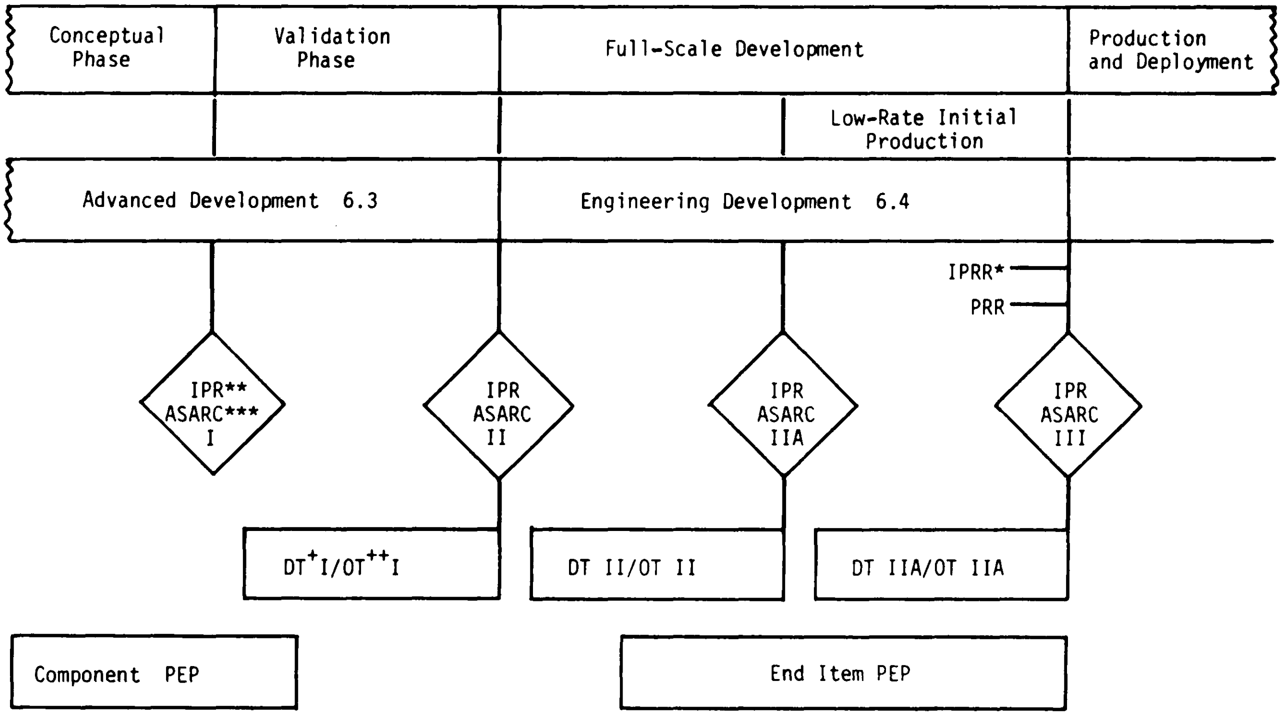
● Funding categories for RDTE funds



*IPRR = initial production readiness review
**IPR = in-process review
***ASARC = Army Systems Acquisition Review Council
+DT = development test
++OT = operational test

Figure 2-6. Producibility Engineering and Planning

remain so. Frequently it will be necessary to purchase producibility engineering as a data item under a research and development contract for an end item, To assist the producibility engineer in the preparation of the data item description, the information in the paragraphs that follow maybe helpful.

2-4.3.2.1 Data Item Description Producibility Program Plan

2-4.3.2.1.1 Description/Purpose

The producibility program plan permits the determination of the manufacturer's ability to maximize system, subsystem, and/or component producibility through the use of an effective organization to identify, establish, and accomplish specific producibility tests and responsibilities.

2-4.3.2.1.2 Application

This data item description is applied when a producibility task has been included in the contract statement of work.

2-4.3 .2.1.3 References

Appropriate references are

1. DoD Directive 5000.34, Defense Production Management
2. DoD Directive 5000.1, Major System Acquisitions
3. DoD Instruction 5000.2, Major System Acquisition Procedures
4. MIL-STD-1528, Production Management.

2-4.3.2.1.4 Preparation Instructions

The producibility program shall be documented in the producibility program plan, which shall contain (but not be limited to) these items:

1. A detailed listing of tasks and procedures used to conduct the producibility program
2. A description of each task
3. An identification of the unit or persons having the task assignment and their responsibility and authority
4. An assessment of known or potential problem areas and their impact on the progress of the program

5. A milestone planning chart or other graphic portrayal of scheduled events

6. The plan shall provide for and schedule producibility analyses to be conducted on each design concept being considered.

7. Alternate approaches will be reported. The plan shall clearly show costs of alternate approaches and the rationale for choosing the approach selected. The costs associated with the selected approach shall be identifiable and integrated into the design to cost estimates. Negative approaches or considerations will also be shown.

8. Detailed procedures and checklists for accomplishing the producibility analyses

9. Detailed procedures and checklists for accomplishing the producibility design reviews.

2-4.3.2.1.5 Producibility Objectives

Considerations should include but are not limited to these areas:

1. To maximize:
   a. Simplicity of design
   b. Use of economical materials
   c. Use of economical manufacturing technology
   d. Standardization of materials and components
   e. Confirmation of design adequacy prior to production
   f. Process repeatability
   g. Product inspectability
   h. Acceptable materials and processes.
2. To minimize:
   a. Procurement lead time
   b. Generation of scrap, chips, or waste
   c. Use of critical (strategic) materials
   d. Energy consumption
   e. Special production testing
   f. Special test systems
   g. Use of critical processes
   h. Pollution
   i. Skill levels of production personnel
   j. Unit costs
   k. Design changes in production
   1. Use of limited availability items and processes
   m. Use of proprietary items without release of production rights
   n. Use of single material or process without alternative.

2-4.3.2.1.6 Need for Requirement

Too often, it is assumed that designing for the use of existing tooling is the most economical approach without giving due consideration to new, more economical materials and processes. Further, designers also tend to design around their most familiar existing processes without due consideration to ongoing manufacturing technology developments. This has detrimental effects on current producibility, and future purchases often result in excessive engineering change orders.

2-4.3.2.1.7 Use of Data

The producibility plan will identify the contractor's system of review of engineering design to assure that the composite of characteristics, which, when applied to equipment design and production planning, leads to the most effective and economic means of production.

2-4.3.2.2 Data Item Description Producibility Analysis

2-4.3.2.2.1 Description/Purpose

The producibility analysis permits the evaluation of the manufacturer's methods of conducting the analysis to determine the most effective manufacturing methods of the end product.

2-4.3.2.2.2 Application

This description is applied throughout the acquisition process of any program whose end result is a production program. The purpose is to assure that the component, subsystem, and system designs meet the standards of producibility.

2-4.3.2.2.3 References

Appropriate references are

1. DoD Directive 5000.34, Defense Production Management
2. DoD Directive 5000.1, Major System Acquisitions
3. DoD Instruction 5000.2, Major System Acquisition Procedures
4. MIL-STD-499, Engineering Management
5. MIL-STD-1528, Production Management
6. MIL-STD-881, Work Breakdown Structures for Defense Materiel Items.

2-4.3.2.2.4 Preparation Instructions

1. Producibility Analysis. The manufacturer shall analyze all engineering drawings, technical data, and the program as a whole for producibility considerations throughout the acquisition process. The manufacturer shall insure that the design will have, consistent with quality and design requirements, the specific characteristics of producibility such as:

   a. Liberal tolerances (dimensions, mechanical, electrical)

   b. Use of materials that provide optimum machinability, formability, and weldability

c. Shapes and forms designed for castings, spinnings, stampings, extrusions, etc., that provide maximum economy

d. Inspection requirements that are the minimum needed to assure desired quality and maximum usage of available and standard inspection equipment

e. Assembly by efficient, economical methods and procedures

f. Minimized requirements for complex or expensive manufacturing tooling or special skills.

2. *Recommendations. The* manufacturer shall submit to the program manager recommendations or changes required to provide the design characteristics specified in the Producibility Analysis paragraph. All recommendations shall include positive and negative alternatives that were considered prior to making the final selection. These shall be supported by appropriate time and cost analyses.

3. *Cost Data.* The manufacturer shall submit "before" and "after" cost data with each recommendation. The cost data shall include all applicable costs of materials, fabrications, assembly, inspection, test, and tools.

4. Producibility Analysis Checklists. The manufacturer shall develop and use checklists in performing the producibility analysis. The contractor may use the following producibility checklists for information and guidance only:

a. *Genera! Aspects of Design:*

(1) Have alternative design concepts been considered and the simplest and most producible one selected?

(2) Does the design exceed the manufacturing state of the art?

(3) Is the design conducive to the application of economic processing?

(4) Does a design already exist for the item?

(5) Does the design specify the use of proprietary items or processes?

(6) Is the item overdesigned or underdesigned?

(7) Can redesign eliminate anything?

(8) Is motion or power wasted?

(9) Can the design be simplified?

(10) Can a simpler manufacturing process be used?

(11) Can parts with slight differences be made identical?

(12) Can compromises and trade-offs be used to a greater degree?

(13) Is there a less costly part that will perform the same function?

(14) Can a part designed for other equipment be used?

(15) Can weight be reduced?

(16) Is there something similar to this design that costs less?

(17) Can the design be made to secure additional functions?

(18) Are quality assurance provisions too rigorous for design or functions?

(19) Can multiple parts be combined into a single net shape?

b. Specifications and Standards:

(1) Can the design be standardized to a greater degree?

(2) Can the design use standard cutting tools to a greater degree?

(3) Is there a standard part that can replace a manufactured item?

(4) Can any specifications be relaxed or eliminated?

(5) Can standard hardware be used to a greater degree?

(6) Can standard gages be used to a greater degree?

(7) Are nonstandard threads used?

(8) Can stock items be used to a greater degree?

(9) Should packaging specifications be relaxed?

(10) Are specifications and standards consistent with the planned product environment?

c. Drawings:

(1) Are drawings properly and completely dimensioned?

(2) Are tolerances realistic, producible, and not tighter than the function requires?

(3) Are tolerances consistent with multiple manufacturing process capabilities?

(4) Is required surface roughness realistic, producible, and not better than function requires?

(5) Are forming, bending, fillet and edge radii, fits, hole sizes, reliefs, counterbores, countersinks, O-ring grooves, and cutter radii standard and consistent?

(6) Are all nuts, bolts, screws, threads, rivets, torque requirements, etc., appropriate and proper?

(7) Have requirements for wiring clearance, tool clearance, component space, and clearance for joining connectors been met?

(8) Have all required specifications been properly invoked?

(9) Are adhesives, sealants, encapsulant, compounds, primers, composites, resins, coatings, plastics, rubber, moldings, and tubing adequate and acceptable?

(10) Has galvanic corrosion and corrosive fluid entrapment been prevented?

(11) Are welds minimal and accessible, and are the symbols correct?

(12) Have design aspects that could contribute to hydrogen embrittlement, stress corrosion, or similar conditions been avoided?

(13) Are lubricants/fluids proper?

(14) Are contamination controls of functional systems proper?

(15) Have limited life materials been identified, and can they be replaced without difficulty?

(16) Have radio frequency interference (RFI) shielding, electrical, and static bond paths been provided?

(17) Have spare connector contacts been provided?

(18) Are identification and marking schemes for maximum loads, pressure, thermal, nonflight items, color codes, power, and hazards on the drawings properly?

(19) Do drawings contain catchall specifications that manufacturing personnel would find difficult to interpret?

(20) Have all possible alternatives of design configuration been shown?

d. *Materials:*

(1) Have materials been selected that exceed requirements?

(2) Will all materials be available to meet the required need dates?

(3) Have special material sizes and alternate materials been identified, sources verified, and coordination effected with necessary organizations?

(4) Do design specifications unduly restrict or prohibit use of new or alternate materials?

(5) Does the design specify peculiar shapes requiring extensive machining or special production techniques?

(6) Are specified materials difficult or impossible to fabricate economically?

(7) Are specified materials available in the necessary quantities?

(8) Is the design flexible enough so that many processes and materials may be used without functionally degrading the end item?

(9) Can a less expensive material be used?

(10) Can the number of different materials be reduced?

(11) Can a lighter gage material be used?

(12) Can another material be used that would be easier to machine?

(13) Can use of critical materials be avoided?

(14) Are alternate materials specified where possible?

(15) Are materials and alternates consistent with all planned manufacturing processes?

e. Fabrication Processes:

(1) Does the design involve unnecessary machining requirements?

(2) Have proper design specifications been used with regard to metal stressing, flatness, corner radii, types of casting, flanges, and other proper design standards?

(3) Does the design present unnecessary difficulties in forging, casting, machining, and other fabrication processes?

(4) Do the design specifications unduly restrict production personnel to one manufacturing process?

(5) Can parts be economically subassembled?

(6) Has provision been made for holding or gripping parts during fabrication?

(7) Are expensive special tooling and equipment required for production?

(8) Have the most economical production processes been specified?

(9) Have special handling devices or procedures been initiated to protect critical or sensitive items during fabrication and handling?

(10) Have special skills, facilities, and equipment been identified and coordinated with all affected organizations?

(11) Can parts be removed or disassembled and reinstalled or reassembled easily and without special equipment or tools?

(12) Is the design consistent with normal shop flow?

(13) Has consideration been given to measurement difficulties in the production process?

(14) Is the equipment and tooling list complete?

(15) Are special facilities complete?

(16) Can a simpler manufacturing process be used?

(17) Have odd size holes and radii been used?

(18) In the case of net shape processes, have alternate processes been specified?

(19) Can a fastener be used to eliminate tapping?

(20) Can weld nuts be used instead of a tapped hole?

(21) Can any machined surfaces be eliminated?

(22) Can roll pins be used to eliminate reaming?

(23) Do finish requirements prohibit use of economical speeds and feeds?

(24) Are processes consistent with production quantity requirements?

(25) Are alternate processes possible within design constraint?

f. Joining Methods:

(1) Are all parts easily accessible during joining processes?

(2) Are assembly and other joining functions difficult or impossible due to lack of space or other reasons?

(3) Can two or more parts be combined into one?

(4) Is there a newly developed or different fastener to speed assembly?

(5) Can the number of assembly hardware sizes be minimized?

(6) Can the design be changed to improve the assembly or disassembly of parts?

(7) Can the design be improved to minimize installation or maintenance problems?

(8) Have considerations for heat-affected zones been considered when specifying a thermal joining process?

g, Coating Materials and *Methods:*

(1) Are protective finishes properly specified?

(2) Has corrosion protection been adequately considered from the standpoint of materials, protective measures, and fabrication and assembly methods?

(3) Have special protective finish requirements been identified and solutions defined?

(4) Can any special coating or treating be eliminated?

(5) Can precoated materials be used?

h. Heat Treating and Cleaning Processes:

(1) Is the specified material readily machined?

(2) Are machining operations specified after heat treatment?

(3) Have all aspects of production involving heat treating and cleaning processes and their interaction with other production areas been reviewed?

(4) Are heat treatments properly specified?

(5) Are process routings consistent with manufacturing requirements (straightness, flatness, etc.)?

i. *Safety:*

(1) Have static ground requirements been implemented in the design?

(2) Have necessary safety precautions been initiated for pyrotechnic items?

(3) Have RFI requirements been implemented in the design?

(4) Have necessary safety requirements for processing materials, such as magnesium and beryllium copper, been considered?

j. Environmental Requirements:

(1) Have adequate provisions been included to meet the thermal, humidity, or other special environmental requirements?

(2) Has adequate heating and/or cooling been identified and implemented?

k. Inspection and Test:

(1) Are inspection and test requirements excessive?

(2) Is special inspection equipment specified in excess of actual requirements?

(3) Is the item inspectable by the most practical method possible?

(4) Have conditions or aspects anticipated to contribute to high rejection rates been identified and remedial action initiated?

(5) Have required mock-ups and models been provided?

(6) Are special and standard test and inspection equipment on hand, calibrated, proofed, and compatible with drawing requirements?

(7) Are master and special gages complete?

(8) Have nondestructive testing techniques been implemented?

(9) Have adequate provisions been made for the checkout, inspection, testing, or proofing of functional items per operational procedures?

(10) Is nonstandard test equipment necessary?

2-5 PRODUCIBILITY ENGINEERING DURING ACQUISITION

Producibility engineering must be included throughout the acquisition process. However, its major thrust varies with each phase. The producibility engineering activities that occur during each of these phases and how these activities evolve into a producibility plan are described in the paragraphs that follow.

2-5.1 CONCEPTUAL PHASE

During the conceptual phase the system is evolving and is in general poorly defined. Producibility consideration should be introduced in considered, advanced technologies. In assessing advanced technologies and the coordinated design of components and manufacturing processes, simplicity and standardization are two requirements that must be established early and considered throughout the program. However, all requirements of the system, such as performance, reliability, maintainability, safety, and producibility, etc., heavily interact with each other as shown in Fig. 2-7, which creates the need for trade-offs. These can only be considered in light of all their possible ramifications and with recognition that the means to achieve producibility must not result in performance that is less than the minimum level required. Therefore, it is imperative that, as a separate task in the conceptual phase, the manufacturer be required to develop, for submission with his validation phase proposal, a producibility plan of the type described in par. 2-4.3,2. This plan formulates the baseline from which the program office conducts incremental producibility or production readiness reviews during the validation phase. This constitutes the initiation of efforts toward achieving a state of production readiness, which must be achieved by the end of the full-scale development (FSD) phase.

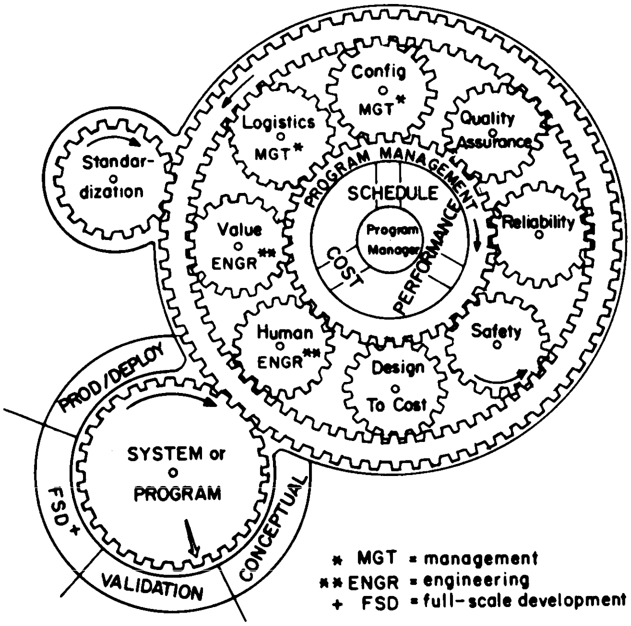


Figure 2-7. System Requirements Interaction

2-5.1.1 Producibility Considerations

An initial producibility estimate is prepared using data from contract studies, advanced technology programs, and previous production experience. This initial producibility estimate is essentially an assessment of current and projected production capacity and capability. This is essential to system trade-offs so that the need for new development can be separated from the existing state of the art technology. Producibility considerations in system feasibility studies require that design/support/production trade-offs be performed. These trade-offs should consider:

1. Alternative fabrication and assembly methods and capabilities/capacities
2. Alternative machine capabilities
3. Available versus required techniques and controls for installation, inspection, test, quality, and cost and schedule balance
4. Critical material status and forecast
5. Available versus required expertise to resolve risk areas
6. Preliminary manufacturing cost estimates
7. Available versus new real property, production equipment, tools, and test equipment
8. Risks associated with production planning based on proposed and projected capabilities, especially when state of the art advances are required.

2-5.1.2 Implementation

Successful implementation of producibility during this phase is dependent upon the availability and use of knowledgeable personnel in the areas of design and methods. This includes present and planned development programs. These experts must represent design engineering, materials engineering, manufacturing engineering, quality assurance, and logistics. During this phase manufacturing personnel will identify current and required industry capabilities and capacities and assure that planning for follow-on phases includes sufficient time for scheduling required developments and manufacturing activities within schedule constraints.

2-5.1.3 Technical Reviews

One means of achieving the desired engineering and manufacturing interface during this phase is through manufacturing participation in system, subsystem, and component technical reviews. One such review, the system requirements review (SRR), may be levied by the program manager in accordance with MIL-STD-1521. The SRR is a formal program review conducted either during the conceptual phase or early in the validation phase. This review is to determine the appropriateness of the initial direction and progress of the contractor's engineering management effort and his convergence upon an optimum configuration. The total engineering management activity and its output are reviewed for responsiveness to the statement of work and system requirements. Areas relevant to producibility efforts include:

1. System/cost-effectiveness analysis
2. Trade-off studies
3. Program risk analysis
4. Producibility analyses performed and planned
5. Engineering integration
6. Life cycle cost analysis.

During the SRR the contractor describes his progress and problems in:

1. Risk identification and risk ranking
2. Risk avoidance or reduction and control
3. Significant trade-offs among stated system specification requirements and constraints, resulting engineering design requirements and constraints, logistic cost of ownership requirements and constraints, and unit production cost and design-to-cost objectives.
4. Significant producibility factors that are visible this early in the program, e.g., critical materials, tooling, manufacturing methods and processes, and facilities.

2-5.2 VALIDATION PHASE

Early producibility analysis will provide a valuable source of information required to meet the objectives of the decision coordinating paper (DCP). The DCP is prepared at the end of the conceptual phase to get the program into the validation phase. The DCP is updated as needed as the system develops. Early producibility analysis will assist in the identification of risks, preliminary cost and schedule estimates, and issues that must be resolved during the validation phase leading to the ASARC II program justification. The objective of the validation phase is to prove the design concept, and this includes validation of performance, cost, and schedule. The results of this phase will be the basis for reaching a decision on whether or not to proceed into full-scale development. The validation phase affords engineering and manufacturing personnel the opportunity to conduct trade-off studies, refine development, and conduct tests. Producibility considerations are more specific and in greater quantity at this time than during the conceptual phase. These considerations create opportunities at this stage of development, when the design is still somewhat fluid, to achieve significant benefit as the design evolves.

2-5.2.1 Producibility Considerations

The producibility considerations during the validation phase enlarge on the detailed producibility objectives and further refine the risks identified during the earlier phase since producibility must be thoroughly' examined prim- to the ASARC II decision. Consideration should include, but not be limited to, the following items:

1. Materials:
   a. Are materials, including alternatives, off-the-shelf put-chases? Are they available where needed?
   b. Have materials been standardized to the maximum extent possible?
   c. Have estimated lead times for the delivery of materials been established?
2. *Manufacturing Processes:*
   a. Will planned manufacturing technology developments be available?
   b. Have all production feasibility}' risk analyses been completed?
   c. Are plans for proof testing critical processes adequate?
   d. Are plans for proof testing tooling adequate?
   e. Are plans for proof testing test equiptment adequate?
   f. Do planned processes have necessary tolerance capabilities?
3. Design *Process:*
   a. Have component and material standardization been maximized?
   b. Have the effects of trade-off studies for producibility been reflected in the design?
   c. Have critical materials (types and quantities) been minimized?
   d. Have constraints on fabrication and assembly been minimized?
   e. Has the use of existing or new industrial resources been proven?
   f. Have adequate management initiatives and organization been established?

2-5.2.2 Implementation

Verification of a contractor's producibility effort, effectiveness, and adequacy will require support from knowledgeable engineering and manufacturing personnel. Program reviews will determine the status of state of the art developments previously undertaken and will identify any new risks and further development requirements resulting from prototype tests and demonstrations.

2-5.2.3 Technical Reviews

Continuing the engineering manufacturing interface established previously, the system design review (SDR) is the final review conducted prior to the submission of the validation phase products. In terms of producibility the purposes of the SDR are to insure that:

1. The updated system specification is adequate and cost-effective.
2. Allocation of required resources is optimally compatible with the requirements of the system.
3. The technical program risks are identified, ranked, negated, and or reduced through adequate trade-offs, hardware proofing, test programs. and comprehensive integration of engineering and manufacturing disciplines.
4. Design decisions resulting from prodiucibility analyses have been reflected in the design and do not adversely impact required operational capability.

2-5.3 FULL-SCALE DEVELOPMENT PHASE

The intended output of the full-scale development (FSD) phase is a preproduction system that closely approximates the final product, written documentation, and actual practices neccssary to entcr the production phase, together with test results that meet requirements. Although manufacturing and engineering problems were addressed during the conceptual and validation phases, additional problems will need resolution as the design evolves from a prototype to a production configuration. During the FSD phase all production and support equipment must be designed and proven capable and within an acceptable cost. on major programs production readiness reviews (PRR) may be conducted in accordance with MIL-STD-1528. These reviews assess the manufacturer's progress toward establishing that engineering and operational systems development and testing hate been substantially completed, that all major development problems have been resolved, and that the weapon system is ready for transition to production. The culmination of producibility efforts to achieve an optimized production schedule and cost should strongly support the program manager's presentation on production readiness at ASARC III.

2-5.3.1 Producibility Considerations

During design and manufacture of FSD units, evaluations of materials, lead times, fabrication techniques, and assembly methods must be accomplished to assure achievement of producibility objectives. The producibility plan will be maintained, implemented, and updated on a continuing basis until a production readiness posture is achieved. The producibility checklist for this phase includes, but is not necessarily limited to, the items that follow.

1. *Materials:*
   a. Do material properties exceed the requirements?
   b. Are material lead times satisfactory?
   c. Have all special material needs been identified?
   d. Does the design permit alternate materials?
   e. Can a lighter gage material be used?
   f. Can a lower cost material be used?
   g. Are materials and alternatives consistent with the most efficient manufacturing process?
   h. Have material producibility trade-offs caused deterioration of the minimum design requirement?
   i. Have the proper design specifications been used to specify material properties after the manufacturing processing?
2. *Manufacturing Processes:*
   a, Does the design create unnecessary difficulties in forging, casting, machining, and other processes?
   b. Are materials and quantities consistent with the planned processes?
   c. Are there satisfactory alternative processes?
   d. Are production processes and production personnel available?
   e. Has necessary tooling (jigs and fixtures) been adequately considered?
   f. Is any special tooling or equipment critical?
   g. Have the most economical processes been specified?
   h. Have production requirements been coordinated?
   i. Are tolerances and sizes consistent with the manufacturing process?
   j. Has consideration been given to assembly and disassembly?
   k. Has consideration been given to test and evaluation?
   1. Are facilities for test and evaluation available? Location? Quantity?
   m. Have long lead time facility needs been identified?
3. *Design Process:*
   a. Can the design be replaced by a commercially available item? By an existing design?
   b. Can the design be simplified, i.e., fewer parts?
   c. Can similar parts be made identical?
   d. Are test, inspection, or evaluation criteria too stringent?
   e. Can proprietary items or processes be eliminated?
   f. Are contours and configurations consistent with the most efficient manufacturing method?
   g. Are tolerances overly restrictive?
   h. Has maximum standardization been employed?
   i. Are specifications consistent with requirements?
   j. Are there any nonstandard or special design requirements?
   k. Are the drawings totally adequate and descriptive?
   l. Have all possible alternatives been shown?
   m. Are any catchall specifications improperly applied?
   n. Can replacement parts be disassembled and reassembled without special tools or equipment?
   o. Are protective finishes necessary and properly specified?
   p. Are process routings consistent with product requirements?

In this phase of the process, producibility efforts are directed toward:

a. Facilitating the readiness of the system to enter the product ion process
b. Assuring that the system can be acquired on schedule at minimum cost
c. Assuring that manufacturing cost estimates are realistic.

The program situation may require additional decisions, such as release of funds for long lead time material or effort and additional hardware for test evaluation. Producibility efforts will help to minimize long lead time requirements, and the producibility reviews conducted during this phase can be either independent or integrated with other reviews. For a major program producibility reviews will be an integral part of the required incremental and final production readiness reviews, Each review subteam that deals with areas related to producibility should have at least one member identified as the producibility focal point. Thus considerable man-hours will be saved both in planning for and conducting these reviews. Since producibility reviews consider some of the same information, there will be less data duplication. For programs not requiring formal reviews, independent producibility reviews should be conducted incrementally throughout FSD.

2-5.3.2 Implementation

FSD requires continuing support from engineering and manufacturing with emphasis on the verification that the final design evolves with maximum producibility. Manufacturing engineering skills are now a predominant factor in achieving a smooth transition from development to production. Producibility efforts must consider such activities as production planning and scheduling, manufacturing flow, plant layout, material handling, manufacturing methods and processes, tooling, and inspection and test equipment. Use of outside technical consultants may be required.

2-5.3.3 Technical Reviews

In addition to the SRR and the PRR, there are about five other formal system reviews or audits conducted during FSD that have a varying effect on producibility. These include preliminary design reviews (PDR), critical design reviews (CDR), functional configuration audits (FCA), physical configuration audits (PCA), and formal qualification reviews (FQR). The PDR is conducted on each configuration item (CI) to evaluate the progress, consistency, and technical adequacy of a selected design and test approach and to establish compatibility with program requirements. A successful PDR is required for each CI before detail design is begun. The contractor presents his approach to designing each equipment CI and related support equipment. The following review items are of direct producibility concern during the PDR:

1. *Equipment CI:*
   a. Results of trade-off and design studies
   b. Equipment layout drawings and preliminary drawings
   c. Preliminary mechanical and packaging design
   d. Preliminary lists of materials, parts, and processes
   e. Mock-ups, models, breadboards or prototypes, and preproduction hardware where appropriate
   f. Value engineering consideration
   g. Standardization considerations
   h. Description and characteristics of off-the-shelf equipment
   i. Existing documentation for off-the-shelf equipment and copies of contractor specifications used to procure equipment
   j. Life cycle cost analysis
2. *Support Equipment:*
   a. Verify optimal trade-off of built-in test equipment versus separate test equipment
   b. Verify that the existing Government support equipment is planned to be used to the maximum extent practicable
   c. Review progress of identifying long lead time support equipment items.

The other technical reviews previously identified involve basically the same producibility concerns. However, as the design is firmed up, the producibility opportunities become progressively more restricted.

2-5.4 PRODUCTION AND DEPLOYMENT PHASE

The initiation of this phase does not mark the end of the producibility efforts. Often design and production are concurrent efforts, especially with long lead time items, such as tooling, materials, and purchased parts. Emphasis on cost reduction is a must during production. Although the impact of producibility will be less dramatic than during the previous phases, producibility can achieve significant cost reductions by striving for use of emerging manufacturing technology and by insuring that design changes are producible. Potential producibility design or process changes, especially late in this phase, should be analyzed for the cost of implementing the change then a trade-off decision should be made against the benefits to accrue both to the present program and to follow-on procurements. Since there is considerable overlap between production and deployment, the producibility studies conducted during development and production can be viewed for their impact on the operational activities, such as reliability and maintainability.

2-5.4.1 Producibility Considerations in Initial Production

The producibility plan developed during the conceptual phase and implemented and updated throughout the validation and FSD phases furnishes program management a continuous thread of documentation to evaluate and verify the achievement of producibility during the fabrication, assembly, installation, acceptance tests, and final checkout of the equipment of the first operating units. The experience and related information documented in the development phases would be useful in achieving more efficient use of manufacturing resources in the production phase. The specific producibility activities include, but are not limited to, the following checklist items:

1. Process and methods analysis to minimize the manufacturing costs and lead times and to maximize quality
2. Application of alternative materials
3. Investigate manufacturing design changes for cost reduction
4. Evaluation of engineering change proposals to insure producibility
5. Application of new manufacturing technology.

As experience in production is gained, process and methods refinements may be required. The user may identify deficiencies in the operational units that require product redesign, hence, further producibility analyses. The results of these analyses may not only lead to manufacturing cost reductions, but also may help to develop the initial producibility estimate portion of future requirements.

2-5.4.2 Implementation

During the production phase engineering and manufacturing will again be required to support producibility activities. Major effort will be exerted by engineering and manufacturing staffs during evaluation of change proposals. The manufacturing department is responsible for resolving production problems in the most efficient and effective manner to assure continued producibility.

2-5.5 PROGRAM PHASE SUMMARY

The intensity of the producibility effort will be dependent on the forcefulness of the program manager and will vary for each supporting resource during the various program phases. Producibility programs will be most active during validation and FSD when the vast majority of system design takes place. However, if producibility is to achieve significant benefits for a program, it must be addressed continuously from the initial production feasibility estimate during the conceptual phase through production and deployment.

2-6 USEFUL TECHNIQUES FOR PRODUCIBILITY ENGINEERS

Numerous methods exist for analysis and quantitative decision making by the producibility engineer. Brief descriptions of several of these methodologies are provided, and knowledge of these methodologies by the producibility engineer will permit an analysis of his own producibility problems. They also may be used as a tool for verifying a contractor’s analysis. The techniques discussed in subsequent subparagraphs are cost estimating, network techniques, simulation, break-even analysis, sensitivity analysis, value engineering, relevance trees, and tolerance analysis.

2-6.1 COST ESTIMATING

Product costs include the costs of material, labor, and equipment. There can be trade-offs between the various costs. For example, a more expensive material may reduce the machining costs. In order to develop the least costly product design, the designer must have a way of estimating those costs. For more information on cost estimating than is presented in this handbook, see Ref. 4.

Estimating material costs is reasonably straightforward. It is necessary to consider the cost of the raw material minus the value of the scrap, and volume may influence the cost per piece.

Estimating labor requirements is less straightforward. Given the operations that must be performed, one must estimate the time required to perform those operations and the skill level required.

There is a variety of methods for estimating time requirements in advance of production. The methods to be used will be different during different stages of the design processes. Coarser estimates are adequate during the earlier stages while more precise estimates are needed at the later stages. Four basic methods are described: technical estimates, historical data, predetermined time standards, and elemental standard data.

2-6.1.1 The Technical Estimate

As the title implies, this is an estimate provided by a person technically qualified to recognize the various phases of the work to be accomplished. The job is broken down into phases, and time is estimated for each phase. For more detail see Ref. 4.

2-6.1.2 Historical Data

These data rely on a statistical standard and have been developed to a high degree in the Federal Government. This standard establishes a statistical relationship between gross work units, such as tons handled and man-hours expended. This requires data on the past performance of individual jobs producing similar products. The data are expressed in man-hours expended and units produced. For more detail see Ref. 4.

2-6.1.3 Predetermined Time Standards

These standards, often called microdata, are derived from tables of time values for fundamental types of motions. The method for performing the job must first be described in terms of elements. Then the elements are broken down into basic motions pertinent to the particular predetermined time systems. Widely used systems include methods-time-measurement (MTM), work factor, and basic motion/time study. The result provided by these synthetic standards is an estimate of normal time for the task.

With MTM for each type of motion element, the standard time is dependent on certain physical variables, such as distance, and on classifications of the sensory control required. For example, for the element “reach” the major variable is distance, but there are five classifications of “reach” that specify the conditions of the object to which one is reaching, such as an object in a fixed location or an object jumbled with others in a group.

In developing the r-notion analysis for a task, the appropriate reaches, grasps, and moves are matched to fit the general situation of required sensory control. For example, to obtain a part from a supply bin and place it in a fixture, one would first reach to an object jumbled with others in the bin. For grasping the object the tables indicate that the grasp time will depend on the part size classification. Moving the part to the fixture requires close control because the fixture is placed in an exact location. The time required to position the part in the fixture depends on the closeness of the fit between the part and fixture, the symmetry (how much orientation is required to align the mating parts), and the ease of handling (characteristics of the material, its size and flexibility). Once positioned in the fixture, the part must be released. For more information see Ref. 4.

2-6.1.4 Elemental Standard Data

These data (often called macrodata) give normal time values for major elements of jobs. Also time values for machine setup and for different manual elements are given, so a normal time for an entirely new job can be constructed by an analysis of blueprints to see what materials are specified, what cuts must be made, how the workpiece can be held in the machine, etc.

Macrostandard data are in common use, especially in machine shops where distinct job families have a long-standing tradition. However, the occurrence of this kind of standard data is by no means limited to machine shops. It is likely to exist wherever job families exist or when parts or products occur in many sizes and types. For more information see Ref. 4.

The number of units to be produced should be considered in estimating labor requirements because the learning curve comes into play. The learning curve assumes that practice leads to improvement; therefore, as learning takes place, workers need fewer hours for producing given quantity of work. Learning, with its reduced man-hour input implications, is always at work in manufacturing. Experience at making anything can almost always lead to more economical methods.

Airplane and electronics manufacturers have found that the learning curve operates when they make products in large numbers. Knowing about the curve and expected rates of improvement allows the managers to project the need for fewer man-hours per unit of product as well as lower costs per unit. All airplane and electronics manufacturers, therefore, use the learning curve to estimate the cost of direct labor and in scheduling, planning, budgeting, purchasing, and pricing. The Government requires industry, on all Government contracts, to anticipate lower unit costs as quantities increase.

Usually these companies use an 80% learning curve or something very close to it. An 80’% curve means that every time the production quantity doubles, the average amount of direct labor for all units produced up to that point goes down to 80% of its former level. This is an average for all units and not just the direct labor hours put into the last unit. Thus if the first 10 units require an average of 100 direct labor hours per product, the first 20 units (including the first 10) will average 80 direct labor hours per unit of product. Airplane companies plot their figures on double logarithmic graph paper, so that the curve depicting the relationship appears as a straight line.

The equation for the line is

$$\log Y = -S \log X + \log C \qquad (2\text{-}1)$$

where

S = slope
X = number of units of product
C = direct labor hours required by the first unit of product
Y = average number of direct labor hours per unit of product.

The equation for the slope of the line is

$$S = \frac{\log L}{\log 2} \qquad (2\text{-}2)$$

where

L = learning rate.

For an 80% curve the equation becomes

$$S = \frac{\log 0.8}{\log 2}$$

$$S = \frac{-0.09691}{0.30103}$$

$$S = -0.322.$$

Since L will always be less than one, the logarithm of L will be negative; therefore, the slope will be negative. A negative slope is expected since costs go down as quantity goes up. To get the slope of a value other than 80%, the procedure is the same. An example of an 82% curve is shown in Fig. 2-8.

There are instances in which the curve should be expected to differ from 80%. If the product that will be produced is very similar to ones that have previously been produced in large quantities, costs should not be expected to go down as rapidly as they would on an 80’%

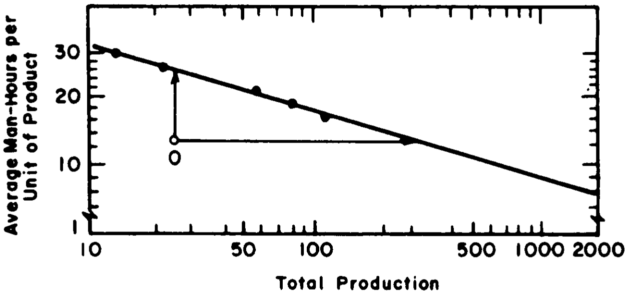


Figure 2-8. An 82% Curve

curve. On the other hand, on crash programs without enough time for adequate planning before manufacturing begins, it can be expected that costs will decrease more rapidly than predicted by an 80% curve.

A limitation of this procedure is that the curves are concerned only with manual work. Where machines are involved, an 80% curve calls for more improvement than can be realized because the learning curve may not apply to machine time.

Still another problem is that curves exaggerate the savings somewhat, To achieve reductions in direct labor costs, it is necessary to put industrial engineers, tool engineers, supervisors, and others to work trying to make improvements. But these are indirect labor, and their costs are not shown as offsets against the gains in direct labor costs. For more information on learning curves see Ref. 4.

2-6.2 NETWORK TECHNIQUES

Periodically throughout the design process, the designer should consider the sequence of operations (including inspection) that will be required to manufacture the product. If there is a frequent review of the production sequence, illogical or undesirable sequences may be avoided. For example, the designer should avoid designs that require the insertion of a fragile component prior to press fit operation or a heat sensitive component prior to welding. A designer should try to design a product so that there can be operational testing of the product prior to permanent joining, i.e., adhesives or welds. There should bean attempt to design the product so that major disassembly is not required for units that fail the operational tests. For example, if a design had an engine mount as part of the cabinet assembly, it may not be possible to test the engine until after the cabinet has been assembled. However, with a design change it may be possible to test the engine prior to installation in the cabinet.

The design analysis defines which sequences are feasible and which are infeasible. Therefore, the designer should be constantly considering the sequence he is building into the design. There are several tools the designer can use to illustrate and evaluate the sequences.

In all stages of the design it is necessary to consider the precedence relationships between operations. In fact, in the early stages that maybe the only consideration. Precedence relationships can be illustrated with arrow diagrams. There are two major types of arrow diagrams: program evaluation review technique (PERT) diagrams and critical path method (CPM) diagrams. For more information on PERT and CPM than is presented in this handbook see Ref. 5.

To develop an arrow diagram, the user lists the operations or activities to be performed and then asks these three questions:

1. Which activities must be completed before each given activity can be started?
2. Which activities can be carried out in parallel?
3. Which activities immediately succeed other given activities?

The common practice is simply to work backward through the activity list and generate the immediate predecessors for each activity listed as shown in Table 2-1. The arrow diagram may then be constructed to represent the logical precedence requirements shown in Table 2-1.

TABLE 2-1. PRECEDENCE CHART SEQUENCE OF OPERATIONS

Operation	Immediate Predecessors
A	
B	A
C	A
D	A
E	B
F	E
G	F
H	D
I	C
J	I
K	J
L	H, K
M	G
N	M
O	N
P	L
Q	P
R	O, Q
S	R

2-6.2.1 Program Evaluation Review Technique (PERT)

In a PERT diagram the arrows represent the operations coded by letters as shown in Fig. 2-9. The length of the arrows has no significance. The numbered circles define the beginning and ending points of operations or activities and are called events or nodes. The direction of the arrows indicates flow in the sense that node 2 marks the end of operation A and the beginning of operations B, C, and D. The network then also represents the required precedence relationships of activities. For example, operations B, C, and D cannot start until operation A has been completed, but operations B, C, and D can all proceed simultaneously.

Care must be taken to represent correctly the actual precedence requirements in the arrow diagram. For

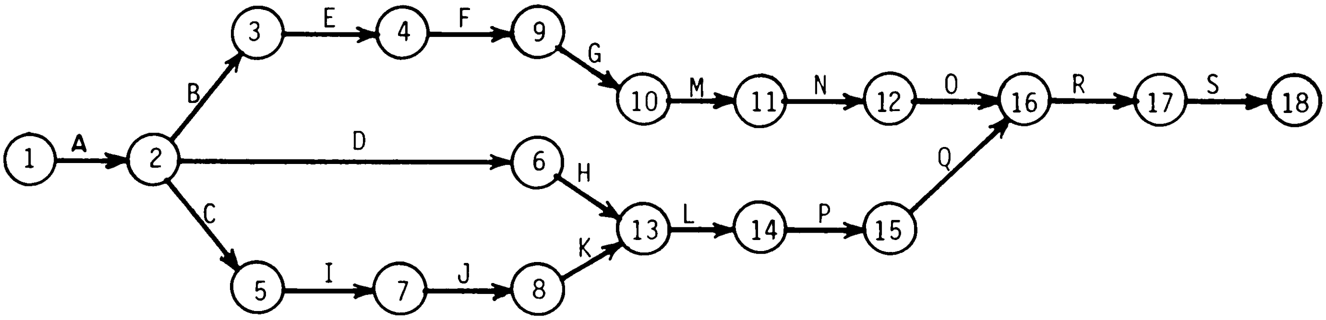


Figure 2-9. PERT Network

example, there could be a requirement that operation H must precede operation M with the immediate predecessors as shown in Table 2-2.

TABLE 2-2. REVISED PRECEDENCE CHART

Operation	Immediate Predecessors
G	
H	
K	
L	H,K
M	G.H

One could not draw the PERT diagram as shown in Fig. 2-10 because that would also say that operation M cannot begin until operation K is complete and that operation L cannot begin until operation G is complete. Neither of those requirements is necessary. To represent the situation correctly, dummy operations are used as shown in Fig. 2-11.

2-6.2.2 Critical Path Method (CPM)

The CPM diagram differs from a PERT diagram. A CPM diagram represents operations as occurring at the nodes with the arrows showing the sequences. The CPM results in a slightly simpler diagram because it is not necessary to invoke the use of dummy operations to represent the proper sequencing. A comparison of the two methods is shown in Fig. 2-12. Both diagrams illustrate the same precedence relationships.

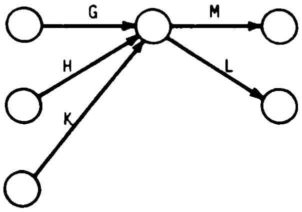


Figure 2-10. Incorrect PERT Diagram

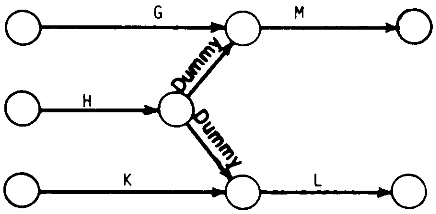


Figure 2-11. PERT Diagram With Dummy Operations

Fig. 2-13 gives the CPM diagram for the operations described in Table 2-1, which can be compared to Fig. 2-9.

2-6.2.3 Arrow Diagrams

The choice of the diagramming procedure is left to the user. Regardless of the procedure used, the designer can use the diagram as an aid to evaluating the design in terms of producibility. For example, if operation H is a finishing operation and operation P is a clamping

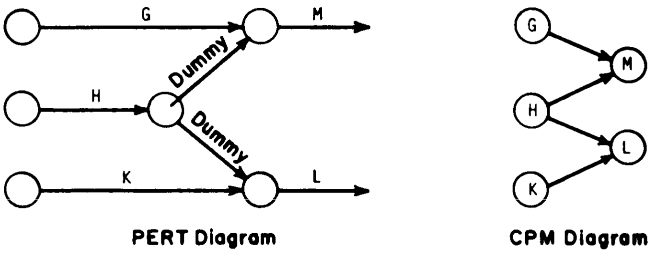


Figure 2-12. Comparison of PERT and CPM Diagrams

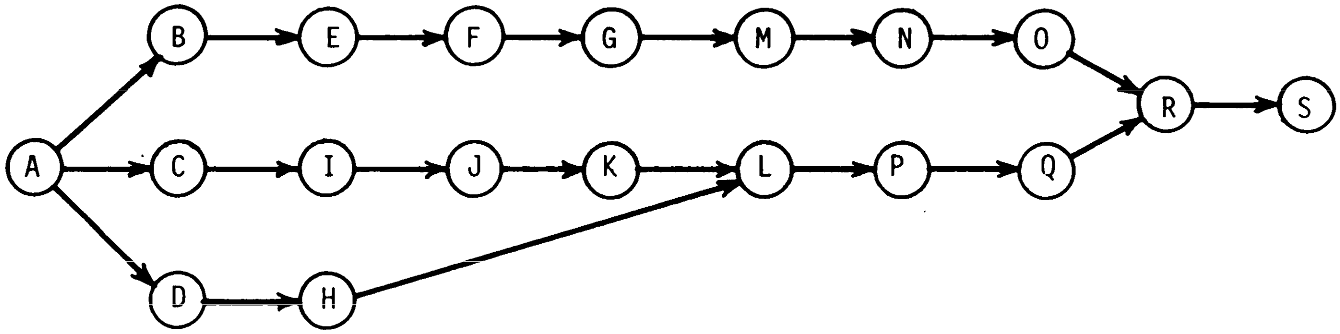


Figure 2-13. CPM Network

operation that could damage the finished surface, the designer may want to redesign the part so that operation P is not necessary or so that operation H can be done after operation P.

The diagram can be used to identify possible subassemblies. For example, operations B, E, F, G, M, N, and O may constitute the operations for a subassembly, but a redesign or design modification maybe required if the subassembly is to have integrity. A subassembly has integrity if it can be moved, stored, and inserted or assembled into the final product without need or danger of disassembly.

The arrow diagram (either PERT or CPM) should be used by the designer frequently regardless of the product being designed. There are other network techniques that can be used profitably, but their selection is somewhat dependent upon the type of product and the projected demand for the product.

2-6.2.4 Bar Charts

If a single unit is to be produced or if the units are to be produced one at a time, a bar chart may be useful. To use such a chart, the designer must have estimated times for each of the operations as well as the precedence relations as shown in Table 2-3.

The bar chart, as shown in Fig. 2-14, has the operations down the side and time across the top. The lengths of the bars correspond to the operation time. The starting time for each operation is determined by looking at the latest finishing time for the predecessor operations. For example, B, C, and D cannot begin until operation A is finished. Operation L cannot start until operations H and K are finished. Operation H ends on day 12, and operation K ends on day 17. Operation L starts immediately after operation K ends.

One may wonder why a product designer would be interested in a bar chart. Producibility constraints include time restrictions as well as processing restrictions. If in the preceding example the objective is to build one unit per month, some changes would be necessary. Perhaps the design could be changed so that more operations could be done concurrently.

TABLE 2-3. PRECEDENCE CHART SHOWING SEQUENCE OF OPERATIONS AND REQUIRED TIMES

Operation	Immediate Predecessors	Time, days
A		4
B	A	2
c	A	4
D	A	6
E	B	1
F	E	2
G	F	3
H	D	2
I	c	4
J	I	3
K	J	2
L	H,K	6
M	G	5
N	M	3
o	N	2
P	L	1
Q		1
R	O,Q	5
S	R	3

The bar chart does not illustrate the precedence relationships or the slack time. A time-based network chart, of which Fig. 2-15 is an example, overcomes those deficiencies. The heavy line indicates the critical path, and the dotted lines indicate the slack time. It should be noted that there is no slack time along the critical path; therefore, an increase in the time required to accomplish an operation will increase the time

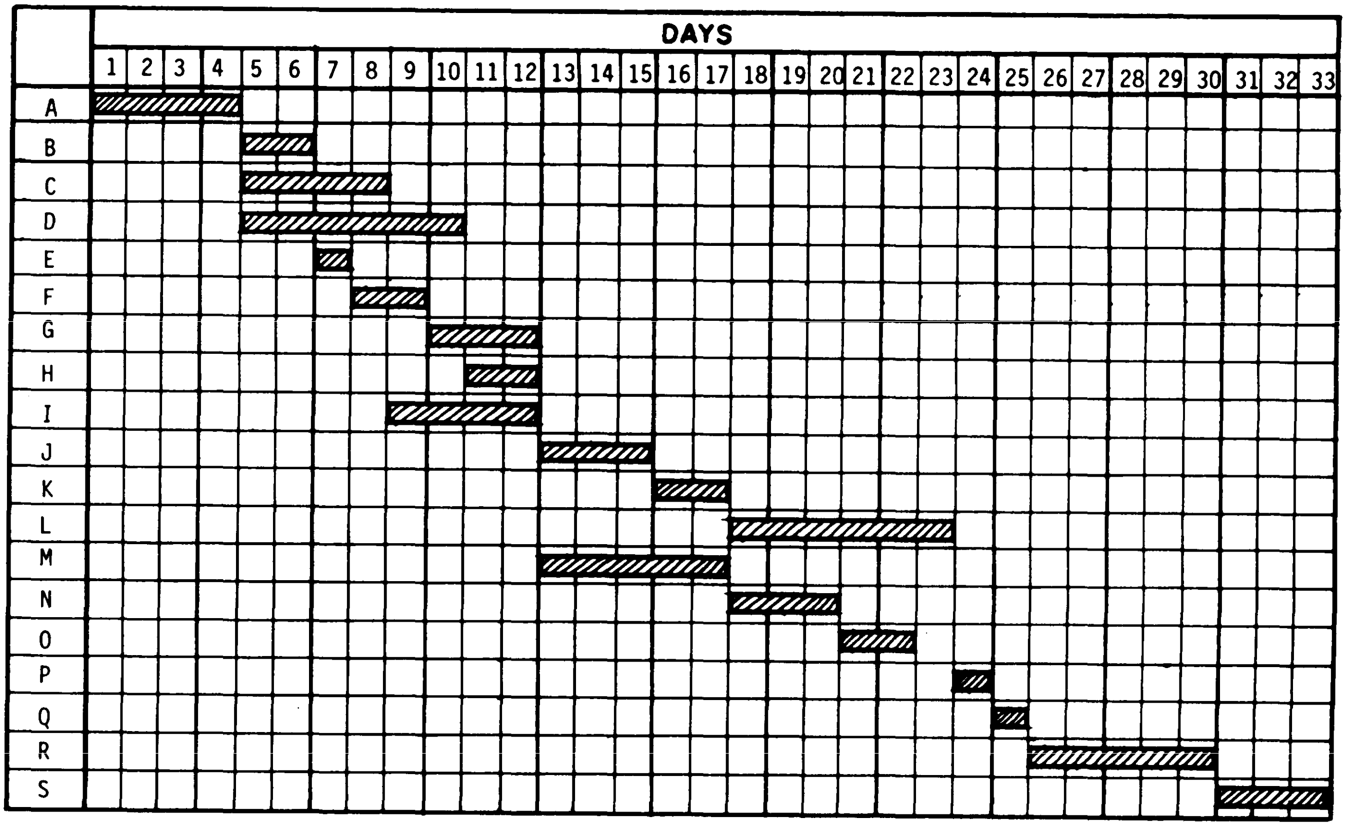


Figure 2-14. Bar Chart

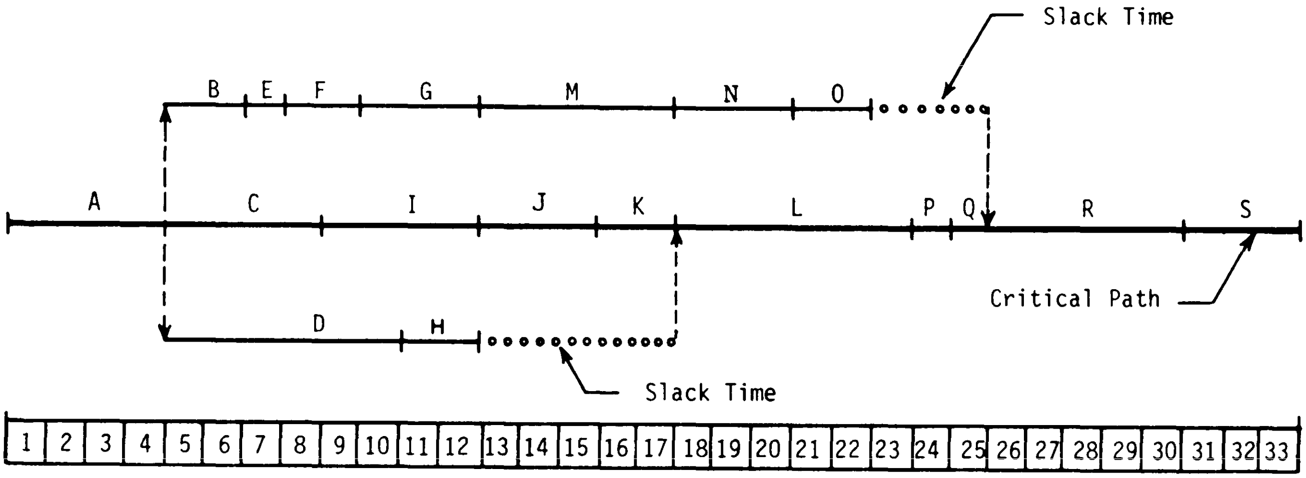


Figure 2-15. Time-Based Network

required to complete the overall project. Thus the designer should pay particular attention to these operations with concern for tolerances or any other processing requirement that might cause difficulty.

2-6.2.5 Daily Automatic Rescheduling Technique

The bar chart and the time-based network illustrate time requirements. The daily automatic rescheduling technique (DAR-I’) is a variation of PERT that considers the allocation of three kinds of resources to be used:

1. Time-consumed resources (job sequence, labor, and work areas)
2. Use-consumed resources (material, parts, and supplies)
3. Nonconsumed resources (facilities, tools, and data).

The DART system starts with a PERT-type master network with the additional information describing the arrows. For more information on DART see Ref. 5.

2-6.2.6 Decision Box Technique

The preceding techniques assume that each activity must be performed and that there are no alternatives to the activities that have been defined. In 1960 Mr. H. Eisner introduced into the network model the concept of a “decision box” which is an event that leads several alternative paths or activities. As in PERT, arrows (or arcs) represent the activities, but decision boxes replace the circles as nodes. The various types of nodes are illustrated in Fig. 2-16.

The activities or arcs are characterized by a normal, triangular, uniform, or constant time distribution. An interactive computer program, called risk analysis (RISKA), facilitates the analysis of these network structures. After the user describes the network, RISKA is used to generate activity times based upon the time distribution and to follow the activities according to the logic of the decision boxes or nodes. Further discussion of this process is given in par. 2-6.3. For more information contact US Army Logistics Management Center, Fort Lee, VA 23801.

2-6.3 SIMULATION

Simulation permits the study and optimization of a system or activity without actually constructing the system itself. The bar chart and the time-based network shown in par, 2-6.2 are simulations. In recent years, the term “simulation” has come to mean computer experimentation on mathematical models, which may be deterministic or stochastic. In a deterministic model it is assumed that all events are known with a high degree of certainty and that times for each activity are relatively constant. In a stochastic model it is assumed that there is a randomness or uncertainty in the operation of the model; events may or may not occur, and times may vary. Stochastic simulations that use random numbers to define specific events are also called Monte Carlo simulations. In either case, the user can make changes in the model and determine the impact of the changes.

2-6.3.1 Deterministic Model

As an example of a deterministic model, one could describe machine capacity and the operations to be performed in terms of operating times, setup times, machine selections, and precedence relationships. The computer simulation could be used to prepare a Gannt chart following a predescribed dispatching rule such as first in, first out. A Gannt chart is a bar graph that displays the schedule for the operations. The user could then make changes in the number of available machines, operating times, or machine selections and prepare a new Gannt chart. In each case it would be assumed that setup and operation times, operation sequences, and machine availability are constant and known in advance.

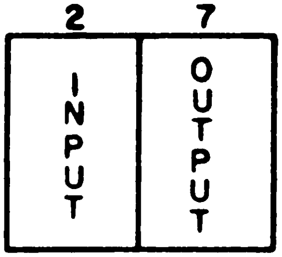
2-6.3.2 Stochastic Model

For a stochastic model one might say that the operation times might vary by plus or minus 10%, that there is a probability that a machine will break down, that 10% of the pieces will require repair or rework, and so on. The stochastic, or Monte Carlo, simulation would generate times according to the input distributions, repairs according to the reject rate, and machine donntimes according to downtime rates and downtime distributions. The operations would then be scheduled according to those specific times and events. The process can be repeated to have the program generate a new set of times and events. The user would have a sample of schedules that could be used to estimate the distribution of throughput times.

For exatnple, the information in the operation sheets shown in Table 2-4 for a shop indicates that there is only one machine of each type. If 10 units of each part are to be produced, the Gannt chart could be as shown in Fig. 2-17, and the throughput time would be 22.3 h.

TABLE 2-4. OPERATION SHEET

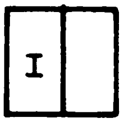
Part	Operation	Machine	Setup, h	Cycle, h
1	1	Turret lathe (TL)	0.50	0.70
	2	Turret lathe (TL)	0.80	0.25
	3	Arbour press (AP)	0.20	0.15
	4	Drill press (DP)	0.30	0.20
	5	Lathe (L)	0.50	0.30
	6	File (F)	—	0.20
2	1	Turret lathe (TL)	0.70	0.60
	2	Turret lathe (TL)	0.30	0.25
	3	File (F)	—	0.20



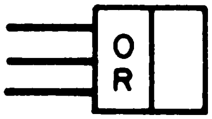
Characteristics:

1. Node name, two-digit number, 01-99
2. Node input rule
3. Node output rule

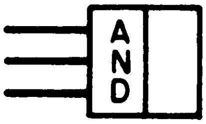
(A) Nodes



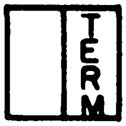
Initial. Source node or beginning of network (has no input arcs, only output arcs).

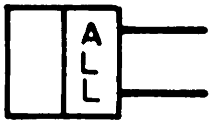


Or. The input arc that is successfully completed first will fire the node.

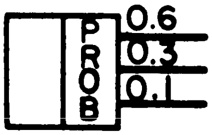


(B) Input Rules





All. Initiates all output arcs.

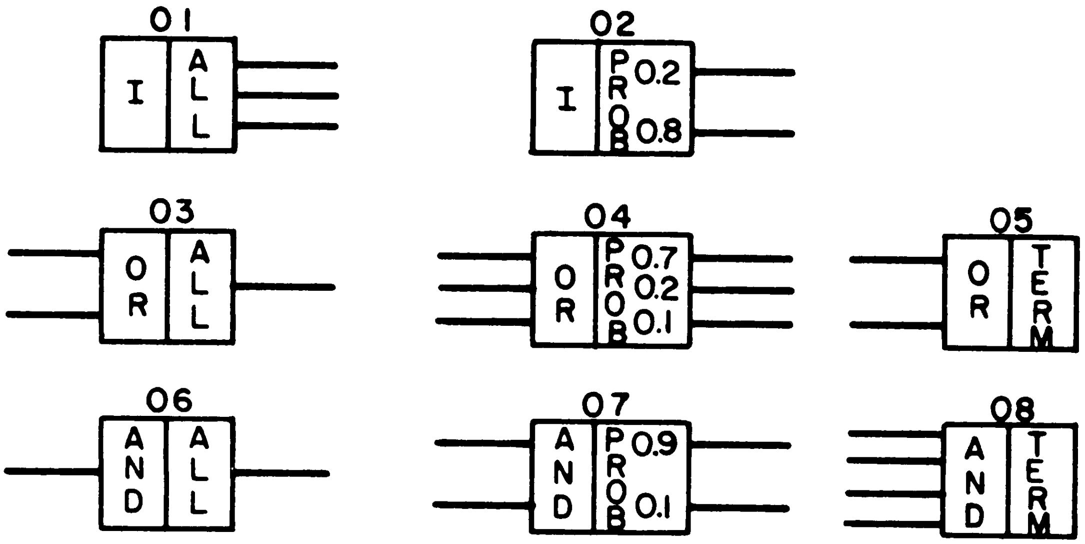


Probabilistic. Initiates only one of the output arcs according to the probabilities given.

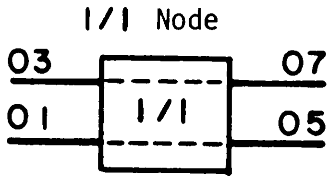
(C) Output Rules

(cont'd on next page)

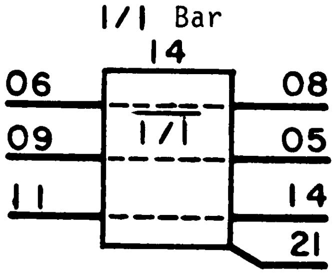
Figure 2-16. Decision Box Nodes



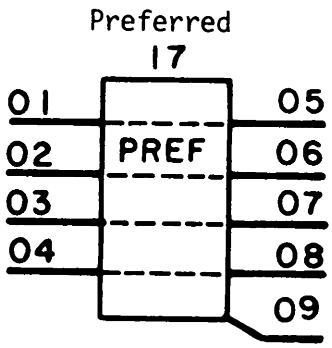
(D) Possible Node Combinations



The first (time sense) input arc that completes successfully, initiates (fires) its output arc and none of the other output arcs will be initiated on this iteration.



1/1 Bar is exactly like the 1/1 Node except that if all input arcs (3) are in the unsuccessful state, the extra or default arc is initiated.

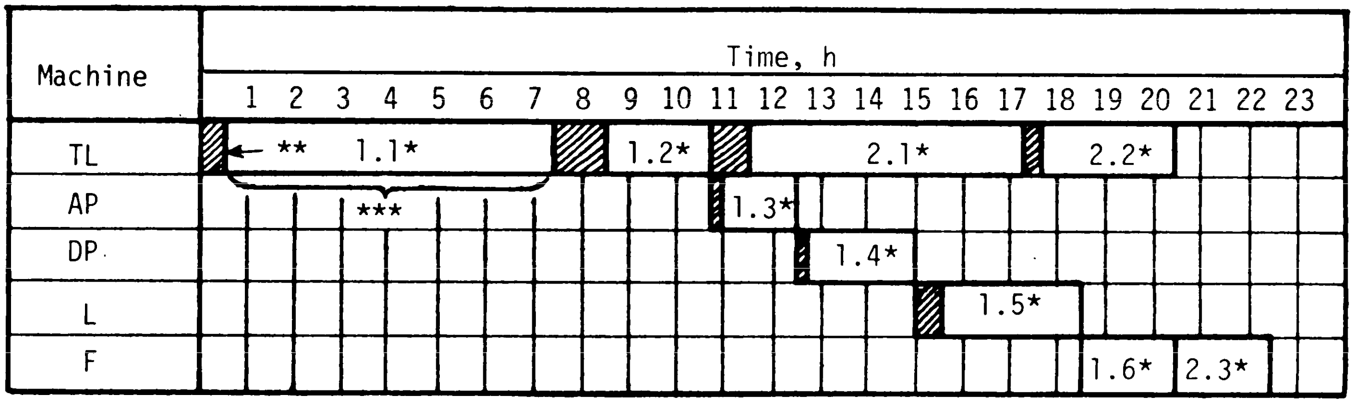


The most preferred input arc that completes successfully will initiate its output arc.

If all input arcs are in the unsuccessful state, the default arc will be taken.

(E) Special Nodes

Figure 2-16. (cont'd)



*Part and operation number, i.e., 1.1 = part one, operation one

**Setup time

***Time required to perform the operation on 10 units of the part

Figure 2-17. Gannt Chart

If the setup times on the turret lathes were within plus or minus 10%, a Monte Carlo simulation might generate the times shown in Table 2-5 resulting in a throughput time of 22.26h. In this simple example the results can be calculatedly hand, but with more operations and the possibility of rework, the calculations can become cumbersome.

TABLE 2-5. TURRET LATHE SETUP TIME

Part	Operation	Setup Time, h
1	1	0.52
	2	0.74
2	1	0,6.5
	2	0.33

2-6.3.3 Simulation Programs

2-6.3.3.1 introduction

There are several special purpose and general purpose simulation languages and programs that can be used. Two of the more widely used simulation languages are the general purpose simulation system (GPSS) and general activity simulation program (GASP). General assembly line simulator (GALS) and RISKA are simulation programs for network analysis.

2-6.3.3.2 Risk Analysis Program

RISKA networks are described in par. 2-6.2. The program provides the user with the capability to construct the desired network representation of the system. The program will then run Monte Carlo simulations of the network; the number of iterations of the simulation is set by the user.

For example, given the network in Fig. 2-18, the program will show whether or not activity 01 will be successful. The activity has an 80% probability that it will be completed successfully. In each iteration the program will generate a pseudorandom number between 0 and 1. If the number generated is less than or equal to 0.8, the activity will recompleted successfully. If the activity 01 is not completed successfully, the program will look at activity 02, which has a 90% probability that it will be completed successfully. If neither are completed successfully, the program will go to arc 09 and terminate. otherwise the program continues

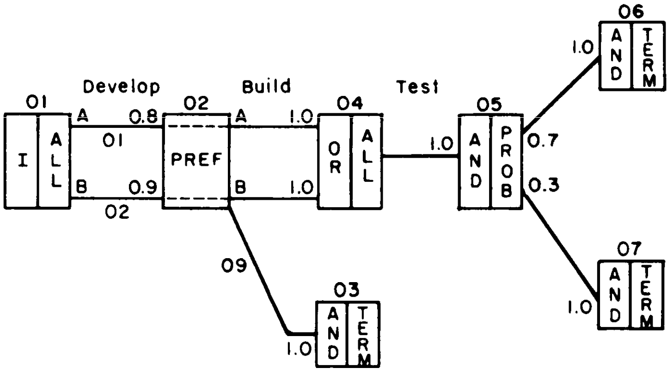


Figure 2-18. Network

through the subsequent boxes in the network. In each iteration the random numbers generated will be different, so after several iterations, the user has a sample of outcomes all based on the same assumptions.

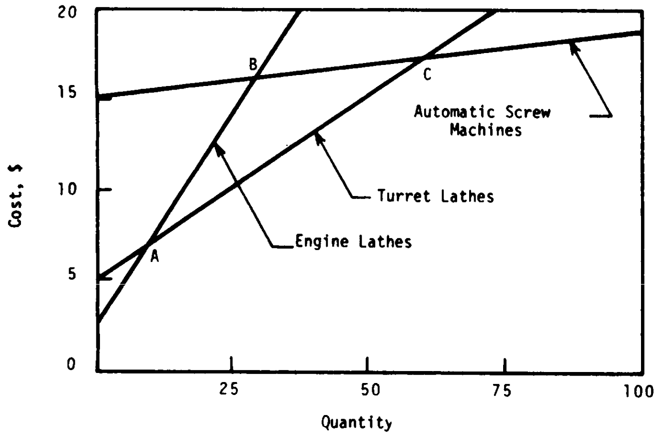
The user can vary the assumptions; for example, probability that activity 01 will be successful may be reduced to 75%. Several iterations with that assumption can be run. The two samples can be compared to determine whether there is a significant difference between them.

When using Monte Carlo simulations, it is important to remember that the result from each iteration is just a single observation from the entire population of possible outcomes. Many iterations must be run to get parameters or descriptive statistics (mean, standard deviation, and measures of skewness) for the distribution of the population.

Decisions should be based upon the population parameters rather than on the individual observations.

2-6.4 BREAK-EVEN ANALYSIS

A break-even chart is a tool for considering projected volume or demand when comparing alternative processes. For example, processes requiring simple machines are usually easy to set up but slow and costly to operate. Bigger quantities allow for the use of faster machines, which are costly to set up but which, once set up, are much less costly to operate. Often there are several alternative methods, each of which is the most economical for a certain volume range. (It has a "domain", or volume range, for which it is the best method.) The method that should be used depends on the expected volume, and Fig. 2-19 shows how this would work.



Franklin Moore, PRODUCTION MANAGEMENT, 6th ed. (Homewood, 111.: Richard D. Irwin, 1973), p. 24@ 1973 by Richard D. Irwin, Inc.

Figure 2-19. Methods Comparison (Ref. 4)

The lines in Fig. 2-19 compare methods for making a small bushing on three kinds of machines. Each of the three lines in the figure shows what it would cost to make these bushings on one kind of machine. Engine lathes are general purpose machines and are easy to set up for new jobs, but they are not very efficient in production. Setup costs cover the costs of getting the machine ready (installing the tools and the clamps to hold the bushings in place). These figures **also** include the later teardown time, i.e., taking the tools and holding clamps off the machine. Turret lathes require more setup time but produce at lower unit costs once they are set up. However, neither of these machines can compare with automatic screw machines when volume begins to mount. Automatic screw machines produce at low unit costs; unfortunately, they have lengthy setup times, so setup costs are high.

In Fig. 2-19 the lines all start with certain costs before production starts. These starting amounts ($2.50, .$5, and $15) are the setup costs. The lines in Fig. 2-19 are all straight lines, which go up steadily, and show the effect of operating costs, which, once operations start, are constant per unit of product. These costs, $0.45, $0.20, and $0.04, cover the cost of the operation of the machines, including labor, electricity, depreciation, and all other costs, on a unit cost basis. Sometimes a chart is all that is needed for deciding which machine to use for a job because the size of an order is not close to a crossover point on the chart. But if it is necessary to know the exact crossover points (points A, B, and C in Fig. 2-19), these can be calculated by using simple equations. In our example the equations for the three cost lines (with X equal to the quantity) areas shown in Table 2-6.

TABLE 2-6. COST EQUATIONS FOR PROCESSING ALTERNATIVES

Machine	Cost Equation
Engine lathes	$2.50 + $0.45X
Turret lathes	$5.00 + $0.20X
Automatic screw machines	S15.00 + $0.04X

The crossover points A, B, and C can be found by setting pairs of equations equal to each other and solving for X:

1. Engine lathes versus turret lathes:

$$\$2.50 + \$0.45x = \$5 + \$0.20x$$

$$\$0.25X = \$2.50 \qquad (2\text{-}3)$$

X, point A on Fig. 2-19, = 10 units

2. Engine lathes versus automatic screw machines:

$$\$2.50 + \$0.45X = \$15 + \$0.04x$$
$$\$0.41X = \$12.50 \qquad (2\text{-}4)$$

X, point B on Fig. 2-19, = 30 units

3. Turret lathes versus automatic screw machines:

$$\$5 + \$0.20X = \$15 + \$0.04X$$
$$\$0.16X = \$10 \qquad (2\text{-}5)$$

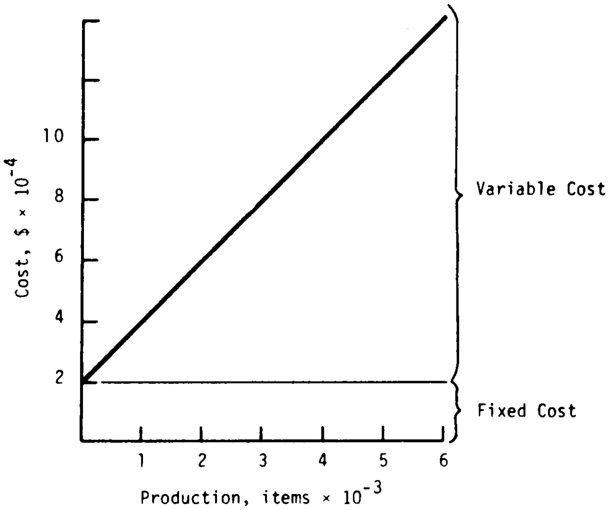
X, point C on Fig. 2-19, = 63 units.

Eq. 2-3 shows that for orders of 10 units (or fewer) engine lathes should be used. For more than 10 units turret lathes should be used. But if all the turret lathes are in use and not available, it is necessary to go to Eq. 2-4. This shows that, in this case, engine lathes should continue to be used for orders up to 30 units. Orders calling for more than 30 units should be shifted to automatic screw machines. But if turret lathes are available, they should be used for all orders for more than 10 and up to 63 units. Eq. 2-5 shows that all orders for more than 63 units should be put on the automatic screw machines.

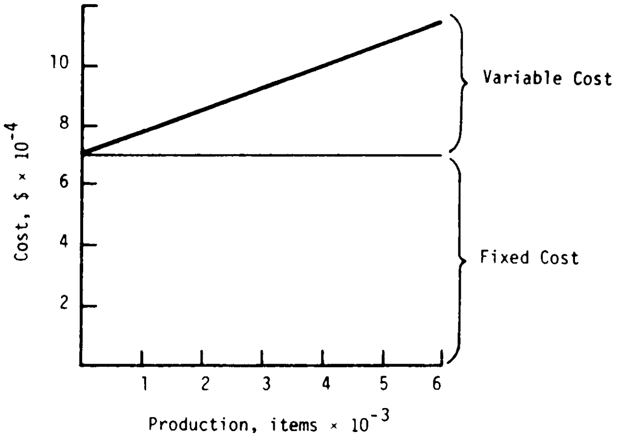
In the preceding example it was assumed that all three machines were available. Break-even charts can also be used when considering the acquisition of machines. In this case fixed costs including depreciation, insurance, and maintenance would reconsidered. The fixed and variable costs for each alternative would be plotted as shown in Fig. 2-20, In this example manual assembly is to be compared to an automatic assembly line. The lines representing total cost (fixed plus variable costs) for the two methods are then drawn on a common chart as shown in Fig. 2-21. In this example manual assembly is better if production is less than 4000, but if the projected volume is greater than 4000, automatic assembly should be used.

If the projected volume is less than 4000, the designer should consider ease in manual assembly while designing the product. If the projected volume is greater than 4000, the designer should consider the requirements of automatic assembly. If this consideration is not given in the design phase, the fixed and variable costs may be much higher than anticipated.

This concept can be used to compare the effects of life cycle costs between two alternatives. In this situation, the production costs represent the fixed costs while future year support costs are the variable costs. The break-even point will be expressed in terms of years of operation. Break-even analysis should be used when the investment required does not meet the contractor's accounting requirements for capitalization or when it is appropriate for the analysis to ignore the time value of money. For more information on break-even analysis see Ref. 4.



(A) Manual Assembly Line



(B) Automatic Assembly Line

Figure 2-20. Fixed and Variable Costs

2-6.5 SENSITIVITY ANALYSIS

Sensitivity analysis is a method by which characteristics of a system are evaluated for their impact on other system characteristics. These characteristics must be evaluated to achieve an optimum balance of all system characteristics. This balance is obtained by varying the value of one or more characteristics while holding all others fixed. This will determine the impact each characteristic or group of characteristics has on the system, i.e., the sensitivity of the system to changes in these characteristics. This type of analysis can be used to determine the effects that the requirements of the svstem will have on producibility or the effects of producibility changes on the other system requirements. Due to the potential of having a large number of variables or characteristics to be evaluated, this method is best performed with the assistance of a computer system.

To use the techniques described in the preceding paragraphs (network techniques, simulation, and break-

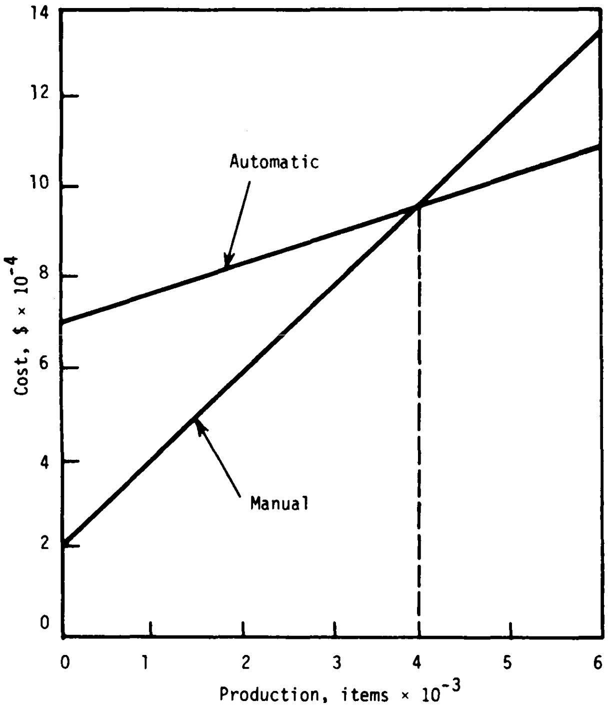


Figure 2-21. The Total Cost

even analysis), times or costs must reestimated. Sensitivity analysis is the determination of the effect on the answer of a change or an error in one of the variables used to compute the answer. Expect to find that some variables may change by substantial amounts without greatly changing the result; there is little concern for risk arising from such sources. On the other hand, there may be other variables to which the result is highly sensitive, and it would be important to consider the risk arising from these.

Sensitivity analysis is used primarily as a supplement to judgments about risky decisions. For example, it suggests such useful questions as, "If an automatic screw machine is preferred to a turret lathe using the break-even analysis, will the choice be the same if the setup cost for the automatic screw machine has been underestimated by an amount x and the setup cost for the turret lathe overestimated by an amount y?". Similar questions may be formulated to include judgments about the risk involved in operating cost estimates and soon. One hopes that the answer to such questions will be that, within the range where any given variable will fall, say 90% of the time, the automatic screw machine is always preferred to turret lathes. If the answer is not such, then one moves further into the realm of judgment, and it becomes impossible to set down explicit rules. In the example that follows, some of the ways of setting up a process selection decision for the application of these judgments are illustrated.

A decision is to be made between two machines. The initial predictions of the relevant costs are given in Table 2-7.

TABLE 2-7. RELEVANT COSTS

	Turret Lathes	Automatic Screw Machine
Setup cost	$5.00	$15.00
Operating cost/unit	$0.20	$0.04
The expected volume is 100 units.		

The expected cost of the turret lathes is $25.00 ($5.00 -1- 100 X 0.20), and the expected cost of the automatic screw machines is $19.00 ($15.00+ 100 X 0.04). If the variables used to compute the costs are correct, clearly the automatic screw machine is to be preferred.

If, however, there is an error in the variables, the decision may be reversed. Total costs can be calculated by using a range of setup costs as shown in Table 2-8.

TABLE 2-8. RANGE OF SINGLE COST VARIABLES

Turret Lathe		Automatic Screw Machine	
Setup cost	Total cost	Setup cost	Total cost
$1.00	$21.00	$15.00	$19.00
2.00	22.00	16.00	20.00
3.00	23.00	17.00	21.00
4.00	24.00	18.00	22.00
5.00	25.00	19.00	23.00

Table 2-8 provides the basis for exercising judgment about the possible variation in the setup cost and the resulting choice. Let ST refer to the setup cost for the turret lathe and S_A apply similarly to the automatic screw machine. For any pair of values ST and S_A, with the help of the table, one may see which machine would be preferred. Expressing this graphically often helps. In Fig. 2-22 a line passing through pairs of values ST and S_A, for which the two machines have equal total costs, has been drawn. For any point below this line, the turret lathe will be preferred. For any point above it, the choice will fall on the automatic screw machine. As previously emphasized, this type of graph does not itself determine the choice; it is intended merely to furnish a background over which judgments about the probabilities of various values or ranges of the variable may be placed.

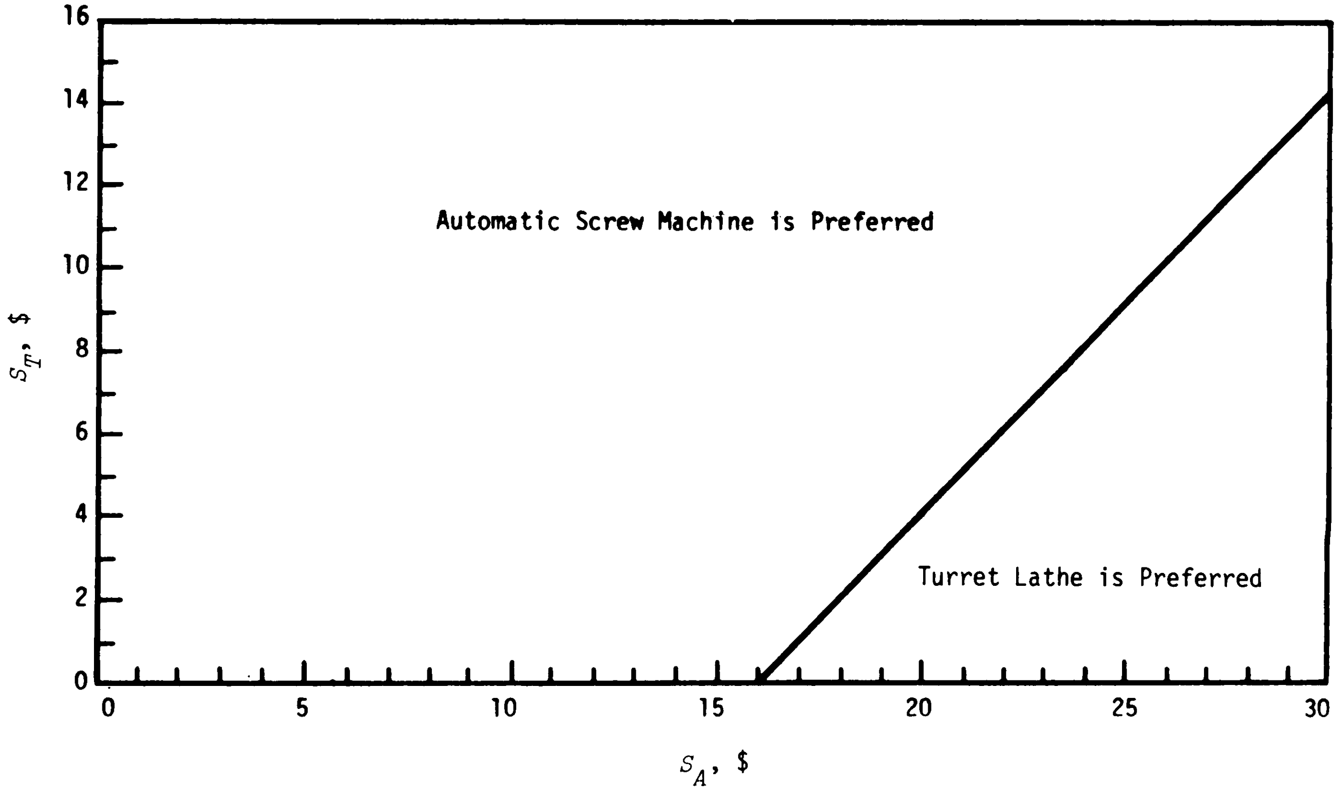


Figure 2-22. Regions of Machine Preference With Single Cost Variables

There is no reason why this kind of exploration should be confined to one variable alone. If variation in the operating costs is suspected in addition to variation in setup cost, they may be investigated together. The data for such an analysis of the turret lathe and automatic screw machine are given in Table 2-9. From this table graphs similar to Fig. 2-22 showing the regions for which each machine is preferred, as shown in Fig. 2-23, may be constructed. Let 0_T refer to the operating cost for the turret lathe and 0_T refer to the operating cost for the automatic screw machines. Pairs of values for s_A and S_T were selected. For each pair of values a line has been drawn that passes through pairs of values 0_T and 0_A, for which the two machines have equal total costs. Several graphs may be made as the requirements of judgment dictate.

The example illustrates a sensitivity analysis of a break-even chart. The procedure is basically the same regardless of the technique used to determine the original answer. One varies the variables over the variable range and identifies the points at which the decision would change. For more information on sensitivity analysis see Ref. 6.

2-6.6 VALUE ENGINEERING

Value engineering (VE) is an organized effort for analyzing the function of hardware or software for the purpose of achieving the required function at the lowest overall cost. There are seven basic elements of the VE methodology. These elements are not always distinct and separate—in practice they often merge or overlap. The seven elements are

1. *Product Selection.* The selection of the hardware system, subsystem, or component to which VE efforts are to be applied
2. *Determination of Function.* The analysis and definition of function(s) that must be performed by this hardware
3. *Information Gathering.* The pulling together of all pertinent facts concerning the product, i.e., present cost, quality and reliability requirements, development history, etc.
4. *Development of Alternatives.* The creation of ideas for alternatives to this established design
5. *Cost Analysis of Alternatives.* The development of estimates of the cost of alternatives and the selection of one or more of the more economical alternatives for further testing of technical feasibility
6. *Testing and Verification.* Proof that the alternative(s) will not jeopardize fulfillment of performance (functional) requirements
7. *Proposal Submission and Follow-Up.* Preparation and submission of a formal VE change proposal. “0

A brief discussion of these elements is given in the

TABLE 2-9
RANGE OF MULTIPLE COST VARIABLES

Turret Lathe			Automatic Screw Machine		
Setup cost	*Oper-sting cost	Total cost	Setup cost	Oper-sting cost	Total cost
$1.00	$0.10	$11.00	$15.00	$0.02	$17.00
1.00	0.15	16.00	15.00	0.03	18.00
1.00	0.20	21.00	15.00	0.04	19.00
1.00	0.25	26.00	15.00	0.05	20.00
2.00	0.10	12.00	$16.00	0.02	18.00
2.00	0.15	17.00	16.00	0.03	19.00
2.00	0.20	22.00	16.00	0.04	20.00
2.00	0.25	27.00	16.00	0.05	21.00
3.00	0.10	13.00	$17.00	0.02	19.oo
3.00	0.15	18.00	17.00	0.03	20.00
3.00	0.20	23.00	17.00	0.04	21.00
3.00	0.25	28.00	17.00	0.05	22.00
4.00	0.10	14.00	$18.00	0.02	20.00
4.00	0.15	19.00	18.00	0.03	21.00
4.00	0.20	24.00	18.00	0.04	22.00
4.00	0.25	29.00	18.00	0.05	23.00
5.00	0.10	15.00	$19.00	0.02	21.00
5.00	0.15	20.00	19.00	0.03	22.00
5.00	0.20	25.00	19.00	0.04	23.00
5.00	0.25	30.00	19.00	0.05	24.00

‘Based upon producing 100 items.

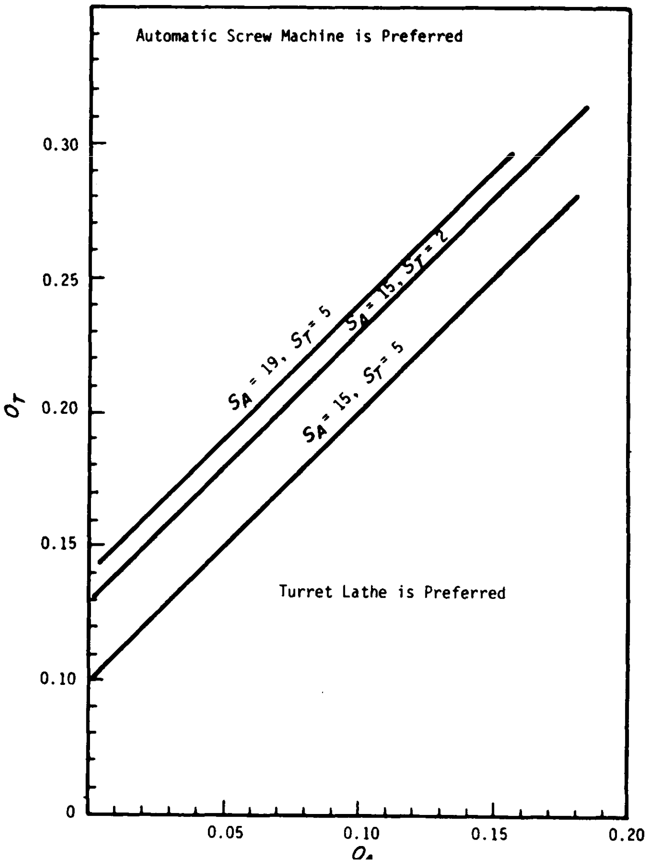


Figure 2-23. Regions of Machine Preference With Multiple Cost Variables

subparagraphs that follow. For additional information on VE, see Ref. 7.

2-6.6.1 Product Selection

The amount of resources that can be allocated to the VE function is limited. Therefore, it is of the utmost importance that these scarce resources be applied where there is high potential for cost reduction. In other words, VE should concentrate on products exhibiting high total costs in relation to function performed.

2-6.6.2 Determination of Function

By "function" is meant the purpose or objective of the hardware (subsystems or components) under consideration. In simple terms, functional requirements are those explicit performance characteristics that must be possessed by the hardware if it is "to work". The requirements define the limits of what the hardware must be able to do in relation to the larger system of which it is a part. The definition of function in explicit, quantitative terms is a difficult task. Many times there is a temptation to look at the product and say it defines the required function. Actually, the designer often assumes that certain functions are required. Thus many of the benefits of defining the function are obtained when a clear statement of which characteristics of the design are required is prepared. Often, components of the product (or the product itself) can be eliminated, and the entire assembly or system still will perform satisfactorily. When this occurs, the ideal of VE has been achieved—elimination of an unnecessary component with a 100% cost reduction for that component. Care must be exercised to insure that all required functions, whether primary or secondary, are identified. For example, a light source may be required to withstand severe environmental conditions, or a handle also may be required to provide for searching. The accurate description of each required function in quantitative terms is a prerequisite for successful value engineering of the product.

2-6.6.3 Information Gathering

Having defined the function, the next task is an intensive information gathering effort in two phases:

1. Specific information about the product itself—such as cost of the present design, quality and reliability requirements, maintainability characteristics, quantity to be produced, and development history

2. General information concerning the technology of the product, including present state of the art, vendor sources of supply for components of the item, manufacturing processes to be employed, and establishment of contact with individuals in the organization who have technical knowledge of this type of product.

2-6.6.4 Development of Alternatives

At this point an intimate knowledge of the item under analysis has been developed, and a basis for the most difficult and tangible portion of the process formulated. This is the creative portion of the VE activity, and depending upon the individual or individuals involved, it may take many forms. The purposes are to generate ideas about the function and design of the item and to conceive of more economical and equally effective means of performing the same function. Analytical methods, iterative methods such as checklists, and unstructured procedures such as brainstorming may also play a part in this process. Whatever methods are used, the basic purpose is to create a series of alternative designs—all of which will guarantee required function, and one of which will, hopefully, reduce cost.

2-6.6.5 Cost Analysis of Alternatives

The various alternatives, developed in the previous step of the VE process, next are subjected to a test of their economic feasibility. That is, each alternative is costed with the goal of finding the least costly, the next least costly, and soon until all alternatives are ranked according to cost. This, then, permits detailed technical (and economic) study of the alternatives on a priority basis, with the highest potential savings alternative considered first, to determine whether the alternative will lead to significant cost reduction. This cost analysis may also cause further efforts to develop alternatives or may lead to a cancellation of the VE study since it may show that no alternative is significantly less costly than the present method of meeting the required function.

2-6.6.6 Testing and Verification

All economically feasible alternatives developed in the VE study must be tested to insure that they will provide the required function. If they do not, they are rejected from further consideration unless modified to meet functional requirements.

In assessing technical feasibility, each required function is examined in turn. As previously described, primary and secondary functions are originally defined in terms of what the product or item must do, the accuracy with which it must perform, how dependable the product must be, and under what environmental conditions it must operate. In addition, the required function may include elements related to operation or maintenance—such as safety, ease of repair, and accessibility.

2-6.6.7 Proposal Submission and Follow-Up

Once the decision is reached that an alternative is economically and technically feasible and is the best alternative developed, a formal proposal is prepared recommending adoption and implementation of the alternative. Once the proposal is submitted, it must be followed up periodically in order to monitor its progress. The responsible individual should regularly make a check of who has the proposal and the current status of it.

2-6.7 RELEVANCE TREES

Important to the producibility engineering effort is the establishment of key objectives. These objectives might be the high-cost components or long lead time components. Either or both of these may we]] become the prime targets of intense producibility engineering efforts. The advantages of targeting producibility efforts in this manner are evidenced by an understanding of the Pareto distribution concept, which is derived from Pareto's law. This law, developed by a 19th century Italian engineer, states that the significant items in any given group represent a relatively small percentage of the total group, In a study of the distribution of wealth among the citizens of Florence, Pareto discovered that a very large percentage of wealth was concentrated amongs very small percentage of the citizens. By generalizing from Pareto's work one can state that whenever we are examining a problem, it is probably true that a large percentage of the problem is caused by a small percentage of the possible causes. This was substantiated shortly before World War II when inventory control analysts discovered that when inventory items were analyzed in order of value, Pareto's distribution concept was apparent. Between 10 and 20'% of the items in their inventory constituted 80 to 90'% of the total value of the items in the inventory. Therefore, the largest \olume of their inventory represented a very small portion of the total value. Subsequent observations of distribution in business management substantiate the widespread application of Pareto's law. Consider:

1. 20'% of a company's products represent 80% of its sales.
2. 20% of a firm's employees account for 90% of its tardiness.
3. 10% of the parts in a new design represent 80% of its cost.

This concept can be applied to producibility problems. For example, in examining an assembly comprised of several components, it would be wise to rank these components in terms of their cost. Most likely we will find that a large percentage of the assembly cost is composed of a small percentage of the components. Therefore, a given amount of engineering effort will have a much greater effect if it is focused on this small percentage of components, and such an effort will probably have a large impact on reducing costs.

In terms of return on the investment of time and effort, the uniform control approach is not sound. Efficient management exists when the amount of management effort applied varies in direct relationship to the importance of the item being managed. A uniform control system that provides adequate control for the high-value items overcontrols the low-value items. Conversely, the uniform system that is economically justifiable for the low-value items does not provide adequate control for the high-value items. Effective management requires the isolation of the vital factors of an operation from the insignificant factors and the development of management systems that are economically justified for each of these groups.

Some examples of how Pareto's law might apply to producibility are given in subsequent paragraphs.

2-6.7.1 An Auditing Tool

Frequently, producibility engineers will perform an audit of a contractor's producibility plan. In order to form an opinion of a contractor's producibility plan, the auditor must test many of the records. The areas that must be tested include levels of effort, types of effort, reliability of effort, adequacy of resources, and many others. In most of these areas, we can expect the relationship represented by Pareto's law to exist. When it does exist, the auditor can concentrate testing efforts on the high dollar value area and test the relatively insignificant area on a statistical sampling basis. This allows the auditor to determine whether or not the plan is reasonable.

2-6.7.2 Cost Reduction in Manufacturing

"A large industrial valve manufacturer found itself in an increasingly competitive market and consequently launched a drastic cost reduction program. " (Ref. 8).

One of the areas selected for a concentrated cost-saving effort was product design. Most of the designs used by the firm were many years old and had been developed when materials and labor were inexpensive. Therefore, almost all of the product lines had excesses of material and unnecessarily expensive machining requirements. However, a line design change would be expensive since it required engineering for each size valve in the line, new patterns for the cast parts of each size, and new shop tooling to cover each size valve in the redesigned line, In addition, there were the ever-present problems of the limited available engineering time and limited capital for new patterns and tooling.

Redesign of the company's 129 different lines with limited resources was obviously impossible. Once again Pareto's law became a valuable tool to use in the solution of the problem.

The cumulative curve shown in Fig. 2-24 was plotted, and 10% (13) of the product lines were found to account for 87% of the total unit sales.

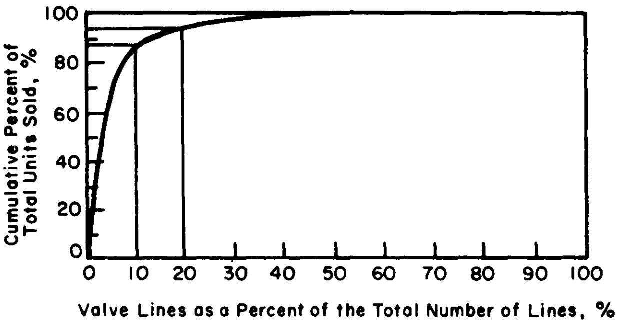


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Figure 2-24. Distribution of Units Sold by Product Line (Ref. 8)

Studies were then made by the engineering group to determine the expected unit savings on each of the 13 high-volume lines. The average unit savings on each line, extended by the number of units sold per year, provided the total estimated savings that could be expected from the redesign of the line. Given this information and the estimated cost of the alterations required by each line, redesign priorities were readily established.

This procedure eliminated the temptation to redesign only those valves with high unit savings. For example, use of this analysis emphasizes the fact that a $2-per-unit saving on a valve with sales of 90,000 units per year is much more worthwhile than a $l00-per-unit saving on a valve with sales of 250 units.

The cost reduction effort discussed in this example not only-improved the company's profit picture but also improved its products. As each valve was redesigned, it was possible to incorporate all of the minor design improvements that previously, by themselves, could not justify new patterns, new tooling, etc.

2-6.7.3 Other Applications

The examples and distribution curves discussed previously illustrate just a few of the many possible applications of Pareto's law and its application to marketing, purchasing, accounting, systems and procedures, data processing, and virtually any other phase of industrial management can be cited.

As a brief illustration of this point some other possible applications are

1. The parts usage graph would be very meaningful to a purchasing agent in directing his efforts to the high dollar usage items when considering cost reduction through alternative supply source development or when attempting to reduce costs through price negotiations.
2. This parts usage graph would also be quite useful to a value analysis staff in directing its studies toward the high dollar usage parts. The units sold graph would also be useful to the value analysts in pointing out the relative number of items manufactured and sold to help direct their design evaluation efforts.

Pareto's law cannot be applied to every management system, but it can be applied often enough so that the manager should always look for it. When it does exist, it should be used to help allocate the majority of management resources, including the manager's own time, to those areas of operation that will provide the maximum economic return.

Efficient management exists when the amount of management effort and cost applied varies in direct relationship to the importance of the item being managed.

2-6.8 TOLERANCE ANALYSIS

There are a number of methods for analyzing tolerances of piece parts and assemblies. These include statistical techniques as well as tolerance charts. More recently the Air Force Materials Laboratory at Wright-Patterson Air Force Base, OH, completed a study of relaxed manufacturing design tolerance concepts that is particularly impressive as a means of tolerance analysis. This process is briefly reviewed in subsequent paragraphs. However, for those interested in a more in-depth understanding of the concept, copies of the final report are available from Manufacturing Technology Division, Air Force Materials Liboratory, Wright-Patterson Air Force Base, OH 45433.

2-6.8.1 Data Collection

In order to make recommendations on relaxing dimensional tolerances, it was found necessary to determine the capability of the machine shop to meet the then current dimensional and surface quality requirements of the engineering drawings. Over a period of five months production inspectors surveyed milled aluminum parts. Thorough analysis of these data revealed a wealth of useful information on the cost-effectiveness of engineering requirements and resulted in some useful changes in the configuration, dimensioning, and tolerancing of machined parts. These were incorporated into and were part of the instructions to designers issued at the beginning of the design phase. All milled aluminum airframe parts incorporate one or more of the design benefits derived.

Eleven major aluminum milled parts were inspected with up to five pieces of each design—for a total of 36 pieces. A total of 1070 thickness measurements were made on areas cut with the end of the end mill (webs), and 866 measurements were made on areas cut with the side of the end mill (stiffeners and flanges). Parts known to have problem areas were excluded for separate consideration on the assumption that anticipated design guidelines would reduce the likelihood of unnecessarily difficult designs in the future. This has generally held true.

Measurements were recorded on sketches of each part and tabulated. The drawings were then consulted for the required thicknesses and pocket widths, and these values were entered. The deviations from the nominal drawing dimensions were then calculated and entered.

The deviations were next tabulated to create a frequency distribution. The total number of deviations were determined versus the magnitude of the deviation. The totals were then accumulated from the largest minus value to the highest plus value, and these cumulative were then converted to a percentage of the total number of measurements. Deviations from web nominal dimensions were plotted versus panel width for several designs to observe the tendency of deviations from the nominal thickness for various web thicknesses. This led to proposed limits on pocket width for each nominal web thickness.

2-6.8.2 Data Analysis

The survey data were analyzed to determine to what degree present design practices were within the shop capability for milled aluminum. As expected, elements cut with the side of the end mill (stiffeners/flanges) showed the larger positive dimensional deviation caused by inherent flexibility in both cutter and part material due to lateral loads.

Stiffeners/flanges exceeded the conventional +0.25-mm (0.010-in.) tolerance in a surprising 24% of the occurrences and in 10% exceeded +0.38 mm (0.015 in.). Webs exceeded +0.25 mm (0.010 in.) 12% of the time. Negative deviations did not appear to be significant. These results suggested that tolerances for stiffeners/flanges might be relaxed if accompanied by an acceptably small weight increase. Also a significant amount of hand finishing and inspection rejections could be avoided if, for example, discrepant stiffeners/flanges could be reduced by over 50%, from 23% to 10% by permitting a +0.38-mm (0.015 -in.) tolerance for these elements. Fig. 2-25 shows examples of cost reduction techniques that can be considered.

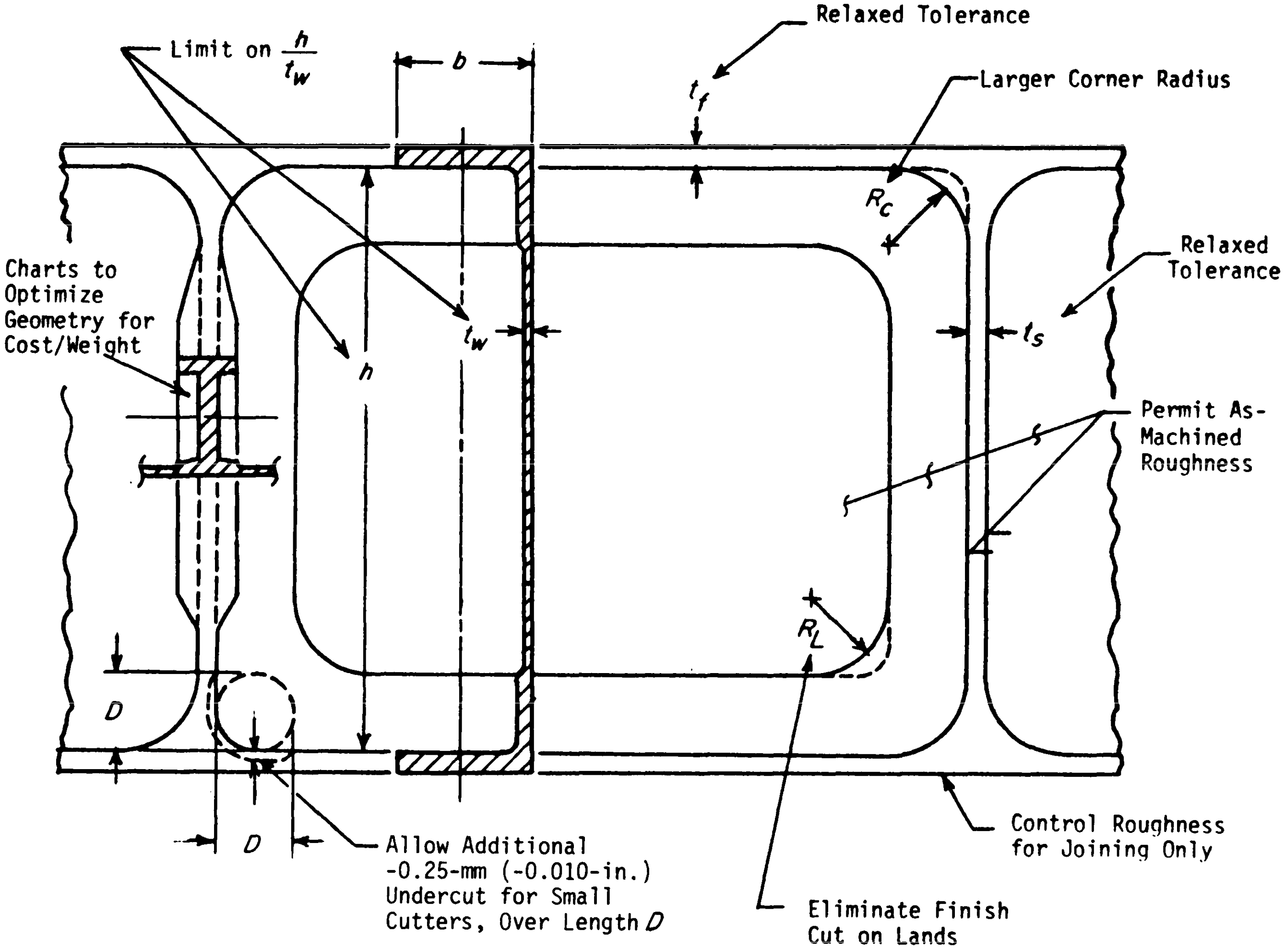

Figure 2-25. Detail Design Cost Reduction Features

With the acceptance of these analyses, recommendations can be made with a reasonable level of confidence that the proposed guidelines are practical and useful and will reduce cost.

2-6.8.3 Recommendations

1. Relax dimensional tolerances on nominal thickness for flanges and stiffeners—elements machined with the side of the end mill—from the traditional ±0.25 mm (0.010in.) to +0.38mm (0.015 in.), and -0.25 mm (0.010 in.). Rejections and hand finishing cost will reduce significantly as will machining cost.

2. Do not relax the traditional ±0.25-mm (0.010-in.) dimensional tolerances on the nominal thickness for webs—elements machined by the end of the end mill. Control is easier to maintain and weight is more sensitive to tolerance than is the case for flanges and stiffeners.

3. Consider relaxation of the requirements on geometric features, such as corners of pockets and "lands", to the extent described in par. 2-2.3. Cost/weight trade-off analysis will usually show this to be profitable for anything other than a space vehicle.

4. Consider allowance of an additional negative tolerance of 0.25 mm (0.010 in.) for a total of –0.51 mm (0.020 in.) in corners that are cut with small flexible cutters, i.e., less than 25.4 mm (1 in.) in diameter. Drafting practice may require that this allowance be set forth in an inspection standard and the standard be referenced on the drawing. Where such a decrease in thickness is not acceptable (and this is seldom the case), the designer should specify an increase of nominal thickness. Undercuts, which are chronic in corners with small radii, are almost always "bought off". The relief offered by the added tolerance will be extremely profitable in terms of reduced inspection and engineering paperwork.

2-7 SUMMARY

Chapters 1 and 2 have covered the philosophy, general application, and basic elements of producibility along with the relatively new discipline of producibility engineering and the tools and techniques available for implementing producibility programs. Good producibility engineering and planning impacts on all the major considerations in electing to proceed either to full production or to regroup to consider the eventual payoff through trade-offs. These factors include cost, time, manpower, facilities, reliability, maintainability, etc. The following chapters will treat the producibility considerations that apply across-the-board as well as those specific to given industries. Chapter 3 considers those elements of producibility that are common to a variety of processes while the remaining six chapters look into those elements particularly applicable to plastics, electronics, and other specific industries as identified in their titles.

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CHAPTER 3

COMMON PRODUCIBILITY CONSIDERATIONS

Reducibility considerations common to all components regardless of material or intended purpose and the factors that impact upon the producibility of all designs are discussed in this chapter,

3-1 INTRODUCTION

The most desirable producible design is one that could be made by any reasonably skilled worker out of a wide variety of materials in a short time. However, all products have limiting parameters imposed by the designer in dimensioning drawings and detailing specifications that describe the components, materials, and often specify the manufacturing processes. These, in turn, are impacted by the quantities required, the expendability of the items, and the quality assurance requirements. The impact of each of these elements can be minimized if proper consideration is given to producibility throughout the design process.

3-2 IMPACT OF DRAWINGS AND SPECIFICATIONS

Drawings control and delineate shape, form, fit, function, and interchangeability requirements for an item. Military design drawings are prepared in accordance with military specification (MILSPEC) DoD-D-1000 (Ref. 1), which is a mandatory specification derived from Military Standard 100 (MIL-STD-100) (Ref. 2). In addition to drawings there are specifications that are basic documents containing general criteria, performance requisites, and inspection procedures not covered by the drawings. Both the drawings and specifications constitute a part of the product documentation and are often called the technical data package (TDP), In Department of Defense (DoD) Instruction 5010.12 (Ref. 3) it is stated that end product documentation must be sufficiently defined to permit a competent manufacturer to reproduce an item without recourse to the design activity. An engineering drawing for a part, when supplemented by the applicable specifications and standards, should include the necessary information (i.e., dimensions, tolerances, notes, and other data) to describe fully the characteristics of the part after all manufacturing has been completed.

This approach to absolute definitiveness tends to make the drawings and specifications highly restrictive, and therein lies the antithesis of producibility. Although producibility is aimed at adjusting design restrictions to permit the maximum number of alternatives in the production process, the necessity for absolute definitiveness in drawings and specifications results in a tightening of the restrictions, which inherently limits the alternatives. It is incumbent upon each designer to review carefully each design to achieve the optimum balance between definitiveness and producibility.

3-2.1 DESIGN PROCESS RESTRICTIONS

There are three basic sources of unnecessary restrictions in drawings:

1. Those that result from decisions early in the design process
2. Those that result from decisions in the documentation process
3. Those that are inadvertent.

A few designs do not achieve the maximum in reliability, maintainability, useful life, producibility, or in any other aspect of theoretical perfection because they are overly complex. The more complex the design, the greater the requirement to increase restrictions. The design may be stronger than actually required or heavier than desired. It may call for an expensive material or finish when a less costly one would suffice; it may require complex cams that could be replaced by simple linkages. Simplifying a given design generally reduces the production cost and produces fringe benefits in reliability, maintainability, quality, performance, and producibility y.

An example of unnecessary design process restriction involves a new design that specifies a high alloy steel for a part for which surface hardness is a prime requisite. Since the rest of the design is metal, the designer naturally chose a hard metal for the part, but this material was much more expensive and far more difficult to use in manufacturing. Subsequently, a composite material was substituted that had the desirable effect of reducing overall weight. The part was acquired in final net shape, which-reduced machining and/or fabrication time and cost. This, like most unnecessary restrictions, was the result of inadequate planning and analysis.

3-2.2 DOCUMENTATION PROCESS RESTRICTIONS

In the process of transferring the design from rough sketches into final drawings, many detail requirements are created through the necessity of absolute definitiveness. For example, a sketch or a drawing restriction often requires that a slot or a groove be cut into one surface of a part as shown in Fig. 3-1. At times, the sketch is given to a draftsman in far less detail than is shown in Fig. 3-1. Without prior knowledge of the functional characteristics of the slot, which may be purely for clearance purposes, the part is put on the drawing exactly as shown in the sketch. This goes to manufacturing as a flat-bottomed, square-cornered slot—an expensive manufacturing operation.

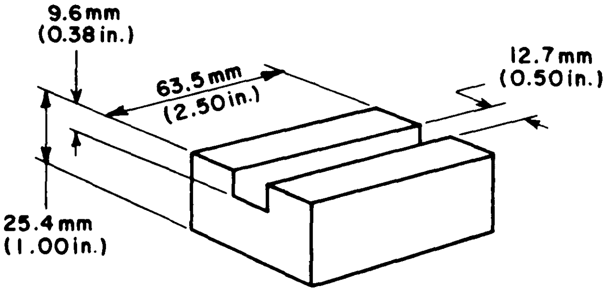


Figure 3-1. Grooved Part

In actuality, there may be any number of alternatives for the cross section of the slot as shown in Fig. 3-2. Any of these alternatives could be acceptable depending on functional requirements; under certain circumstances any one of these might provide an item that has improved producibility characteristics. This is the type of unnecessary restriction that a continuing producibility review should uncover.

3-2.3 DRAWING PROCESS RESTRICTIONS

Drawing process restrictions often are caused by the inadvertent inclusion or exclusion of important data from drawings due to improper drawing preparation. They are a means of communication, and it is critical that proper drafting procedures be used so that everyone concerned interprets the data on the drawing correctly. Ref. 1 provides guidance for the preparation of drawings to military standards. These standards make maximum use of commercial standards, which allows use of commercial drawings in many instances. The drawing legends sometimes tend to be incomplete. For example, Fig. 3-3(A) shows a simple application of tolerancing on all dimensions, and Fig. 3-3(B) shows some of the possible variations that may occur during manufacture of the part. Not all possible variations would occur during any one production run, but any variation could be introduced as a result of the method of manufacture. However, all the variations shown in Fig. 3-3(B) meet the requirements listed in Fig. 3-3(A). Fig. 3-4 shows the application of geometric and linear controls. While variation still exists, it is more controlled. For example, the 76.20-mm (3.000 -in.) dimension may vary by 0.51 mm (0.020 in.), but whatever it is, within that limit, the right side of the item is perpendicular to the top within 0.13 mm (0.005 in.), and the left side is parallel to the right side within 0.13 mm (0.005 in.). Thus there is an allowable variation of 0.51 mm (0.020 in.) permitting machine flexibility, but a control of the resultant surface to within 0.13 mm (0.005 in.). The variations are within limits that in this case assure interchangeability. Form, fit, and function are not violated.

The possibility of variation in production exists within a single shop as well as between different contractor shops in which production techniques and production line equipment are different. This case is illustrated in Fig. 3-5, which shows a reasonably complete drawing. All dimensions are tolerance; surface roughness requirements are noted, and materials are specified. The drawing appears complete, but the controls are missing. Fig. 3-6 shows two production possibilities. If the piece is chucked on the 101.6-mm (4.00 -in.) diameter (Fig. 3-6(A)), the six 7.95-mm (0,313 -in.) diameter holes may be concentric with the 101.6-mm (4.00-in.) diameter; however, the other bores, the diametral bosses, and the keyway may be off center, depending on the process used. If the piece is held in an expanding arbor, everything may be concentric and symmetrical, but the six

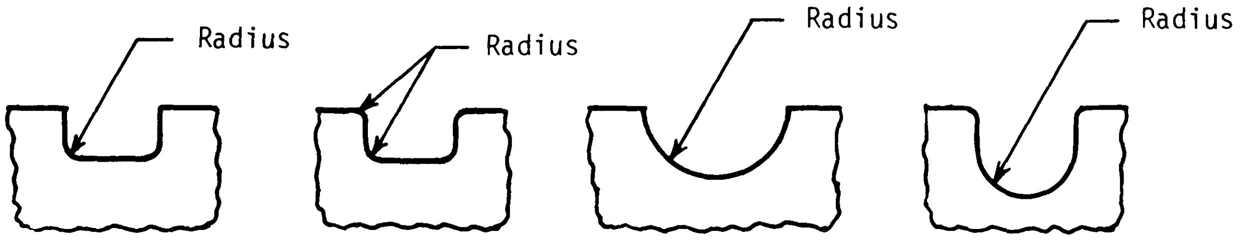
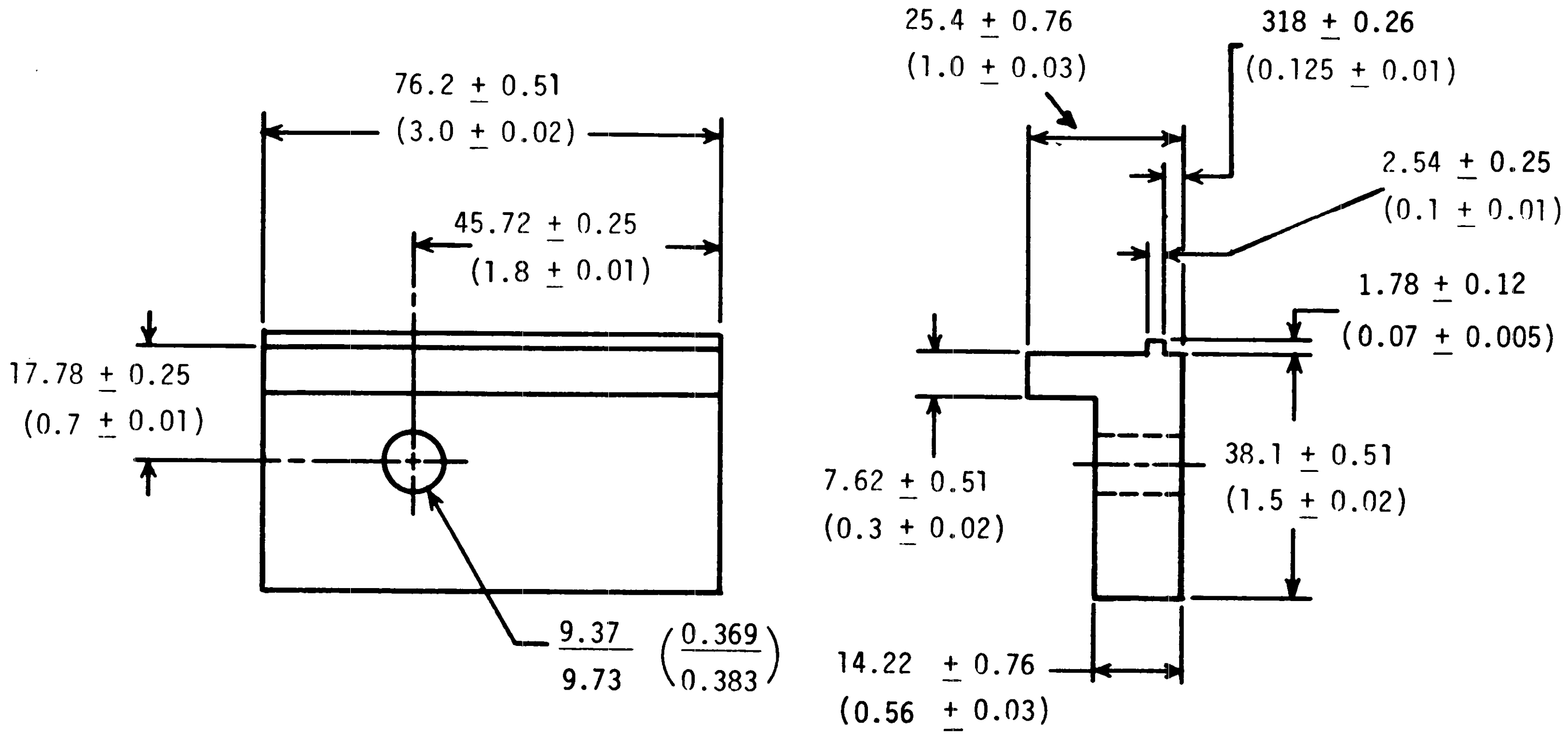
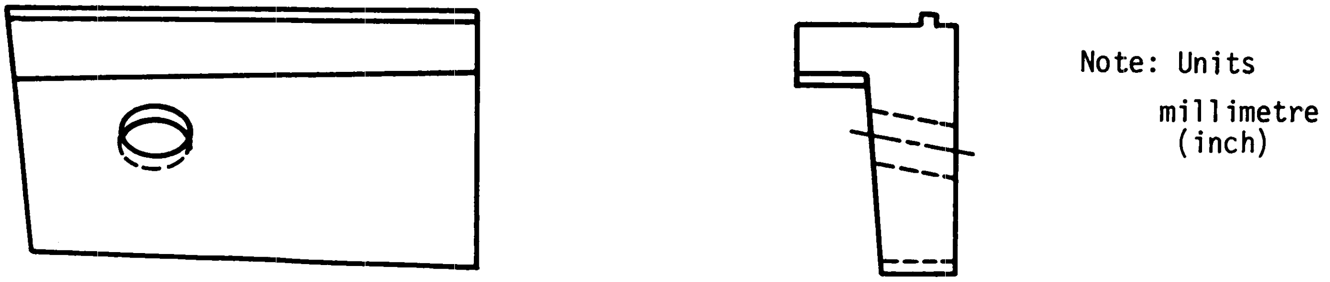


Figure 3-2. Alternative Designs



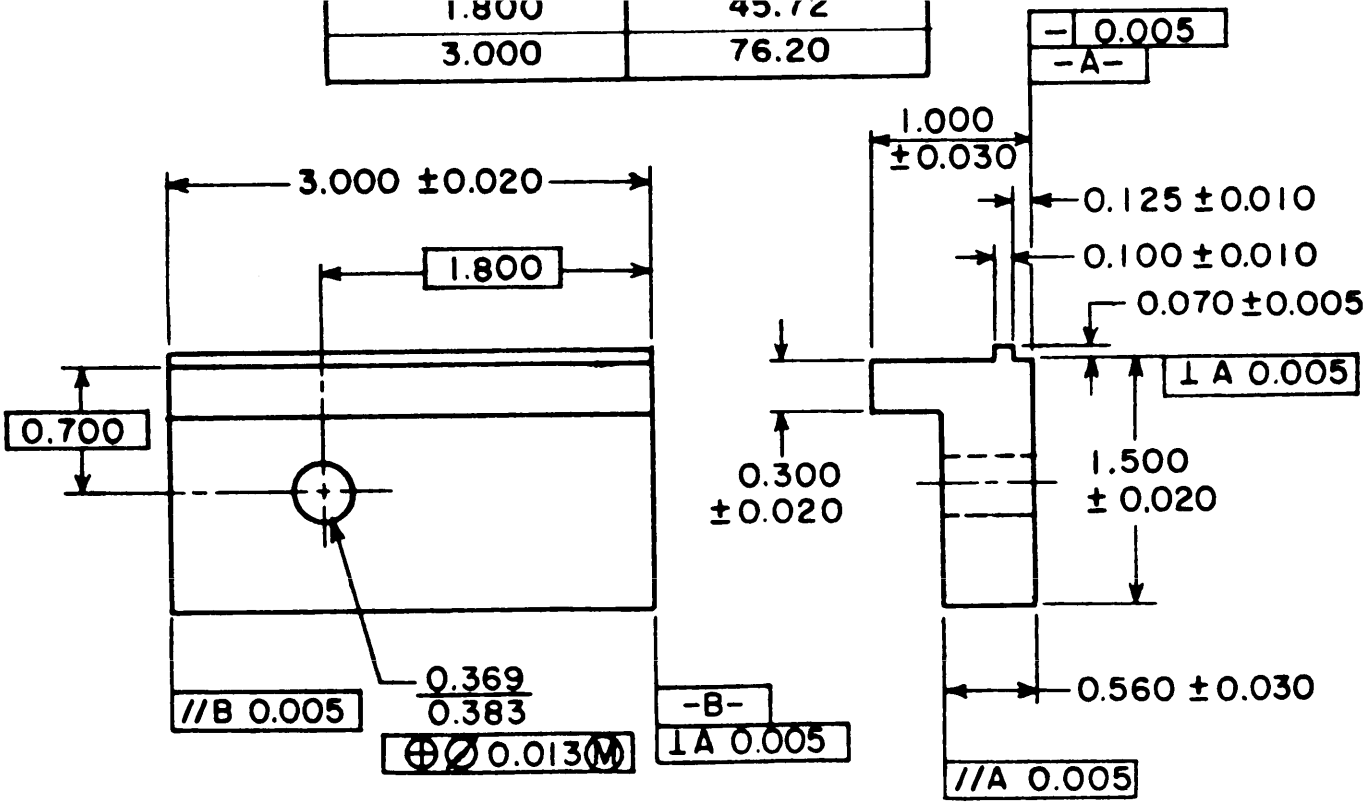
(A) All Dimensions Toleranced



(B) Permissible Interpretation

Figure 3-3. Possible Results of Failing to Provide Positioning Tolerance

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
0.005	0.13
0.010	0.25
0.013	0.33
0.020	0.51
0.030	0.76
0.070	1.78
0.100	2.54
0.125	3.18
0.300	7.62
0.369	9.37
0.383	9.73
0.560	14.22
0.700	17.78
1.000	25.40
1.500	38.10
1.800	45.72
3.000	76.20



All Dimensions Are In Inches.

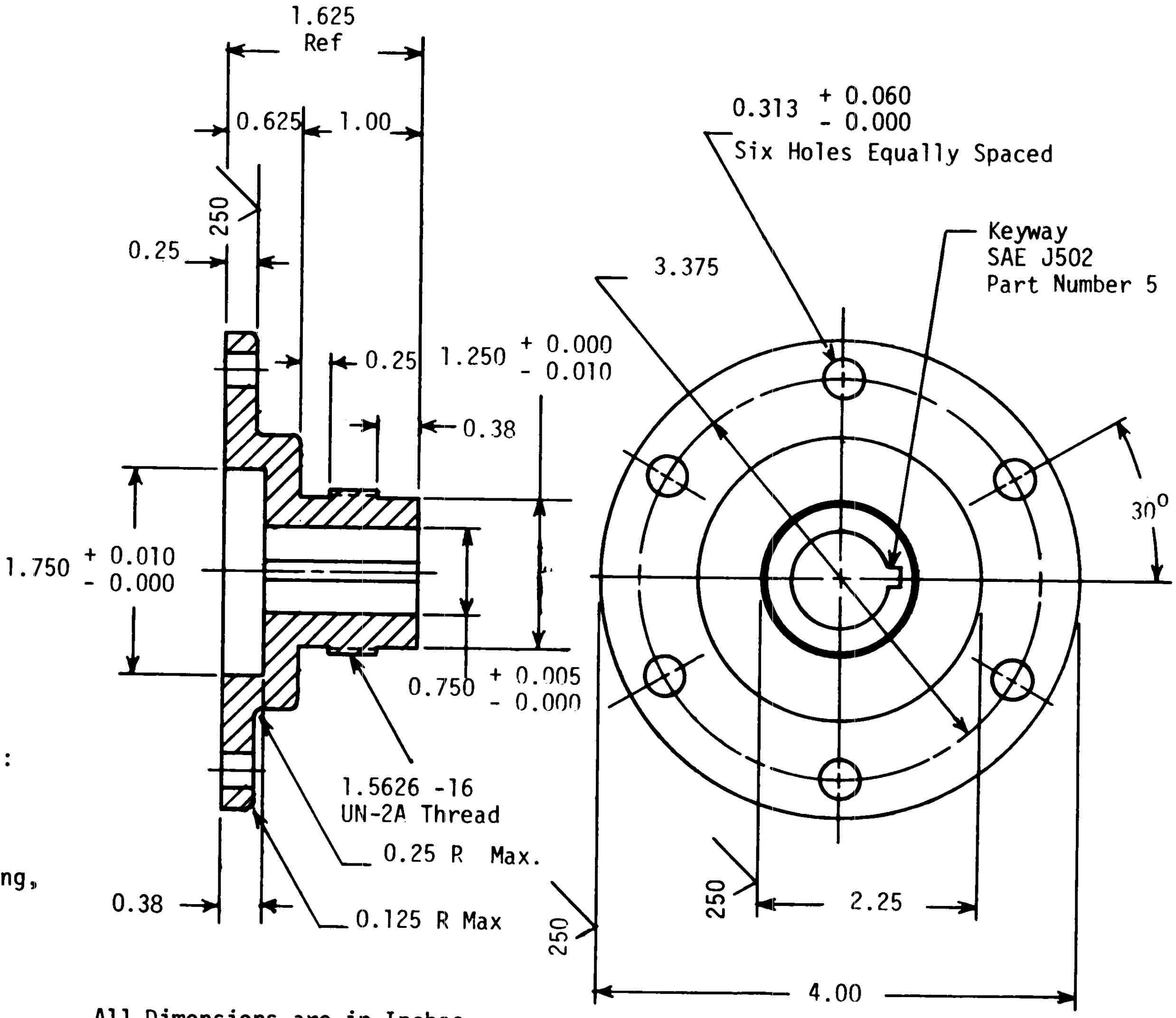
Figure 3-4. Application of Geometric and Linear Controls

INCH–MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
0.005	0.13
0.010	0.25
0.060	1.52
0.125	3.18
0.25	6.4
0.313	7.95
0.38	9.6
0.600	15.24
0.625	15.88
0.750	19.05
1.00	25.4
1.250	31.75
1.5626	39.690
1.625	41.28
1.750	44.45
2.25	57.2
3.375	85.72
4.00	101.6

DEGREE–RADIAN EQUIVALENTS	
DEGREE	RADIAN
30	0.52

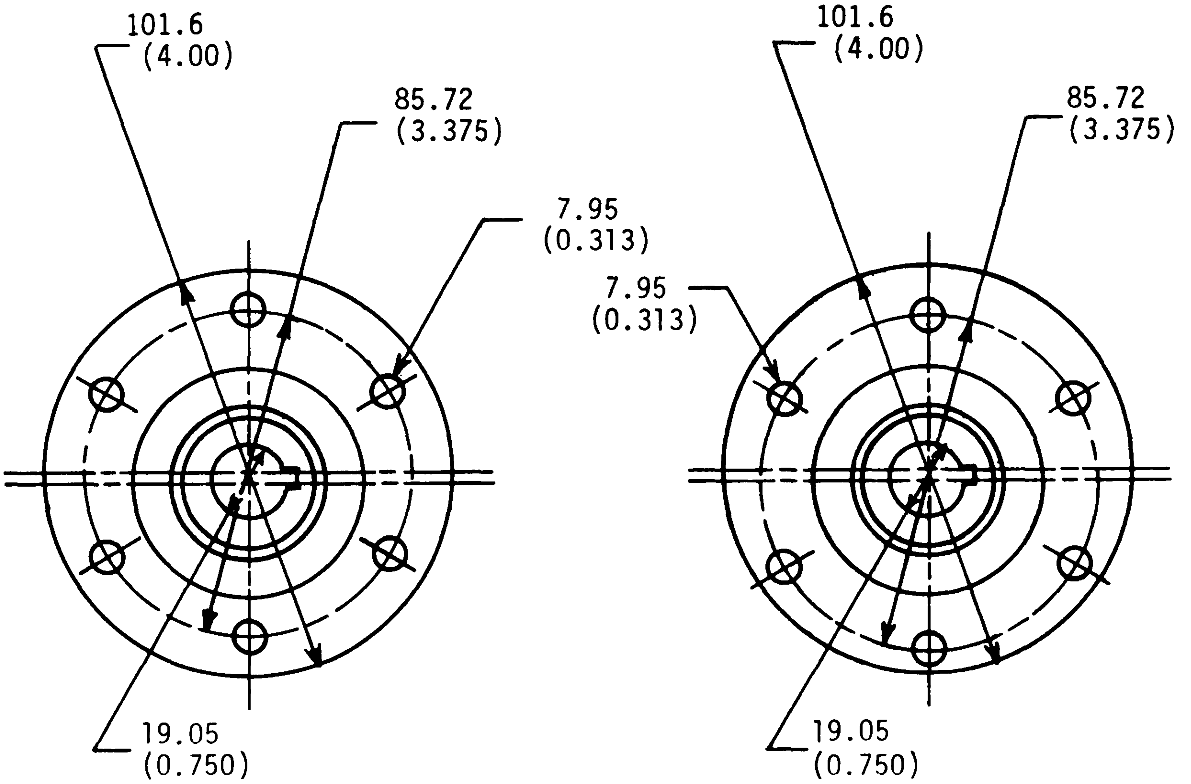
Notes:

1. Unless otherwise specified:
   Surface Roughness 125✓
2. For interpretation of
   Dimensioning and Tolerancing,
   see ANSI Y14.5 and dwg
   13----E----.
   Surface Roughness,
   see ANSI B 46.1
   Tolerances
   .xx * .03
   .xxx * .010



All Dimensions are in Inches.

Figure 3-5. Drawing Without Positioning Controls



(A) 7.95-mm (0.313-in.) Holes Processed With Respect to 101.6-mm (4.00-in.) Diameter

(B) 7.95-mm (0.313-in.) Holes Processed With Respect to 19.05-mm (0.750-in.) Hole

Note: Units--millimetre (inch)

Figure 3-6. Possible Results of Failing to Provide Positioning Controls

7.95-mm (0.31 3-in.) diameter holes may be located off center (as shown in Fig. 3-6(B)). Fig. 3-7, depicting a similar part, gives information that will eliminate the previously discussed incorrect production possibilities by specifying controls using geometric dimensioning and tolerancing. Data are established; geometric requirements are specified; quality assurance is invoked, and all items produced and accepted will meet the form, fit, function, and interchangeability requirements. As a result, the repair parts from any producer will fit.

The majority of the producibility restrictions created in the preparation of drawings could be eliminated with adequate advance planning and with an effective, continuing producibility analysis.

3-2.4 SPECIFICATIONS AND STANDARDS

Specifications and standards are used to define clearly the characteristics of an item to be produced. MIL-STD-961 (Ref. 4), which regulates the preparation and revision of all military specifications, defines a specification as ". . . a document intended primarily for use in procurement, which clearly and accurately describes the essential technical requirements for items, materials, 'or services, including the procedures by which it will be determined that the requirements have been met. Specifications for items and materials may also contain preservation-packaging, packing, and marketing requirements.". The "essential technical requirements" are those necessary to assure that the produced item will perform in accordance with the required performance characteristics. The specification, as placed in the hands of the procuring agency, represents a distillation of the experience and projected needs of the user as translated by the developer into engineering requirements. To the engineer interested in producibility, the important word is "essential". Essential, as the word implies, represents the highest order of dimensional definition of a part. There may be other dimensions that are important in terms of form, fit, function, or weight but not critical. It is those noncritical dimensions, finishes, and tolerances that should be the first target of producibility engineers looking for ways to reduce cost or complexity.

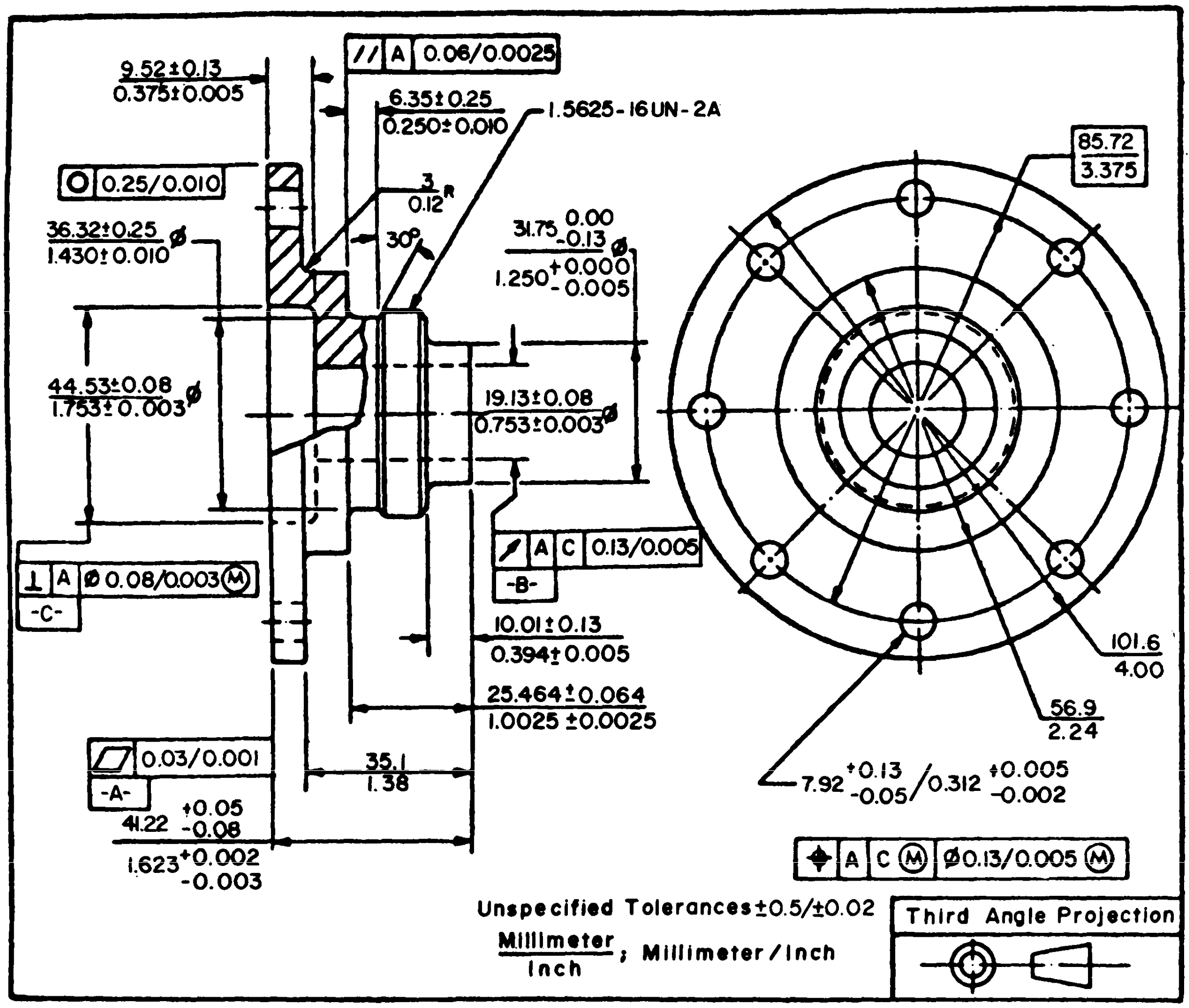


Figure 3-7. Illustration of Proper Positioning Controls

3-2.4.1 The Military Specification

The commercial parts industry almost exclusively originates the commodities that eventually emerge as MILSPEC types. The generic evolution of a large number of parts that can be traced from commercial to MILSPEC is progressing rapidly. Differences between the two are the degree of inspection, test, and control over the parts. As an example, the same basic part used in a helicopter rotor and in an automobile transmission may be identical dimensionally, but it requires a far higher reliability in aircraft use because a stalled engine is not merely a nuisance but most often is a catastrophe. This example demonstrates the need for MILSPEC'S, but it should be emphasized that MILSPEC'S should be used only when commercial specifications are not available. The engineer, to perform his tasks, should be well versed in the DoD system of standards and specifications (Ref. 5). Where possible the DoD encourages the use of commercial specifications rather than development of MILSPEC 's.

MILSPEC'S written today follow the format requirements contained in Ref. 4. This standard contains integrated instructions for the preparation of specifications, amendments, supplements, specification sheets, and notices. For additional guidance in the preparation of specifications, internal documents of individual Government activities may be used as supplemental information. DoD agencies select and standardize items to meet their specific needs. In some instances the specifications are based on commercially available materials; in other instances the specifications may be for materials of interest only to DoD. In either instance the specifications are used so that DoD is certain of receiving material that satisfies its needs. The method for insuring contractual implementation of the MILSPEC system is to state appropriate requirements in contracts between the military procurement activity and the contractor for engineering designs or to cite specific, applicable documents for supply contracts. This is done by using DD Form 1423, Contract Data Requirements List, or by attaching a statement to the contract.

The system of MILSPEC is not infallible, and the individual making use of MILSPEC materials must be careful that the specifications are in fact adequate for the planned use. Examples of factors that might preclude direct use of MILSPEC material are

1. Dimensional tolerance not sufficiently tight
2. Environmental requirements not sufficiently inclusive
3. Lack of coverage for a key parameter
4. Testing not adequate,

Frequently these factors are used to justify abandoning the MILSPEC. A detailed and objective evaluation of the system shows that the MILSPEC system provides ample authorization for a controlled procedure that will accommodate the technical requirements of almost any program. One example is Ref. 1. Among other things, this specification authorizes design activities, when commercial specifications are not suitable, to prepare specifications and specification source control drawings "as necessary" to insure the procurement of the commodities required to achieve the requirements levied on the equipment. By creating these documents and the engineering tasks necessary to determine their content, the design activities have a recognized basis and technical justification for altering, selecting, or modifying parts as necessary. The design activity also may include or exclude, on specification or source control drawings, special inspections as justified and warranted on a technical basis.

The development of the total technical design procedure, which is itself nothing more nor less than a specification, must be conducted in conjunction with MIL-STD-143 (Ref. 6). This standard sets forth the criteria and order of precedence for the selection of specifications and standards to be used by design activities in the design and construction of military equipment. As described in Ref. 5, the procuring agency has the additional responsibility of providing an orderly feedback to the MILSPEC system if the technological data and improvements developed during the course of its procurement activities become candidates for incorporation into the MILSPEC system. The best in inspection and test techniques resulting from experience can also be incorporated. Demonstrated deficiencies or weaknesses in MILSPEC documents can be identified and remedied. This data feedback becomes practical if the design activities participate within the MILSPEC system and this technology becomes documented. The principal weakness of the system is that the time lag between change in the state of the art and specification coverage appears excessive.

3-2..4.2 The Military Standard

Standards establish engineering and technical limitations and applications for items, materials, processes, methods, designs, and engineering practices. They should be complete in their descriptions and provide information required to make application decisions. Details for preparing and revising standards are presented in MIL-STD-962 (Ref. 7). Information from Ref. 7 regarding standards follows:

1. "Standards define terms, establish codes and document practices, procedures and items selected as standard for design, engineering and supply management operations. Military standards shall not be used as the medium for imposing administrative requirements on contractors.

2. "Standards are documents created primarily to serve the needs of designers and to control variety. They may cover materials, items, features of items, engineering practices, processes, codes, symbols, type designations, definitions, nomenclature, test, inspection, packaging and preservation methods and materials, define and classify defects and standardize the marking of material and item parts and components of equipment, etc. Standards represent the best solution for recurring design and engineering and logistics problems with respect to the items and services needed by the military services.

3. "Standards are used to standardize one or more features of an item, such as size, value, detail of configuration, etc. In equipment specifications they are referenced to standardize on those design and testing requirements which are essential to interchangeability, compatibility, reliability, and maintainability. They are prepared to provide the designer with the descriptions and the data normally required for selection and application. Standards disclose or describe the technical features of an item in terms of what it is and what it will do. In contrast, the specification for the same item describes it in terms of the requirement for procurement. Reference to other documents in standards to complete a description should be resorted to only when it is impracticable to do otherwise. "

3-2.4.3 Commercial Specifications and Standards

The oldest, and probably the first, class of standards are those for weights and measures (units for length, weight, and volume that are the basis for commerce, trade, and science). The second class of standards consists of those set for consumer protection in the public interest, such as standards involved in building codes and pollution control. The third class is made up of voluntary industry standards that are set by consensus among concerned parties. American industry is well ahead of the rest of the industrialized nations in the comprehensiveness and dependability of its standards and parts produced according to those standards.

There are some 20,000 voluntary standards in force. These have been created by more than 400 organizations, and they cover a multitude of products, practices, test procedures, materials, and other characteristics that have been found to be in the interest of those parties involved to reach common understanding and common practice. The driving force behind voluntary standards is economic. The first step in this direction occurred at the start of the 19th century when Eli Whitney produced the first rifles from interchangeable parts, which obviated the need for handwork in assembly. Production was then simpler and less expensive. Mass production is the logical extension of this concept, and it requires standardization throughout the entire economy. In fact, it is hard to imagine a time during this century when nuts and bolts would not fit together regardless of manufacturer. Such a situation would obviously bring modern assembly lines to a halt. The economic forces are therefore significant.

For example, Herbert Hoover, as president of the Federated American Engineering Society, initiated a study of six industries in 1920. His study reported that nearly 50% of the cost of production and distribution could be eliminated through standardization and simplification. Fifty percent of the cost of production and distribution should motivate any manufacturing industry to reach a consensus on standards. Product standards can be set, not for the self-interest of the industrial parties involved, but for overriding national interests or national objectives.

There are far-reaching benefits to be gained from voluntary standards set on a national scale. The development of numerical control and advanced programming techniques offers excellent examples of this concept. When numerical control tools were first installed in the aerospace industries between 1958 and 1960, it was almost impossible to interchange the tapes that ran tools. Each different system had its own tape sizes, data codes, formats, and programming requirements, and the programs had to be figured out with a hand calculator and punched on a Flexowriter. This state of chaos was brought under control by standards that are now controlled by the Electronic Industries Association Committee TR-31 on numerical control.

3-2.4.4 Application of Standards and Specifications

Specifications and standards may be applied in a number of different combinations. They may be either commercial, military, or any mixture of commercial and military. The DoD is placing increased emphasis on the use of commercial products and items in the manufacture of military material.

3-2.4.5 Use of Commercial Specifications

In accordance with Ref. 5, it is desired that non-Government specifications and standards be adopted and used in lieu of the development and promulgation of a new Government document when there is no substantial or demonstrable advantage to the DoD in the development of a new document. Criteria for the use of commercial standards are costs, logistic support, performance requirements, quality control, and usable" life of the item when compared with a new military specification for the same item. When commercial specifications are not directly or completely applicable, they often can be modified by the addition of key features of existing military specifications.

Commercial standards are, for the most part, voluntary standards of industrial suppliers and users. As such they represent a level of product quality that reflects industry's best efforts. More important 1 y, they represent the broadest possible base of sources, which assures availability. In addition, they are the basis that permits mass production by the broad base of suppliers, which provides materials and interchangeability at the lowest possible price.

3-2.5 TOLERANCES AND SURFACE FINISHES

Tolerances on dimensions and surface finishes play a very important role in determining item producibility. However, extremely tight tolerances do not necessarily imply poor producibility. The item may be of such a nature that tight tolerances are imperative for the item to function properly. If loosening the tolerances will detract from the function or reliability of the item, then such an action would detract from the producibility also. If, on the other hand, the tolerances can be loosened without detracting from the functional or performance characteristic of the item, the producibility may be enhanced. A comprehensive study of the principles of interchangeability is essential for a thorough understanding and full appreciation of low-cost production techniques. Interchangeability is the key to successful production regardless of quantity. Details of all parts should be surveyed carefully to assure not only inexpensive processing but also rapid, easy assembly and maintenance. It must be remembered that each production method has a well-established level of precision that can be maintained in continuous production without exceeding normal, basic cost. Economic manufacturing does not "just happen". It starts with design and considers practical limits of machine tools, processes, tolerances, and finishes. The production tolerances for various machining operations and cost curves for tolerances and surface roughness show that it is important to analyze the tolerance structure and surface roughness requirements to produce a functional, economical design.

3-2.5.1 Relationship of Surface Roughness and Tolerance

In general, surface roughness is defined as the average deviation expressed in micrometers (microinches) from the mean surface. Some methods may use the root mean square (rms) average deviation, and others may use the arithmetic average deviation. The two averages described are not mathematically equivalent. ANSI B46.1 (Ref. 8) says the rms method will read approximately 11% high; however, there is general agreement that the difference between them is negligible, and the term average is universal. The mean surface is located so that the volume of peaks above the surface cross section exactly equals the volume of valleys below it.

There is an obvious relationship between surface roughness and dimension tolerances. It is not feasible to expect to hold a tolerance of 0.003 mm (0.0001 in.) on a part that is to be machined to an average roughness of 3.2 µm (125 µin,) rms. Likewise, a finish of 0.3 to 0.4 µm (10 to 15 µin.) for a surface that is merely intended to provide a locating surface for subsequent operations cannot be justified. A 1.0- to 1.5-µm (40- to 60-µin.) finish would be satisfactory and would cost at least 50 to 60% less.

3-2.5.2 Application of Surface Finishes

As an aid for understanding the applications of various surface finishes, the paragraphs that follow contain some typical examples and their usage:

1. A 0.1-µm (4-µin.) rms surface results from processes that produce mirrorlike surfaces free from tool grinding or visible marks of any kind. The finish is used on rolls ‘for roller bearings subject to heavy loads, for packings and rings that slide across the direction of the finish grain, and for tool components. Because of the high cost, this finish is used only when essential.

2. A 0.2-µm *(8-µin.) rms surface* results from processes that produce close-tolerance, scratch-free surfaces. The finish is used for the interior surface of hydraulic struts, for hydraulic cylinders, for pistons and piston rods, for cam faces, for raceways, and for rolls of antifriction bearings when loads are perpendicular to the axis of the bearing. This finish is used only when coarser finishes are known to be inadequate.

3. A *0.04-µm (16-µin.) rms surface* results from processes that produce a finish that is essential for those applications for which surface finish is of primary importance for proper functioning. The finish is used for rapidly rotating shaft bearings, for heavily loaded bearings, for rolls in bearings of ordinary commercial grades, for hydraulic applications, for static sealing rings, for the bottom of sealing-ring grooves, for journals operating in plain bearings, and for members under extreme tension.

4. A 0.8-µm (32-µin.) rms surface results from processes that produce a fine machine finish. This finish is normally found on parts subject to stress concentrations and vibrations, for brake drums, broached holes, gear teeth, and other precision machined parts.

5. A *1.6-µm* (63-µin.) rms *surface* results from processes that produce a high-quality, smooth machine finish. It is as smooth a finish as can be economically produced by turning and milling without subsequent operations and can be produced on a surface grinder. This finish is suitable for ordinary bearings, for ordinary machine parts for which fairly close dimensional tolerances must be held, and for highly stressed parts that are not subject to severe stress’ reversals.

6. A *3.2-µm (125.µin.) rms surface* results from high-grade machine work where high speeds, fine feeds, light cuts, and sharp cutters are used to produce a smooth machine finish. It may also be produced by all methods of direct machining under proper conditions. This finish should not be used on sliding surfaces, but it can be used for rough bearing surfaces where loads are light and infrequent or for moderately stressed machine parts that require moderately close fits.

7. A *6.4-µm (250-µn.) rms surface* results from average machine operations using medium feeds. The appearance of this finish is not objectionable and can be used on noncritical component surfaces and for mounting surfaces for brackets, etc.

The only difference in the parts shown in Figs. 3-8 through 3-11 is an increasing level of tolerance, surface finish restrictions, and relative cost to produce. From data on the figures it can be concluded that tolerances on finishes and dimensions play an important part in determining the producibility of an item.

3-2.6 GUIDELINES FOR PRODUCIBILITY REVIEW OF DRAWINGS AND SPECIFICATIONS

The preparers of drawings and specifications should assure that the drawings and specifications conform with the guidance provided in Refs. 1, 2, 3, and 4.

To assure that all aspects of producibility have been considered, the preparers of drawings and specifications should also use a checklist. Obviously, a checklist that is applicable to all types of systems, such as electronic, mechanical, and hydraulic, would be too cumbersome to use. Secondary checklists should be developed by the preparers of documentation for peculiar aspects of specific commodity items.

3-2.6.1 General Checklist for Common Producibility Considerations

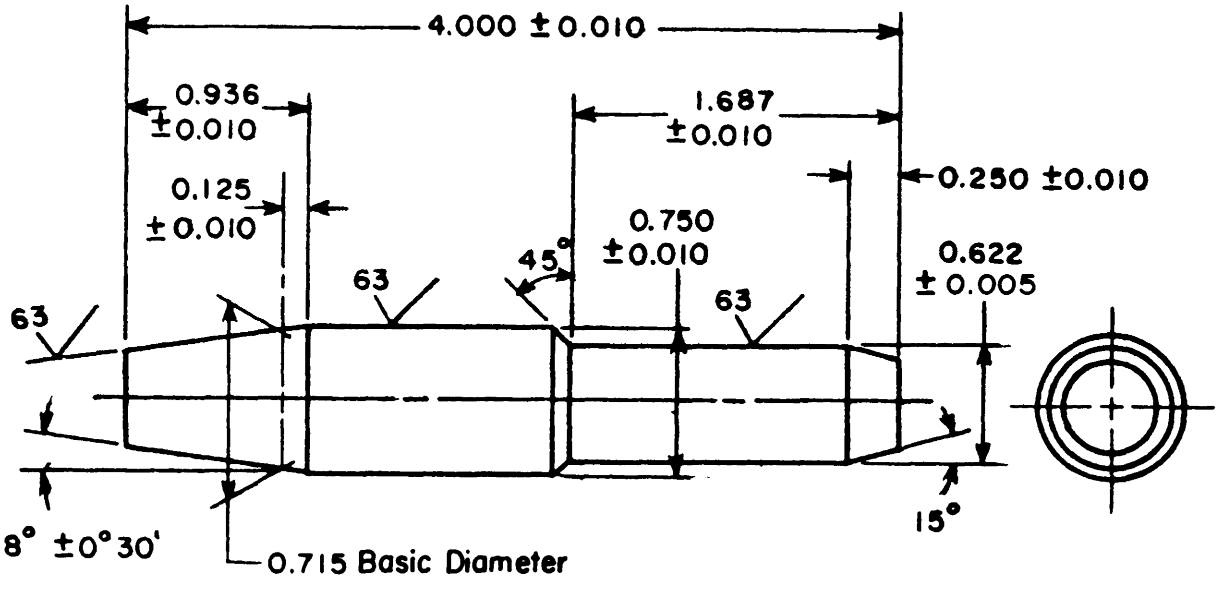
1. *Detail Checklist:*

Are dimensions adequate and properly located to facilitate subsequent use?

Are tolerances realistic for performance ?

Are tolerances consistent with standard manufacturing processes ?

Are tolerance accumulations consistent with interchangeability?



Material: H41300

Manufacturing Tolerances
Unless Otherwise Specified
0.000 ±0.015
Angles ± 1 deg
Surface roughness 125
All Dimensions are in Inches.

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
4.000	101.60
1.687	42.85
0.936	23.77
0.750	19.05
0.715	18.16
0.622	15.80
0.250	6.35
0.125	3.18
0.015	0.38
0.010	0.25
0.005	0.13

DEGREE-RADIAN EQUIVALENTS	
DEGREE	RADIAN
45	0.785
15	0.262
8	0.140
1	0.017
0.50	0.009

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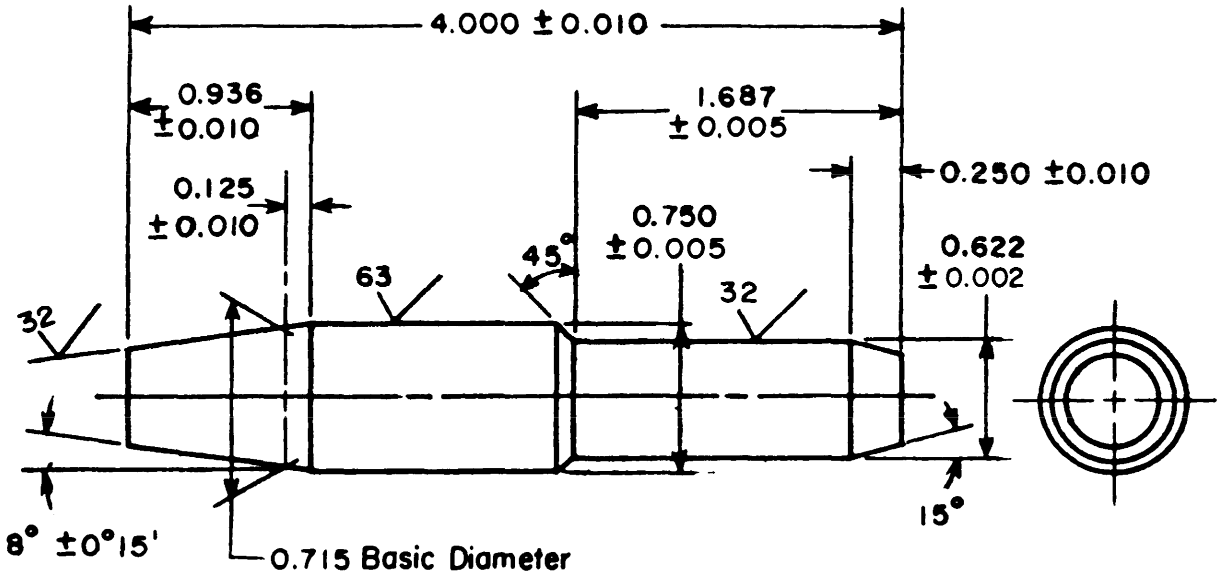
Figure 3-8. Shaft Turning, Forming, and Cutoff (Ref. 9)



Material: H41300

Manufacturing Tolerances
Unless Otherwise Specified
0.000 ±0.015
Angles ± 1 deg
Surface roughness 125

All Dimensions are in Inches.

Note: Cost 16% more to produce than the part in Fig. 3-8.

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
4.000	101.60
1.687	42.85
0.936	23.77
0.750	19.05
0.715	18.16
0.622	15.80
0.250	6.35
0.125	3.18
0.015	0.38
0.010	0.25
0.005	0.13
0.002	0.05

DEGREE-RADIAN EQUIVALENTS	
DEGREE	RADIAN
45	0.785
15	0.262
8	0.140
1	0.017
0.25	0.004

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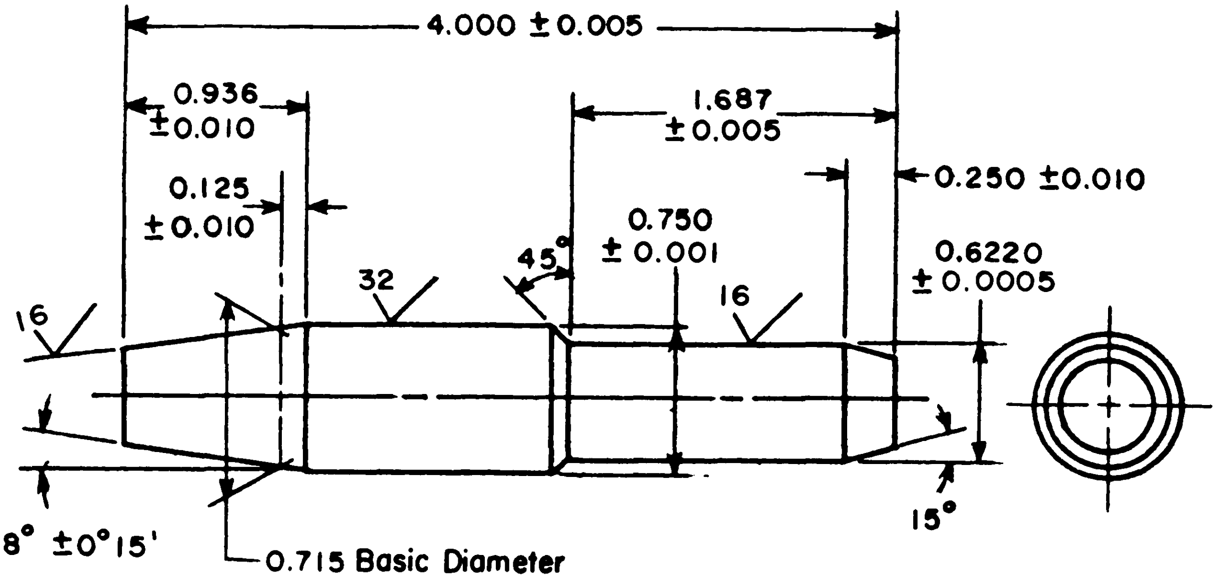
Figure 3-9. Shaft Turning, Forming, and Cutoff to a Closer Tolerance Than Figure 3-8 (Ref. 9)



Material: H41300

Manufacturing Tolerances
Unless Otherwise Specified
0.000 ±0.015
Angles ± 1 deg
Surface roughness 125

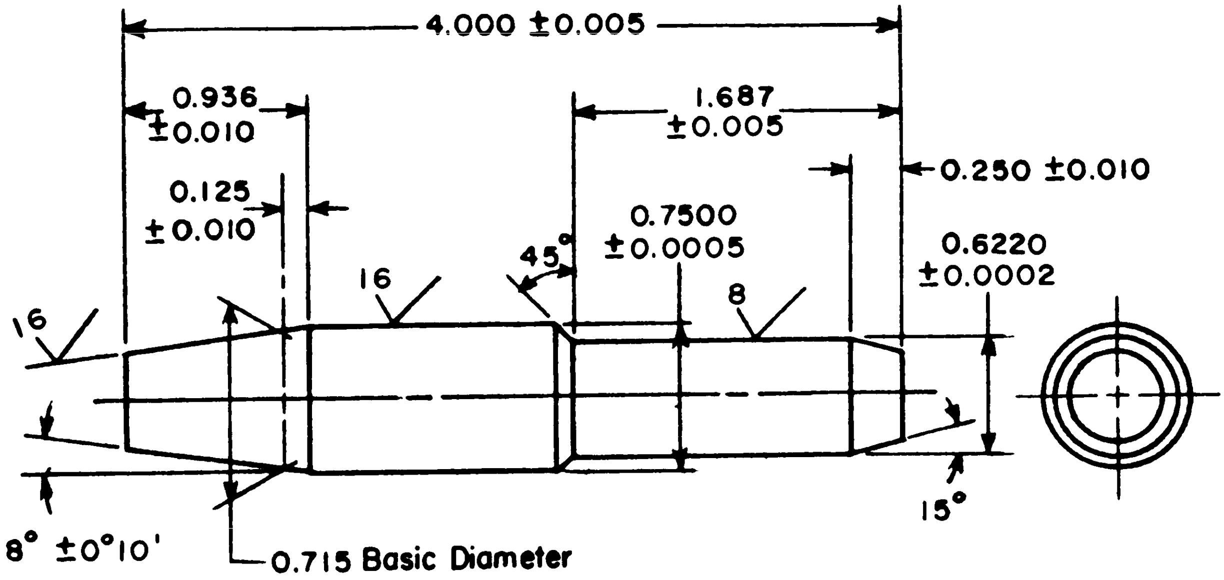
All Dimensions are in Inches.

Note: Cost 326% more to produce than the part in Fig. 3-8.

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
4.000	101.60
1.687	42.85
0.936	23.77
0.750	19.05
0.715	18.16
0.622	15.80
0.250	6.35
0.125	3.18
0.015	0.38
0.010	0.25
0.005	0.13
0.001	0.03
0.0005	0.013

DEGREE-RADIAN EQUIVALENTS	
DEGREE	RADIAN
45	0.785
15	0.262
8	0.140
1	0.017
0.25	0.004

Figure 3-10. Shaft Turning, Forming, Cutoff, and Grinding (Ref. 9)



Material: H41300

Manufacturing Tolerances
Unless Otherwise Specified
0.000 ±0.015
Angles ± 1 deg
Surface roughness 125

All Dimensions are in Inches.
Note: Cost 670% more to produce than the part in Fig. 3-8.

INCH-MILLIMETRE EQUIVALENTS	
INCH	MILLIMETRE
4.000	101.60
1.687	42.85
0.936	23.77
0.7500	19.050
0.715	18.16
0.6220	15.799
0.250	6.35
0.125	3.18
0.015	0.38
0.010	0.25
0.005	0.13
0.0005	0.013
0.0002	0.005

DEGREE-RADIAN EQUIVALENTS	
DEGREE	RADIAN
45	0.785
15	0.262
8	0.140
1	0.017
0.167	0.003

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Figure 3-11. Shaft Turning, Forming, Cutoff, Rough and Finish Grinding (Ref. 9)

Are torque values for assembly/disassembly appropriate?

Are alternative materials specified where possible?

Are standard stock raw materials specified?

Are materials, processes, and tolerances consistent?

Are mating parts physically and chemically compatible?

Are blind holes eliminated where possible?

Are all corners consistent with manufacturing process?

Are all surface finish requirements realistic ?

Are all required specifications realistic ?

2. *Intermediate Checklist:*

Do off-the-shelf and stock parts have alternative sources ?

Are all components producible on commercial equipment ?

Are fasteners and fastening methods optimized?

Are alternative manufacturing processes possible with the specified materials and tolerances ?

Have standard and off-the-shelf parts been used wherever possible either as is or with slight modification?

Have only the necessary inspection points been specified ?

Can any military specification be replaced with commercial specifications ?

3. *Final Checklist:*

Have special tooling requirements been minimized ?

Are protective finishes consistent with requirements ?

Has consideration been given to prefinished material ?

Are there unnecessary sole source or proprietary items ?

Are inspection procedures consistent with quantity requirements ?

Has destructive testing been minimized?

Is the design consistent with planned assembly process ?

Are maximum alternative processes and materials possible?

Is the quantity required consistent with implied manufacturing process ?

3-2.6.2 Metric Conversion

Instructions for the use of the metric system are given in Refs. 10 and 11, It is important to understand the levels of implementation. Significant among these levels are soft metric and hard metric.

In soft metric the standard unit of measure is English. The primary measure is in English units, e.g., a ¼-in. thick steel plate is specified 0.25 in. (6.35 mm). The significant point is that the base unit is a standard English measure.

In hard metric the standard unit of measure is metric. A 25-mm (0.98-in.) thick steel plate would be specified instead of a 1-in. plate. The metric units will become the base measure.

In this handbook soft metric values have the equivalent English values in parentheses and hard metric values have no English values given.

3-3 COMPONENT SELECTION

A diversified complement of industrially supplied, off-the-shelf components are available to structure modern military systems. These parts constitute the building blocks from which systems are fashioned and, as such, greatly impact producibility. Since the producibility of the end item is dependent upon these building blocks, the importance of selecting and applying the most effective parts cannot be overemphasized. The task of selecting, specifying, assuring proper design application and, in general, controlling parts used in complex systems is a major engineering task. Numerous controls, guidelines, and requirements must be formulated, reviewed, and implemented during the development effort. Preferred parts lists, which tabulate specific parts already in use, can help to select proven components that are already available in the supply system. Table 3-1 presents a simplified list of the ground rules and activities needed to assure that this task is adequately considered.

3-3.1 THE NEED FOR STANDARDIZATION

The dependence on sole source suppliers may have a severely adverse impact on producibility because a single source of supply provides no flexibility for delivery times. The delivery and cost schedule of the supplier is the only alternative available to the purchaser of the product. Frequently in a national emergency the Government will actually compete with itself for delivery of critical sole source repair parts. If components available from a wide range of suppliers were standardized originally, greater flexibility of delivery and cost would be possible. This becomes especially important in the face of ever-lengthening lead times in deliveries of frequently unacceptable materiel. The need for standardization is emphasized by the problems inherent in sole source procurements. The significance of a “standard” component is best understood by reviewing the screening process that precedes standardization. Virtually all manufactured devices exhibit a life characteristic that may best be represented by the *bathtub* curve shown in Fig. 3-12. The screening process deals with the first segment of the curve, namely, the infant mortality, or the early failure, period of the equipment life. Experience shows that newly constructed electronic equipment fails more often during its early life (i.e.,

TABLE 3-1. GROUND RULES FOR PART SELECTION AND CONTROL (Ref. 12)

1. Determine part type needed to perform the required function and the environment in which it is expected to operate.
2. Determine part criticality:
    a. Does part perform critical functions (i.e., safety or mission critical)?
    b. Does part have limited life?
    c. Does part have long procurement lead time?
    d. Is the part reliability sensitive?
    e. Is the part a high-cost item, and/or does it require formal qualification testing?
3. Determine part availability:
    a. Is part on a preferred parts list?
    b. Is part a standard military item available from a qualified vendor?
    c. What is normal delivery cycle?
    d. Will part continue to be available throughout the life of the equipment?
    e. Is there an acceptable in-house procurement document on the part?
    f. Are there multiple sources available?
4. Estimate expected part stress in its application.
5. Determine reliability level required for the part in its application.
6. Determine the efficiency of screening methods in improving the failure rate of the part (as required).
7. Prepare an accurate and explicit part procurement specification where necessary. Specifications should include specific screening provisions as necessary to assure adequate reliability.
8. Determine actual stress level of the part in its intended application. Include failure rate calculations.
9. Employ appropriate derating factors consistent with reliability prediction studies.
10, Determine need for nonstandard part, and prepare a request for approval as outlined in MIL-STD-965.

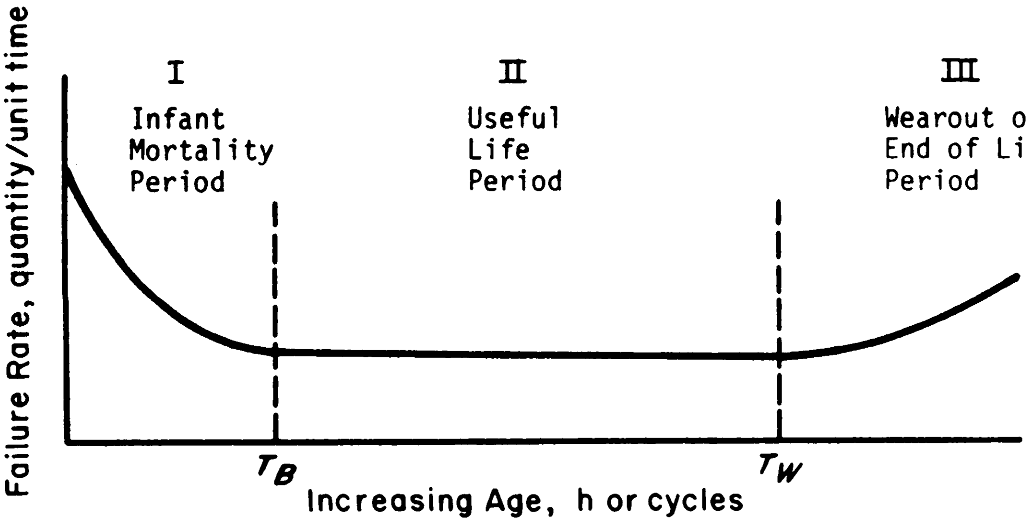

Figure 3-12. Life Characteristic Curve (Ref. 12)

during assembly and testing) than later during use in the field. This indicates that piece parts received from the supplier contain a certain number of weak devices that tend to fail during initial testing of subassemblies or complete equipments.

To eliminate the incipient failures from the manufacturing process, quality and screening tests can be employed. The quality tests are those that reduce the number of defective devices from production lines by means of inspection and conventional testing. The screens are those which remove inferior devices and reduce the hazard rate by methods of stress application. The purpose of reliability screening is to compress the early failure period and reduce the failure rate to acceptable levels as quickly as possible.

Fig, 3-13 illustrates the application of a time stress at, the part level and shows, comparatively, how reliability screening can improve the part failure rate. It also

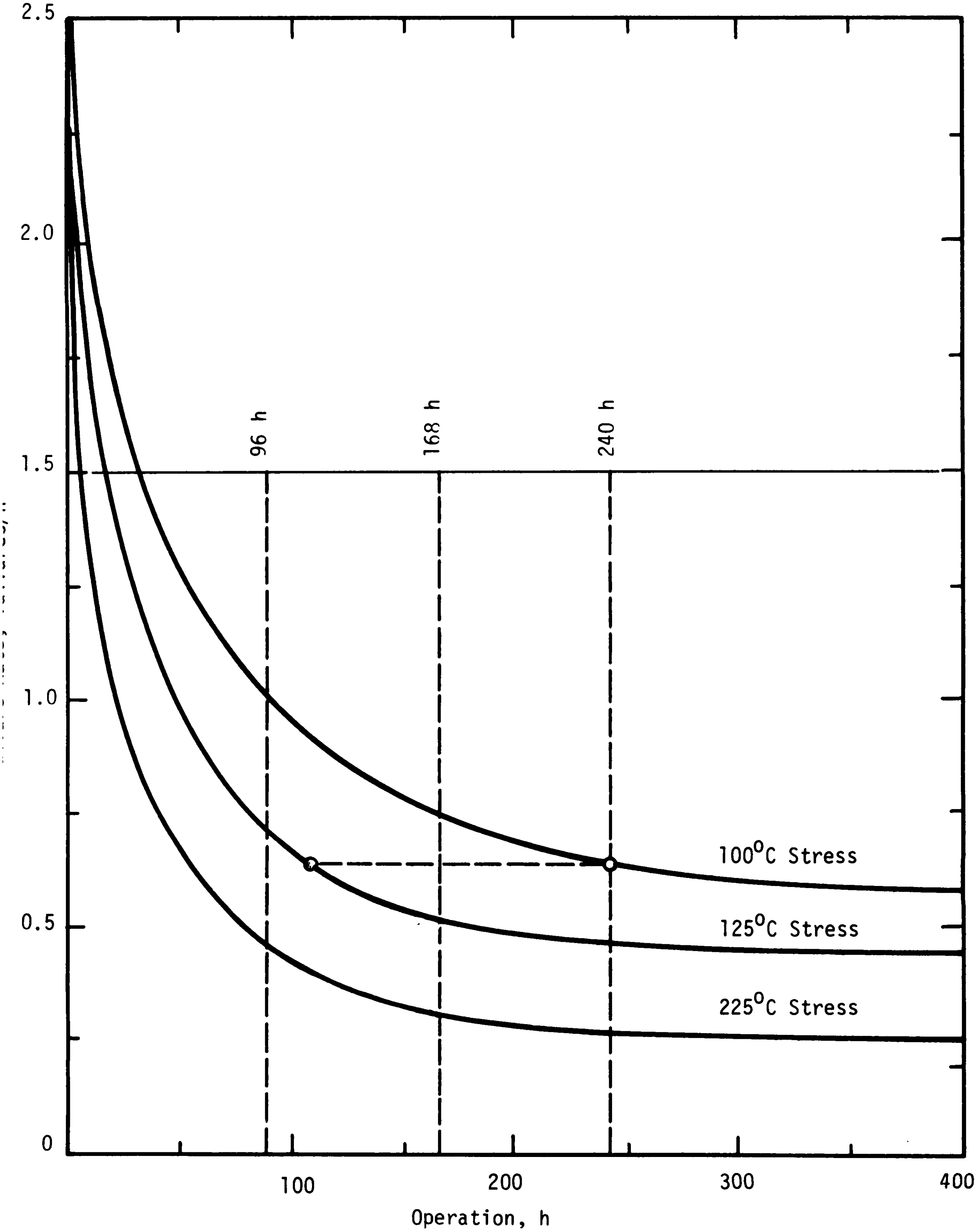

Figure 3-13. Reliability Screens (Ref. 12)

shows that, by applying a higher temperature stress—125°C instead of 100°C-comparable failure rate levels can be achieved in 105 h instead of 240 h. The term "screening" can be said to mean the application of a stress test, or tests, to a device that will reveal inherent weaknesses (and thus incipient failures) of the devices without destroying the integrity of the device, i.e., nondestructive testing. This procedure, when applied equally to a group of similar devices manufactured by the same processes, is used to identify below standard members of the group without impairing the structure or functional capability of the "good" members of the group. The rationale for such action is that the inferior devices will fail and the superior devices will pass if the tests and stress levels are properly selected. If the failed units are removed from the group, the remaining devices are those that have demonstrated the ability to withstand stress, and their reliability under normally rated operating conditions can therefore be assumed to be acceptable.

Screening can be done by the part manufacturer, by the user in his own facilities, or by an independent testing laboratory. No matter which agency is employed to do the screening tests, the user should first acquaint himself with the efficiency of the screening tests used by the vendor in normal production. If such screens exist and are effective, other/additional screens can be designed to supplement the vendor's tests; if the vendor's tests are unsatisfactory, the screening program will have to be a comprehensive one. When particular failure modes or mechanisms are known or suspected to be present, a specific screen should be selected to detect these unreliable elements.

3-3.1.1 Advantages of Standard Components

Component control activities comprise a large segment of the total effort for component selection, application, and procurement. The effort encompasses tasks for standardization, approval, qualification, and specification of parts that meet performance, reliability, and other requirements of the evolving design. One of the key tasks in this process is standardization. By using standard parts in new equipment design and development programs, frequently much time and effort can be saved while obtaining better equipment performance in addition to simpler and better logistic support. The DoD promotes the use of standard parts. Occasionally, the repeated use of parts initially characterized as nonstandard makes their standardization desirable. DoD standardization managers work closely with the military services and industry to develop an effective standardization program for new systems. Therefore, the general rule for part select ion is that, wherever possible, standard devices should be used. Standard devices may be defined as those that, by virtue of systematic testing programs and a history of successful use in equipment, have demonstrated their ability limits and, as a result, have become the subject of military or commercial specifications. Military standards exist that cover the subject of testing methods applicable to military specified components. For example:

MIL-STD-202, *Test* Methods for Electronic and Electrical Component Parts

MIL-STD-750, Test Methods for Semiconductor Devices

MIL-STD- 1344, Test Methods for Electrical Connectors.

In addition, military standards exist that list by military designation those parts or devices preferred for use in military equipment. For example:

MIL-STD- 198, *Capacitors, Selection and Use of*

MIL-STD-199, *Resistors, Selection and Use of*

MIL-STD-701, *List of Standard Semiconductors*

MIL-STD-1353, *Electrical Connectors, Plug In Sockets and Associated Hardware, Selection and Use of*

MIL-STD- 1562, *List of Standard Microcircuits.*

3-3.1.2 Cost Savings Through Standardization

Component standardization can reduce the unit production cost of the system as well as development cost. Standardization allows quantity discounts in the purchase of components and can significantly reduce documentation cost during development. ,4 reliability? study (Ref. 13) of two radar systems (APQ-120 and APQ-113) found the program that emphasized standardization (APQ-113) used one-third fewer piece-part drawings and 2800 fewer piece parts to achieve basically the same functions that the APQ-120 provides. Comparisons of part standardization are shown by part type in Fig. 3-14. This figure shows the number and cost of drawings by component in the two systems.

3-3.2 COMPONENT RELIABILITY

Component reliability is an aspect of both purchasing practices and specifications that insure the procurement of reliable components. The means of assuring component reliability range from adequate test methods and assembly processes to effective formal systems for accurately reporting, analyzing, and correcting failures that occur during use. Many times, only a little additional effort is needed to assure acceptable field reliability. In contrast, the consequences of poor reliability in the field are severe-high cost and excessive maintenance downtime.

3-3.2.1 Reliability and Life Characteristics

Reliability has been described as "quality in the time dimension". It is classically defined as the probability that an item will perform satisfactorily for a specified period of time under a stated set of use conditions. From a functional point of view, for an item to be reliable it must do more than meet an initial factory per-

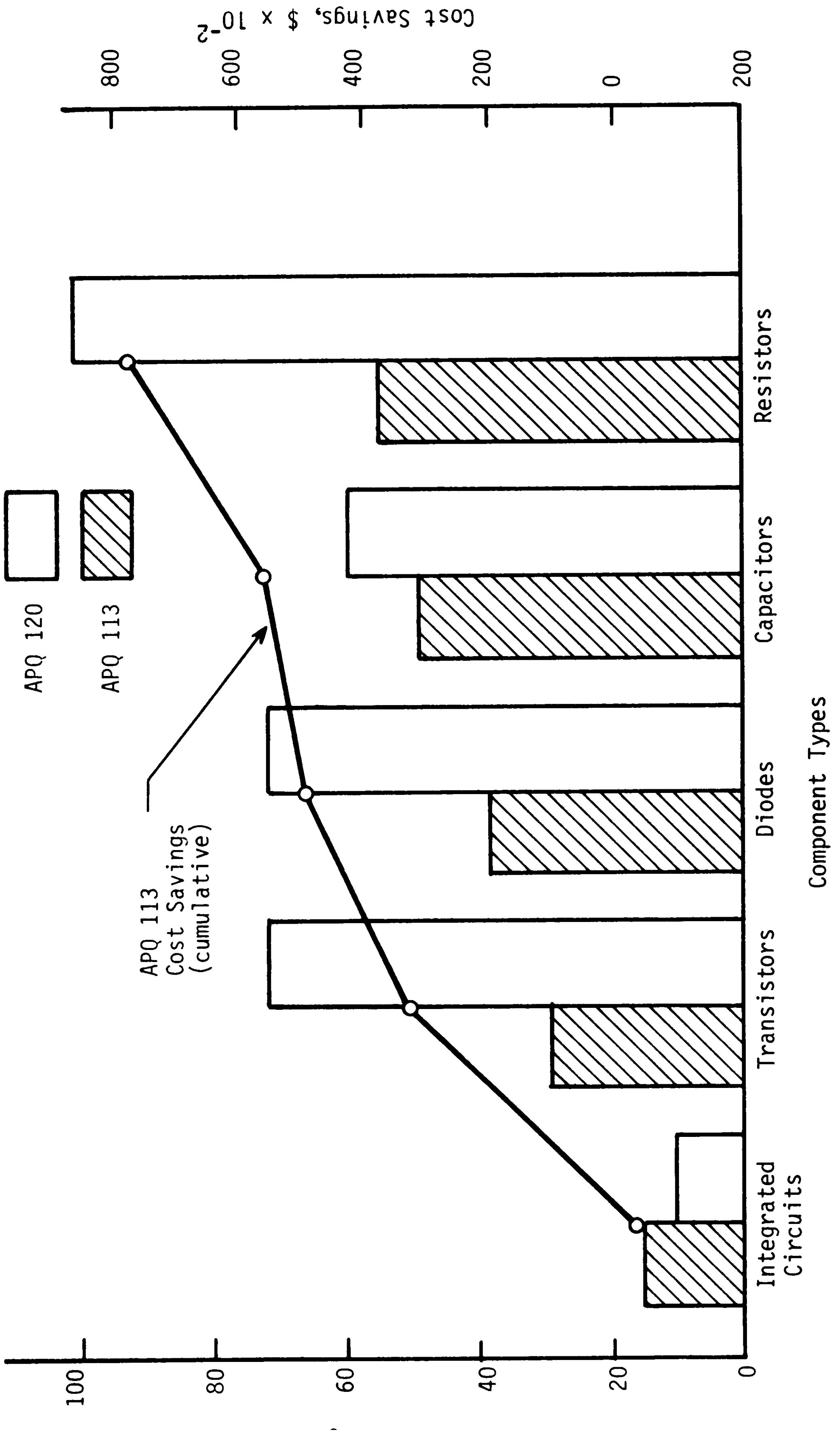

Figure 3-14. Part Standardization Cost Savings (Ref. 12)

formance of quality specification-it must also operate satisfactorily for an acceptable period of time in the field application for which it is intended. This classical definition of reliability y stresses four elements, namely: probability, performance requirements, time and use conditions. Probability is that quantitative term that expresses the likelihood of an occurrence (or nonoccurrence) as a value between zero and one. Performance requirements are those criteria that clearly describe or define what is considered to be satisfactory operation. Time is the measure of that period during which one can expect satisfactory performance and is usually expressed as mean time between failures (MTBF). Use conditions are the environmental conditions under which one expects an item to function.

3-3.2.2 Economic Impact of Reliability

Figs. 3-15 and 3-16 illustrate the relationship between reliability, maintainability, and cost, Fig. 3-1 5 shows that as a system is made more reliable, everything else being equal, the operation cost will decrease since there are fewer failures, i.e., greater MTBF. At the same time, acquisition costs (both development and production) must be increased to attain the increased reliability. There is a break-even point where each dollar spent on increasing reliability will result in a dollar saved in operating costs. This point represents the reliability for which total costs are minimum. Note that there are steps in attaining reliability that are of varying difficulty and cost. The least expensive increase in reliability would be taken first and the most expensive last. Therefore, the cost of reliability must have an increasing slope.

Essential to effective trade-off studies are the definition of each step and the development of accurate reliability/cost curves for equipment that show the sensitivity and breakpoints of critical reliability factors. It is the objective of early trade-off studies to define a band

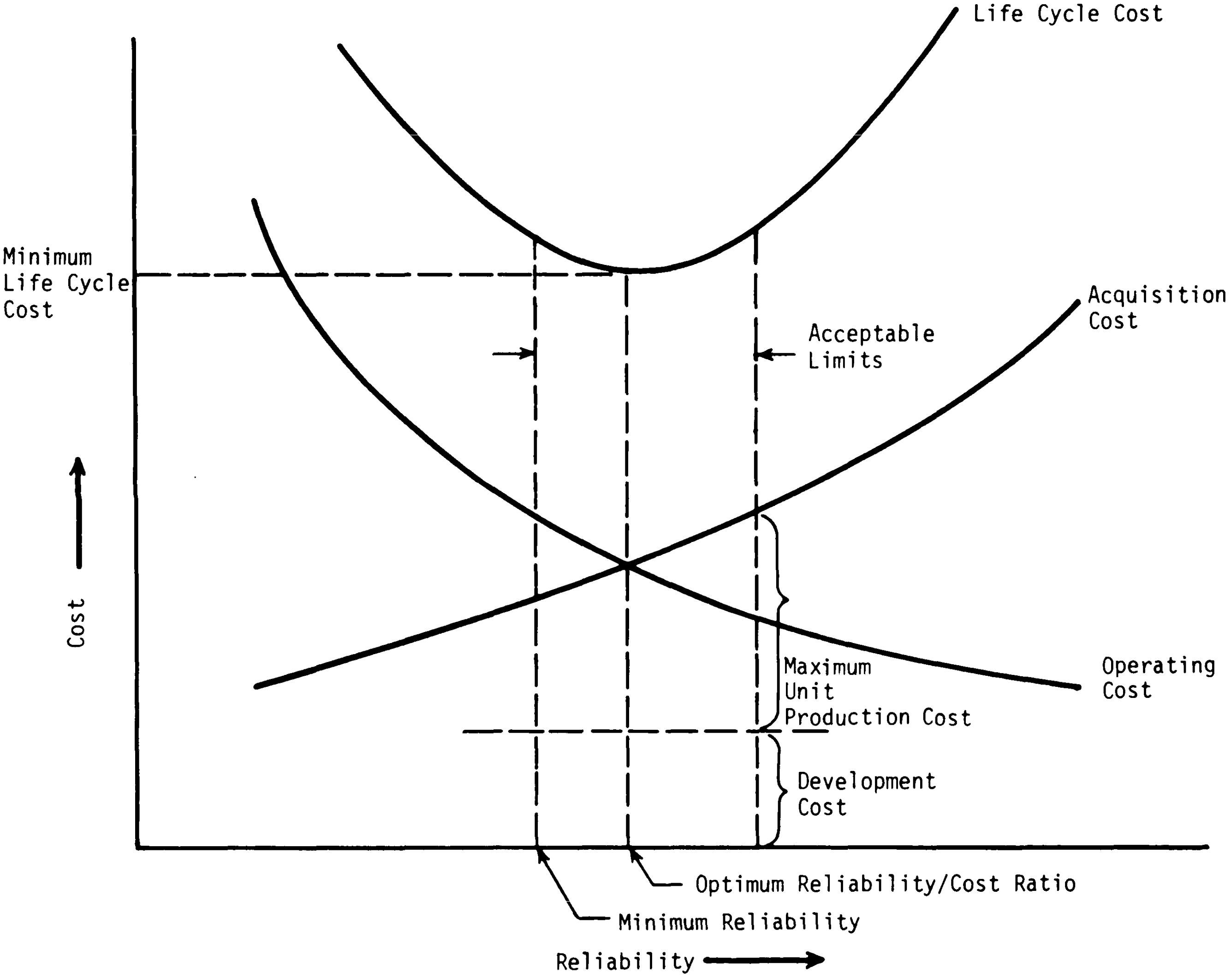

Figure 3-15. Cost vs Reliability (Ref. 12)

of acceptable performance and cost goals. Fig. 3-15 illustrates a method of defining the minimum reliability and the maximum unit production cost based on the minimum ownership cost principles. Assume that development cost is fixed over a limited range of MTBF. The right side of the acceptable bound shown in Fig. 3-15 is constrained by the maximum unit production cost, and this results in a new optimum total cost. The left side bound defines minimum reliability levels, i.e., minimum MTBF. The maximum unit production cost should be based on true affordability considerations, and should be traded off and verified during the development and production phases of the program,

Like reliability, improving maintainability causes increased acquisition costs and reduced operating costs. Maintainability is generally measured in mean time to repair (MTTR); the less time is required to repair an item (the smaller MTTR), the more maintainable the item. If one takes the reciprocal of MTTR to obtain a variable that increases with maintainability and with cost of attainment of acquisition, the same type of curves shown in Fig. 3-16 are obtained as those for reliability. Relationships can be derived to determine cost variations with equipment performance if various technologies and reliability and maintainability approaches are assumed.

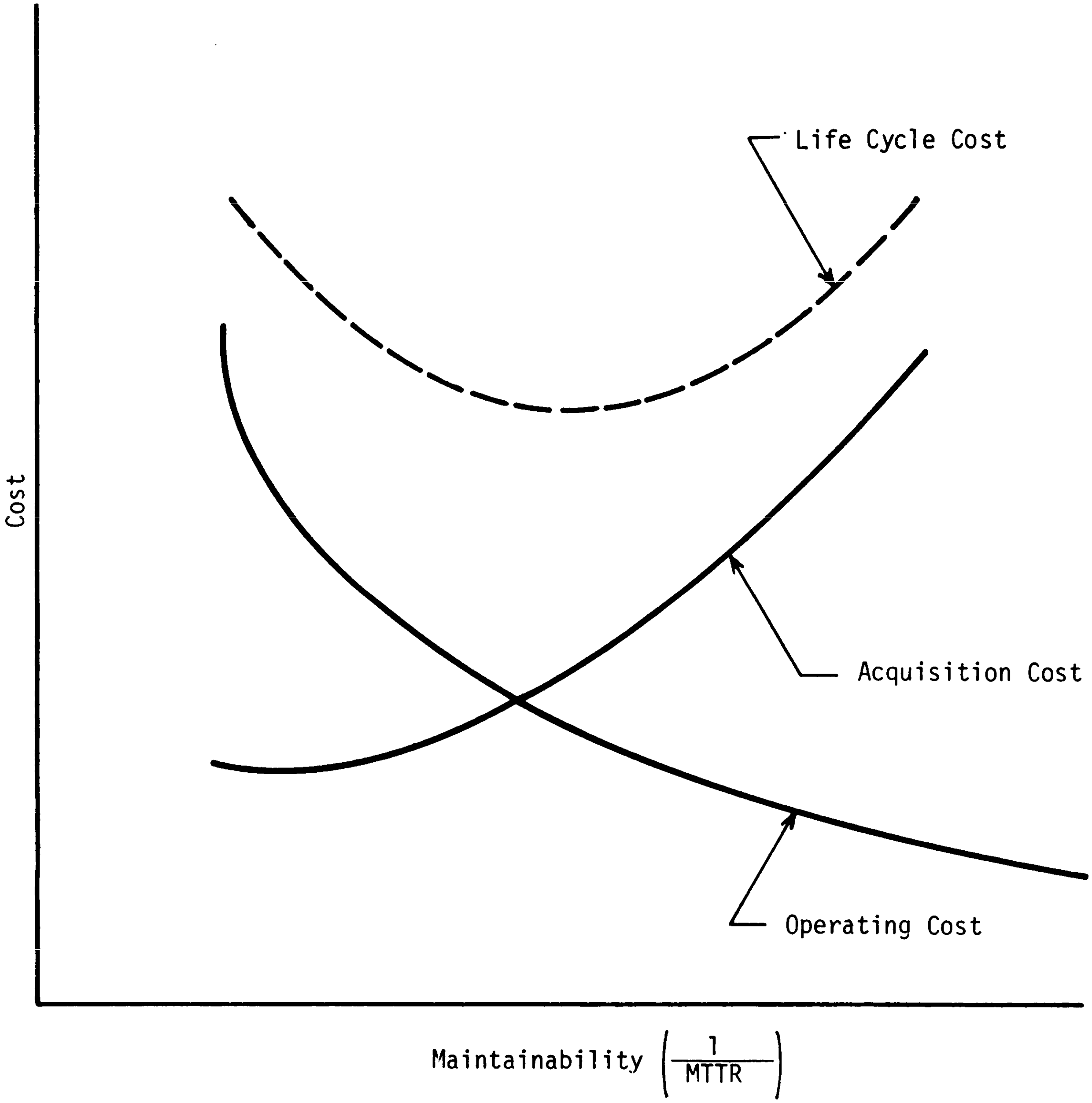

Figure 3-16. Cost vs Maintainability (Ref. 12)

Relationships can also be derived that define how reliability and maintainability vary with performance when cost is held constant. The resultant reliability and maintainability for any given performance can be referred to as the baseline reliability and baseline maintainability. Fig. 3-17 lists some of the elements of a hardware reliability program and shows the importance of each element during the phases of acquisition. This list generally follows the outline of MIL-STD-785 (Ref. 14), which is the basic standard for planning reliability programs for DoD development and production contracts.

Reliability prediction is the process of quantitatively assessing the reliability of a system or item of equipment during its development—prior to large-scale fabrication and field operation. During design and development predictions serve as quantitative guides by which design alternatives can be judged for reliability. Reliability predictions also provide criteria for reliability growth and demonstration testing, logistic cost studies, and various other development efforts.

3-3.3 CONSIDERATION OF REPAIR PARTS

The provisioning of repair parts is an important element in the overall process of component selection. The acquisition of repair parts for components must be considered at the time of the initial buy. The availability of repair parts in the right quantity, at the right time, and in the right place is an important adjunct of producibility. The component MTBF data accumulated during

	Acquisition Process Phase			
Element	Conceptual	Validation	Full-Scale Development	Production and Deployment
Requirements Definition	xxxxxxxxxx	xxxxxxxAAAAA	A..........	
Reliability Model	xxxxx	xxxxxxxxxxxx	xxxxx......	
Reliability Prediction	xxxxx	xxxxxxxxxxxx	xxxxx......	
Reliability Apportionment	ooooo	oooooooooooo	ooooo......	
Failure Modes Analysis	ooooo	ooooooooooox	xxxxx......	
Design for Reliability	ooooo	oxxxxxxxxxxx	xxxxxxxxxxx.	....
Parts Selection	ooooo	oxxxxxxxxxxA	AAAAA.......	....
Design Review	ooooo	oxxxxxxxxxxx	xxxxx......	
Design Specifications	xxxxxxx	xxxxxxxxxxxx	x..........	
Acceptance Specifications	xxx	xxxxxxxxAAAA	A..........	
Reliability Evaluation Tests	---	-xxxxxxxxxxx	xxxxx	
Failure Analysis	---	-xxxxxxxxxxx	xxxxxxxxxxxo	ooooooooooooooooooooo
Data System	---	-xxxxxxxxxxx	xxxxxxxxxxxo	ooooooooooooooooooooo
Quality Control		oooooooooox	xxxxxxxxxxxx	xxxxxxxxxxooooooooooo
Environmental Tests		xxxxx.	......AAAAAA	A.........
Reliability Acceptance Tests		xx.	........AAAA	Aooooooooo

KEY

------	Desirable activity (for highest success probability)
oooooo	Necessary activity (errors seldom disastrous)
xxxxxx	Very important activity (errors often disastrous)
AAAAAA	Critical activity (errors usually disastrous)
......	Low key activity (to update previous results)

Figure 3-17. Reliability Program Elements (Ref. 12)

the reliability studies should provide fundamental input for the provisioning of repair parts. The ability to buy initial requirements and repair parts simultaneously will be beneficial in terms of cost savings, and a quantity buy will further enhance item producibility.

3-4 IMPACT OF MATERIAL SELECTION ON PRODUCIBILITY

The selection of material for a component exerts considerable influence on producibility. However, for other than general design information, data, and characteristics, the reader is advised to refer to other chapters of this handbook, which contain more detailed information about a specific material. The material selected for a given design influences manufacturing processes, production schedules, production lead times, end item cost, end item availability, end item performance, reliability, maintenance, repair parts, and many other things all critical to producibility. The design engineer initially selects a material based on the ability of it to satisfy the design performance requirements. However, certain characteristics or the availability of a material may have an adverse impact on producibility and make some other material more advantageous.

3-4.1 MATERIAL COST FACTORS

The producibility of any item or component is directly affected by the base material from which it is fabricated. Unfortunately, most designs start with a single base material already preconceived by the designer. That material may be glass, plastic, composite, ceramic, metal, or any number of other options. When any one of these materials is preselected without a prior screening of the others, optimum producibility is endangered.

Table 3-2 shows some typical applications for metals, plastics, and composites. A few years ago most of these common, everyday items were designed and manufactured only from metals or wood. However, a few imaginative and innovative designers began to explore the properties of other materials and quickly found some substitute materials that provided, in many cases, a superior product. Most significant was that new materials permitted far more efficient manufacturing processes, which resulted in enhanced producibility.

Table 3-3 shows the comparative properties of a select number of different base materials. As can be seen from this table, the comparative properties of some of these materials overlap. On this basis one might choose from the materials with the desired properties the material that is lowest in price per unit weight or volume. However, there are other equally important cost considerations. Each material carries with it a series of implied manufacturing processes depending on the quantity of parts to be produced. These manufacturing processes can have a far greater impact on the overall cost of the item than the price of the material alone. Consequently, in the cost aspects of the material selection process, the designer should consider the cost of the eligible materials and the cost of the various eligible manufac-. turing processes combined into a single unit cost.

3-4.2 MATERIAL AVAILABILITY FACTORS

There are two key elements affecting material availability: commercial and strategic availability.

To assure the producibility of an item, the engineer must assure the availability of the raw material from the commercial marketplace. This availability must consider standard mill products, geographical location, normal delivery time, and quantity requirements. Since the capabilities of industry and individual suppliers vary under different circumstances and geographical location, information on specific alloy grades, sizes, standard forms, etc., should be obtained directly from potential suppliers.

Certain materials are made from ores or products that are wholly available in the United States; others are imported from friendly or neutral countries. Some materials in ample supply during peacetime become critically short under conditions of wartime mobilization. To alleviate such shortages, the Government (under the Defense Production Act) established stockpile provisions for over 90 materials expected to become

TABLE 3-2. APPLICATIONS OF VARIOUS MATERIALS

Applications	Metals	Plastics	Composites	Wood
Furniture	x	x	x	x
Automotive grills	x	x		
Pipe	x	x	x	
Structural beams	x		x	x
Lenses		x		
Gears	x	x	x	
Bushings	x	x	x	
Pulleys	x	x	x	
Valve bodies	x	x	x	

TABLE 3-3. COMPARATIVE PROPERTIES

Materials	Modulus of Elasticity		Ultimate Tensile Strength		Density	
	kPa	psi	MPa	ksi	kg/m^3	$lb/in.^3$
Steel	103×10^6	$30 X 10^6$	103 to zoo	15 to 300	6900-8000	0.25 to 0.29
Titanium	131×10^6	$19 X 10^6$	410 to 1720	60 to 250	4400	0.16
Aluminum	$68 X 10^6$	10^7	151 to 600	22 to 100	2700	0.10
Boron/epoxy, deg	$204.7 X 10^6$	$29.7 X 10^6$	1720	250	1900	0.07
90° Boron/epoxy	$17.2 X 10^6$	$2.5 X 10^6$	103	15	1900	0.07
E-fiberglass/epoxy, deg	$44.8 X 10^6$	$6.5 X 10^6$	1034	150	1900	0.07
90° E-fiberglass/epoxy	$6 X 10^6$	106	103	15	1900	0.07
Low cost high strength graphic/epoxy, deg	$137 X 10^6$	$20 X 10^6$	1379	200	1300	0.05
90° Low cost high strength graphic/epoxy	$103 X 10^6$	$15 X 10^6$	103	15	1300	0.05
Nylon (glass fill)	$10.3 X 10^6$	$1.5 X 10^6$	117	17	1300	0.05
Phenolic (glass fill)	$13 X 10^6$	$2 X 10^6$	124	18	1600	0.06
Polvstvrene	$3.24 X 10^6$	$0.47 X 10^6$	82	12	1100	0.04

critical in wartime. Table 3-4 is a list of these materials, together with a description of their characteristics, source(s), and principal applications. All of the materials in Table 3-4 are available to defense activities. Some are also available for sale to defense contractors or to private industry. Instructions regarding the conditions under which materials can be made available are published by the General Services Administration (GSA), which controls the stockpile. The Defense Production Act also provides a means of controlling the use of other materials considered critical. This control is exercised by the Defense Materials System (DMS), which operates under the authority of regulations issued by the Business and Defense Services Administration (BDSA), Department of Commerce. AR 715-5 (Ref. 15) describes this operation. The latest edition of the regulation, together with the latest DoD coded list of materials, will help the designer understand the magnitude of effort required to control and allocate critical materials. This regulation states that the design engineer must consider production methods, raw material requirements, sizes, and shapes, quantities to be produced, production lot sizes, and other elements of production often considered beyond the purview of the engineer.

3-5 MANUFACTURING PROCESS SELECTION

As previously noted, the selection of a material is the first step in the selection of a manufacturing process. Each material is amenable to only a limited number of processes. To assure the DoD the most economical product or hardware, the project manager must be aware of the various manufacturing technologies available. This is essential to preclude a manufacturer from designing components expressly for the use of high-cost, in-house tooling and thereby to preclude the use of other manufacturing processes that might be more economical. The selection process within those eligible manufacturing processes can have a significant effect on the final producibility. This selection process requires an intimate knowledge of the interrelationships of design, material, and manufacturing process; considerations of the manufacturing process availability; and an understanding of the need for considering manufacturing process alternatives.

3-5.1 INTERRELATIONSHIP OF DESIGN, MATERIAL, AND MANUFACTURING PROCESS

The performance requirements for a new design dictate the characteristics that a material must have to qualify as an eligible material for use in the design. This material in turn can only be used with a limited number of manufacturing processes, and each of these processes in turn is valid for only certain design requirements of tolerance, finish, configuration, and quantity.

Fig. 3-18 portrays the decision-making flow, showing the interrelationships of the product design process, the material selection process, and the manufacturing process selection. As can be seen from the flow diagram, each of these elements imposes constraining criteria on the subsequent element in a complete loop. In the initial step the designer reviews the performance requirements of the proposed design and determines the specific characteristics required of the materials to be used in the design.

TABLE 3-4. STRATEGIC MATERIALS

Material and Sources	Material Description	Principal Uses
ALUMINUM United States, Canada, France, West Germany, Norway	Bluish white, silvery metal easily drawn or forged. Lightweight (one-third lighter than steel), relatively strong, resistant to corrosion, electrically conductive. Derived from bauxite (see also).	Aircraft and missiles, electrical power transmission cables, containers and packaging, building products.
ALUMINUM OXIDE, ABRASIVE GRAIN United States, Canada, France, West Germany, Austria	Made by crushing fused crude aluminum oxide; dust and iron obtained from crushed material which is screened to 20 grain sizes. Ranging from grit No, 8 through grit No. 220.	Manufacturing grinding and cutting wheels, sharpening stones, coated abrasives, lapping compounds, and nonskid stair treads and steel walkways,
ALUMINUM OXIDE, FUSED CRUDE United States, Canada, West Germany, Yugoslavia, France	Produced by fusing calcined abrasive bauxite, coke, iron, and titanium oxide under intense heat of electric arc reduction for about 24 h, then cooling and crushing.	Manufacturing grinding wheels, sharpening stones, coated abrasives, grinding and lapping compounds, and nonskid stair treads and walkways.
ANTIMONY, METAL Belgium, United States, Mexico, Yugoslavia	White, lustrous, brittle, crystalline, easily powdered metal; principal ore is stibnite.	Metallic: solder, battery plates, cable covers, type metal, and imparting hardness and smooth surfaces to soft-metal alloys. Nonmetallic: flame-proofing chemicals and compounds, ceramics and glass products, and pigments.
ASBESTOS, AMOSITE South Africa	Fibrous amphibole mineral, characterized by long, coarse, strong, resilient fibers. Has good tensile strength and better resistance to heat than crocidolite or chrysotile. Varies in color from gray and yellow to dark brown, with fiber lengths up to 150 mm (6 in.),	Manufacturing woven insulating felt, heat insulation (pipe covering, block, and segments), and marine insulating board. Long fiber amosite used principally in the manufacture of thermal insulation.
ASBESTOS, CHRYSOTILE United States, Zimbabwe, Ganada	Fibrous serpentine mineral characterized by length, strength, toughness, flexibility, a minimum of magnetic or conductive particles. The most flexible of asbestos fibers. Varies in color from green, gray, amber to white. Texture is soft to harsh, also silky, with very good spinnability. Fiber lengths are “ approximately 20 mm (0.75 in.) and longer.	Manufacturing asbestos textile products designed for electrical insulating applications (electrical cables, industrial equipment, magnet wire), Asbestos textiles made to withstand heat (brakeband lining and safety clothing).
ASBESTOS, CROCIDOLITE South Africa, Australia, Bolivia	Fibrous amphibole mineral of hornblende group, the blue asbestos of commerce. Has superior resistance to attack by acids. Texture varies from soft to harsh, with good flexibility and fair spinnability.	Manufacturing asbestos cement pipe, packing, and gaskets.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
BAUXITE, METAL GRADE, JAMAICA TYPE Jamaica, Haiti, Dominican Republic	Fine clay-like material, reddish-brown in color.	Mainly to produce alumina which is converted to aluminum. Also to produce abrasives and refractories, and in the chemical industry.
BAUXITE, METAL GRADE, SURINAM TYPE Surinam, Guyana, Indonesia, Ghana, Australia	Clay-like material, ranging from fine to lumps, dull white to brown in color.	Mainly to produce alumina, which is converted to aluminum. Also, to produce abrasives and refractories, and in the chemical and refractory inclustries.
BAUXITE, REFRACTORY GRADE Guyana	Clay-like material that has been calcined, dull white in color.	To produce high alumina refractories.
BERYL United States, Brazil, Argentina	Opalescent material; blue, green, yellow, brown, or colorless; ranges in size from granular to large lumps or crystals.	To produce beryllium for production of beryllium copper alloys. Also, in the nuclear energy, aircraft, missiles, space fields.
BISMCJTH Peru, Mexico, Canada, Yugoslavia	Grayish-white, brittle, hard, easily powdered metal with reddish tinge. Has low melting point (27(PC) and a low thermal conductivity. Derived chiefly as by-product of lead refining.	For low-melting (fusible) alloys and pharmaceuticals. Also, in other alloys as an additive to improve machinability of aluminum and malleable iron.
CADMIUM Belgium, Canada, Mexico, United States	Soft, bluish, silver-white metal obtained chiefly as by-product of zinc smelting and refining.	Electroplating, pigments, bearing alloys and low melting (fusible) alloys.
CASTOR OIL Brazil, India, United States	Colorless to pale-yellowish viscous oil obtained from castor bean by pressing or solvent extraction.	In paint and varnish, linoleum, oilcloth, printing ink, soap; for petroleum demulsification; in lubricants and greases, hydraulic brake fluids, synthetic resins, textiles. Sebacic acid (important derivative) is starting material for certain types of nylon, plasticizers, synthetic resins.
CELESTITE England, Mexico	Strontium sulfate in form of friable mineral, usually coarsely crystalline. Concentration to usable ore and chemical manufacture of strontium compounds usually required for end use.	To produce dense red flame with high brilliance and visibility range for pyrotechnics (tracer ammunition, military flares, and marine distress signals). Also, glass and ceramics, lubricants, sugar refining, luminescent paints, drilling muds, electrolytic zinc refining, welding rod coating, caustic soda.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
CHROMITE, CHEMICAL GRADE South Africa	Ore having submetallic to metallic luster, ranges in color from brownish to black. Varies in size from fines to granular and large lumps.	To produce chemicals such as chromic acid and zinc chromate. Chemicals used for anodizing and manufacturing pigments for paint and tanning. Also, for production of plating for resistance to wear, corrosion and heat in engines, marine equipment, and military items.
CHROMITE, METALLURGICAL GRADE Turkey, United States, Zimbabwe, U. S. S. R., Philippines	Hard, lumpy ore with a small amount of fines, varying in color from brownish-black to black,	To produce ferrochromium and chromium metals used to produce alloy steel and other alloying agents. Adding chrome to steel improves hardness, tensile strength, and resistance to heat and corrosion.
CHROMITE, REFRACTORY GRADE Philippines, Cuba	Has submetallic to metallic luster, ranges in color from brownish-black to black. Varies in size from fines, granular to large lumps.	Fines used to make mortar for constructing furnaces; larger material used for making furnace brick. Gives brick strength and stability at high temperatures, and resistance to shrinkage, spalling, and corrosion by slags and fluxes.
COBALT Zaire, United States, Morocco, Canada, Zimbabwe	Dark-grayish metal usually produced in form of rondelles, granules, lumps, cones, or thin, broken pieces.	To produce high temperature, high strength alloys, and permanent magnet materials. Also, for porcelain enamel, pigments, catalysts, varnishes, paints, inks, stock feed, cobalt-deficient soils.
COCONUT OIL Philippines	Nearly colorless, fatty oil or white semisolid fat extracted from coconuts.	Making soap, foods, and as raw material in producing fatty acids, particularly lauric acid.
COLEMANITE United States, Turkey	Soft mineral, transparent to translucent and colorless, also milky white, yellowish white, gray or muddy, varies in size from fines to lumps.	To produce boron for compounds used in glass and ceramics industries requiring their low melting point and excellent fluxing properties; used in cleaning hides, and in plasters and paints to prevent mildew. Added to alloy steel to increase hardening qualities.
COLUMBIUM Nigeria, Zaire, Brazil, Canada	Platinum-gray ductile metal of high luster, obtained from columbite or tantalite.	For alloying, especially in stainless steel to inhibit intergranular corrosion and improve creep, impact, and fatigue strength. Columbium carbides used in producing cutting tools.
COPPER United States, Canada, Chile, Zaire, Mexico	Reddish, tough, malleable, corrosion resistant, electrically conductive metal.	Electrical wires and equipment, tubes and pipes, and as base metal in brass and bronze.
CORDAGE FIBER, ABACA Philippines	Fiber (manila hemp) stripped from long leaves of Muss textiles, banana-family plant growing in humid, tropical climates.	Marine cordage, gut ropes, and construction.

(cont'd on next page)

TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
CORDAGE FIBER, SISAL Angola, Mozambique, Tanzania, Brazil	Fiber stripped from large leaves of tropical plant, Agave sisalana.	Rope, baler, binder, and wrapping twine; upholstery and padding; wire rope centers; reinforcement for paper and plastics.
CORUNDUM South Africa, Zimbabwe, India	Naturally crystallized aluminum oxide, the second hardest mineral known. Has abrasive quality largely due to its basal cleavage, imparts new sharp cutting angles when used for grinding.	Grinding wheels used for grinding malleable iron castings; very fine grain generally preferred for grinding and polishing lenses.
CRYOLITE United States	Sodium aluminum fluoride. Natural material largely replaced by synthetic cryolite; fluorspar converted to hydrofluoric acid or fluorine, neutralized with sodium carbonate and aluminum hydrate to produce cryolite.	Reducing alumina to aluminum using a bath of fused cryolite and aluminum fluoride is the electrolyte in which alumina is disassociated by electric current and a seal made between molten aluminum and the atmosphere. Ground cryolite used in enamels, glass, insecticides.
DIAMOND DIES United States, France, Holland, Switzerland	Dies made from selected industrial diamonds by drilling or electrically piercing the die hole.	Drawing fine size wire from hard metals for the electrical industry.
DIAM0ND, INDUSTRIAI. — CRUSHING B0RT Zaire, South Africa	Industrial grade of small, particle size diamonds not suitable for gem or tool use.	Crushed into diamond powder for use in polishing and lapping, and as cutting agent in drilling very small holes in hard materials.
DIAMOND, INDUITSTRIAL: STONES Zaire, Holland	Diamonds unsuitable as gems because of structure, color, flaws, or impurities.	In grinding wheels to shape and sharpen tungsten carbide cutting tools; as cutting edges of tools used for turning, grinding, and drilling hard metals.
DIAMOND, TOOLS United States, England, West Germany	Tools that have industrial diamonds set in the cutting or grinding edge.	Cutting or grinding very hard metals.
FEATHERS AND DOWN, WATERFOWL China, Western Europe	Soft and pliant contour feathers and thick undercoating of down of ducks and geese.	As filler and heat-insulating material in sleeping bags, pillows, other bedding.
FLUORSPAR, ACID GRADE United States, Mexico, Canada, Spain, Italy	Mineral of calcium fluoride. Only source of fluorine for industrial use except for very limited supply of cryolite and very low fluorine content in phosphate rock.	To make hydrofluoric acid. Used to produce synthetic cryolite, freon gas, alkylate for high-octane fuel, pickling steel, etched glass, many other minor uses. Cryolite used in making alloys of aluminum and magnesium and in refining the scrap of these metals.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
FLUORSPAR,METAL-LURGICALGRADE United States, Mexico	Mineral of calcium fluoride. Metallurgical grade is granular; lumps up to 75mm (3 in.) preferred by some steel companies. Contains minimum of 70% effective calcium fluoride, percentage of total calcium fluoride content, less 2-1/2 times silica content.	Facilitates fusion and transfer of impurities (sulfur and phosphorus) into the slag created by open-hearth process of making steel; adds to the fluidity of the slag. Also as fluxes by iron foundries and manufacturers of ferroalloys.
GRAPHITE, NATURAL–CEYLON AMORPHOUS LUMP Sri Lanka	Natural variety of element carbon; commonly known as plumbago. Grayish-black in color, with metallic tinge and unctuous feel. Good conductor of heat and electricity, resistant to acid and alkalies, easily molded.	Manufacturing of carbon brushes in electrical equipment. Also, many other uses.
GRAPHITE, NATURAL–MALAGASY, CRYSTALLINE Madagascar	Natural variety of element carbon; commonly known as plumbago. Grayish-black in color, with metallic tinge and unctuous feel. Good conductor of heat and electricity, resistant to acid and alkalies, easily molded.	Manufacturing of crucibles employed in refining and reducing gold and silver; in melting brass, bronze, and other copper-based alloys; for casting aluminum. Also, many other uses.
GRAPHITE, NATURAL–OTHER THAN CEYLON AND MALAGASY, CRYSTALLINE Canada, Germany, United States	Natural variety of element carbon; commonly known as plumbago. Grayish-black in color, with metallic tinge and unctuous feel.	In lubricants, oilless bearings, packing, foundry facings.
HYOSCINE Australia	Colorless or white crystals known as hyoscine hydrobromide or scopolamine hydrobromide.	control of motion sickness, in anesthetic compounds, in antispasmodic for treating Parkinson's disease.
IODINE United States, Chile, Japan	Dense, grayish-black, crystalline material, having metallic luster and characteristic odor.	In medicine and antisepsis; in food supplements, in industrial processing; in producing titanium, silicon, hafnium, zirconium, and other strategic metals.
JEWEL BEARINGS United States, Switzerland, Japan, Italy, France	Manufactured from natural sapphires and rubies or from synthetic corundum stones.	Universal application in watches, meters, gyroscopes, other precision instruments; in places where friction and wear between small moving parts must be held to a minimum, shocks withstood, high pressures carried.

(cont'd on next page)

TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
KYANITE—MULLITE United States, Kenya	Metamorphic mineral of aluminum silicate used for refractory where low expansion is required; produces hard grog with high constancy of volume. Heated, kyanite becomes mullite, having different ratio of alumina to silica and less affected by high temperature than clay refractories.	Mullite for heavy-duty refractories where low expansion is required (tanks for molten glass and spark-plug porcelain; pouring ladles and electric arc furnaces). Also, for melting high-copper brasses and bronzes, copper-nickel alloys, some ferrous alloys, zinc smelting, gold refining, manufacturing ceramics.
LEAD United States, Canada, Mexico, Peru, Australia	Heavy, bluish-white, soft, easily fusible, malleable metal.	Storage batteries, cable coverings, ammunition, gasoline additives, pigments, solder.
MAGNESIUM United States, Norway, German y	Light, silvery-white, ductile, easily machinable metal.	Structural forms for aircraft and missiles, forgings, castings, extrusions. Also, as alloy with aluminum and other metals.
MANGANESE, BATTERY GRADE, NATURAL ORE Ghana, Greece	Black material ranging from concentrates to small lumps.	In manufacturing dry-cell batteries.
MANGANESE, BATTERY GRADE, SYNTHETIC DIOXIDE United States	Black material, usually passing US standard sieve No. 60.	In manufacturing dry cells for batteries; mixed with natural grade to produce high-standard batteries for military use. Also, for special types of batteries for hearing aids and other small elements.
MANGANESE ORE, CHEMICAL GRADE, TYPE A Morocco, Cuba	Brownish-black to black ore in form of concentrates or lumps.	As oxidizing agent in chemical industry especially in manufacturing hydroquinone by the continuous process. Hydroquinone used as photographic developer, antioxidant, or inhibitor in compounding rubber in finished products, and in gasoline and medicinal processes.
MANGANESE ORE, CHEMICAL GRADE, TYPE B Ghana, India, Chile, Cuba	Brownish-black to black ore in form of concentrates or lumps.	In producing potassium permanganate and other permanganate chemicals. Also in producing manganese chloride, dye intermediates, glass and pottery coloring, electric lamps, welding rods, enamel frit, nicotinic acid.
MANGANESE ORE, METALLURGICAL GRADE India, South Africa, Brazil, U.S.S.R.	Black ore in form of lumpy natural ore or agglomerated nodules or sinter.	In manufacturing manganese metal, ferromanganese, and special manganese alloys which are used to neutralize effects of sulfur and to remove oxygen, Also, added to special steels to contribute toughness and resistance to shock and abrasion.

(cont'd on next page)

TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
MERCURY Spain, Italy, Mexico	Heavy, silvery-white, lustrous metal, liquid at normal temperatures. Primary source is cinnabar.	Metal: in industrial control instruments, thermometers, automatic switches, heat exchange media, cathodes in manufacturing chlorine and caustic soda. Mercury compounds: in pharmaceuticals, chemicals, antifouling paints.
MICA, MUSCOVITE BLOCK, STAINED A/B AND BETTER India, Brazil, United States	Nonmetallic, crystalline mineral easily separated into thin sheets with good dielectric strength. Block mica not less than 0.18 mm (0.007 in.) thick with minimum usable area of 646 mm^2 (1 in^2). Stained A\B and better are higher quality groups containing fewer impurities. Fewer impurities allow a greater dielectric constant.	In electronic tubes as spacers; stained A/B and better quality groups more suitable for specialized tubes.
MICA, MUSCOVITE BLOCK, STAINED B AND LOWER India, Brazil, United States	Nonmetallic, crystalline mineral easily separated into thin sheets with good dielectric strength. Block mica not less than 0.18 mm (0.007 in.) thick with a minimum usable area of 646 mm^2 (1 in^2). Stained B and lower are lower quality groups containing more impurities. More impurities yield a lower dielectric constant.	In electronic tubes as spacers. Stained B and lower quality groups more suitable for less specialized tubes and nonelectric uses (insulation in electrical equipment).
MICA, MUSCOVITE FILM, FIRST AND SECOND QUALITIES India, Brazil, United States	Nonmetallic, crystalline mineral easily separated into thin sheets with good dielectric strength. Film mica split from the higher quality block mica to specified thickness groups ranging from 0.30 to 0.10 mm (0.012 to 0.004 in.). First-quality film equivalent in visual quality to fair stained block mica, and second-quality film to good stained block mica.	As dielectric in electrical capacitors; first and second qualities more desirable for specialized capacitors requiring extremely close capacitance tolerances.
MICA, MUSCOVITE FILM, THIRD QUALITY India, Brazil, United States	Nonmetallic, crystalline mineral easily separated into thin sheets with good dielectric strength. Film mica split from higher quality block mica to specified thickness groups ranging from 0.30 to 0.10 mm (0.012 to 0.004 in.). Third-quality film equivalent in visual quality to stained A block mica.	Dielectric in electrical capacitors; and a small quantity used as interlayer insulation for air-cooled transformer coils.
MICA, MUSCOVITE SPLITTINGS India	Same as muscovite block mica except in form of sheets of maximum thickness of 0.30 mm (0.012 in.) and minimum usable area of 484 mm^2 (0.75 in?),	In making dielectric tape and cloth used as insulation for field coils, armature windings, transformers, other electrical devices operating at high temperatures.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
MICA, PHLOGOPHITE BLOCK Madagascar	Differs from muscovite block in withstanding high temperatures with less deterioration, being resistant to abrasion across the edge of the laminae. "High heat" quality is specified by stating that it must withstand a given temperature for a stated time.	As insulating material in soldering irons, high temperature coils; liners in proximity fuses, transformers, heater elements.
MICA, PHLOGOPHITE SPLITTINGS Madagascar	Same as phlogophite block mica except in form of thin laminae with maximum thickness of 0.30 mm (0.012 in.).	Used to make dielectric tape and cloth which is used as insulation for field coils, armature windings, transformers, and other electrical devices operating at high temperatures.
MOLYBDENUM United States, Chile, Canada	Hard, silver-white metal obtained from molybdenite. Imparts a high melting point, high strength, stiffness, and toughness to alloys.	An alloying metal in iron and steel; also, by electrical, chemical, ceramic industries. Small quantities: as catalysts, welding rods, paints and pigments, lubricants, trace element in plant and animal metabolism.
NICKEL Canada, United States, New Caledonia, Cuba	Hard, silver-white, ductile metal having high resistance to corrosion and abrasion.	An alloy to strengthen and harden steel and other metals and to provide resistance against corrosion. Major use is as an alloy in steel, especially in producing corrosion resistant steels and high-temperature alloys. Essential in production of jet engines, aircraft frames, armor plate, magnets, and in electroplating.
OPIUM Turkey, India	Dried exudate (from unripe capsules of poppy plant, Popaver somoniferum) containing various alkaloids, the most important is morphine. Appears in commerce as dark brown bricks or balls weighing a few pounds each.	As morphine used as an analgesic or pain-relieving agent of particular importance in shock treatment. Also, as codeine, which is used as a cough depressant and in pain relief.
PALM OIL Zaire, Indonesia	Yellowish oil, solid at room temperature, extracted from fruit of certain palms.	Processed into edible oil; in soapmaking; in tinplating and in cold reduction of steel,
PLATINUM GROUP METALS—IRIDIUM South Africa, Canada, United States, U.S.S.R.	Harder, tougher, denser, and higher melting point than other platinum group metals; luster similar to platinum; has slight yellowish cast. Slightly less than twice as heavy as lead and is one of the most corrosion resistant metals. Annealed iridium is four to five times as hard as annealed platinum.	Essentially, for alloying with platinum and palladium to increase hardness and corrosion resistance; small crucibles for high-temperature reactions; for extrusion dies for high-melting glasses. Is difficult to work, few of its mechanical properties are known.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
PLATINUM GROUP METALS—PALLADIUM Canada, South Africa, United States, U.S.S.R.	Least dense and has lowest melting point of six metals in platinum group. Weighs slightly more than half as much as platinum and has more brilliant luster.	Less costly and lighter pallium substituted for platinum (current price of palladium is about one-third that of platinum). Is extremcly ductile and malleable, but its physical and work hardening properties somewhat limit its use; absorbs hydrogcm at moderate temperatuers, which hardens the metal.
PLATINUM GROUP METALS—PLATINUM Canada, United States, South Africa, Colombia, U.S.S.R.	Heavy, grayish-white, noncorroding precious metal; very soft; ductile, malleable; does not tarnish at elevated temperatures; inert to common, strong acids including nitric acid, but aqua regia slowly reacts with it. Alkalimetal hydroxides, especially with oxidizing agents, attack platinum; chlorine and fluorine react with it.	Used separately and in alloys or combinations with each other and other metals. Electrical: contacts, electrodes, filaments, resistance thermometers, resistors, thermocouples. Chemical: vessel cathodes, spinnerettes for organic filaments such as rayon and for fiberglass, burner nozzles, catalysts. Sundry: dentistry, jewelry, purification of hydrogen, precision instruments.
PLATINUM GROUP METALS—RHODIUM Canada, South Africa, United States, U.S.S.R.	Metal of platinum group, between platinum and iridium with respect to hardness, toughness, and melting point; maintains freedom from surface oxidation; has a lower specific electrical resistance than platinum or palladium.	Plating of scientific instruments, silver and platinum jewelry, precision instruments for the measurement of the physical properties of corrosive liquids are plated with rhodium; plating of electric contacts for radio and audiofrequency circuits" because of freedom from oxidation and low-contact resistance; coating of sliding or moving contacts to take advantage of great hardness; coating of mirrors and surfaces to maintain brilliancy. A thermocouple of platinum and rhodium alloy defines the International Temperature Scale between 630.5° and 1063°C.
PLATINUM GROUP METALS—RUTHENIUM Canada, South Africa, U. S. S. R., United States	Gray or silverlike, brittle, nonductile metal of the platinum group; brittle at high temperatures; insoluble in acids; but is attacked by fused alkalies.	Is alloyed with platinum and palladium for a hard, corrosion-resistant metal and is used for jewelry, contact points, and catalysts. Alloys not used at elevated temperatures under oxidizing conditions. Has been used for nibs of pens, phonograph needles, and pivots in instruments. High melting point, hardness, and brittleness limit satisfactory working of ruthenium mechanically.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
PYRETHRUM Kenya, Japan	The kerosene extract of pyrethrum flowers; commonly marketed with the kerosene base containing 20% pyrethrins, the insecticidal principals.	Insecticides.
QUARTZ CRYSTALS Brazil	Form of silica occurring in hard, hexagonal crystals or in crystalline masses; the most common of all solid minerals; maybe colorless and transparent or colored.	In the production of piezoelectric units, optical parts, glass; in steel manufacture.
QUINIDINE West Germany, Holland, Indonesia	White, crystalline powder produced synthetically from quinine or naturally from cinchona bark, where it occurs along with quinine.	In medicine as a regulator of abnormal heart rhythm.
QUININE Indonesia	White, crystalline powder extracted from cinchona bark.	Antimalarial agent.
RARE EARTHS India, Brazil, United States	Group of 15 closely associated and similar elements belonging to rare earth group and often include thorium and yttrium, which are notable for electron-sensitive and light-sensitive nature. Ranges from white to pink powder, to a heavy, fine-grained, hard sand of light-brown to reddish-brown color.	In producing sparking metal in cigarette lighters. As misch metal added to steel bath to improve hot-working qualities. Also used in glass industry as coloring and polishing agent and as core in arc carbons, as well as in projectors and searchlights. Also a source of individual rare earth elements such as europium (used in color television) and cerium (for polishing, flints, etc.).
RARE EARTHS RESIDUE United States	Fine powder, white to gray or light-brown in color; a residue from the processing of euxenite concentrates to produce colombium and uranium compounds.	To produce any of 15 closely associated and similar elements notable for their electron-sensitive and light-sensitive qualities, and yttrium. Also, to produce misch metal used for " alloying purposes, to produce carbon ore, cerium metal for lighter flints, magnesium alloys, and for coloring and decolonizing glass.
RUBBER Indonesia, Malaysia, Vietnam, Thailand, Liberia	Processed juice (liquid latex) obtained from tropical tree, Heavea brasiliensis. Appears in commerce as densely packed bales made up of sheets of natural rubber. Must be vulcanized for useful application.	In the carcass of tires, particularly heavy-duty tires for trucks, buses, and planes; has many miscellaneous industrial applications.
RUTILE Australia, United States, South Africa, India	Fine sand varying in color from reddish-brown to black.	In the production of titanium sponge and as a stabilizer in welding rods. Also in the ceramic industry to add color and strength.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
SAPPHIRE AND RUBY Switzerland, United States	Crystalline aluminum oxide; synthesized by dropping finely ground aluminum oxide of great purity through the flame of an inverted oxyhydrogen blowpipe that operates within a combustion chamber.	Manufacturing jewel bearings.
SELENIUM United States, Canada, Sweden, Japan, West Germany	Allotropic acidic element often called a semimetal or a metalloid; is a grayish-black powder; hexagonal form considered most stable under ordinary conditions, is a fair conductor of heat and electricity, is fairly inert to atmospheric conditions, has fair mechanical strength, and may be produced by heating any form of selenium until crystallization is complete. Some forms of selenium are toxic.	In the electronic industry as a semiconductor for dry plate rectifiers, photocells, solar batteries, television cameras; largest consumers are glass and ceramic industries as a decolorizer for green glass and with cadmium to produce ruby glass now used for permanent labels on bottles. Added to stainless steel for a degasifier and to increase machinability. Selenium dioxide is oxidizing agent for processing cortisone. Oxychloride is one of most powerful solvents known, used as solvent for phenolic resins.
SHELLAC India, Thailand	Purified form of excretion by lac insect; appears in commerce as brownish flakes.	For surface coating, as a binder for abrasives and mica; as an insulator in electrical components; numerous miscellaneous industrial applications.
SILICON CARBIDE, CRUDE Canada, United States	Manufactured by fusing clean silica sand, coke, salt, and sawdust in an electric furnace. Process requires 36 h for fusion and 24 h for cooling. Cooled mass crushed to provide crude material with no lumps in excess of 101 mm (4 in.). Exceeded in hardness by boron carbide and diamonds.	Abrasive grain is processed from crude silicon carbide and is used in the manufacture of grinding wheels, coated sheets, belts, and disks. Silicon carbide is preferred for grinding stone, materials that are hard or brittle or of low tensile strength, such as cast iron, brass, aluminum, and leather. Silicon carbide does not soften or melt at temperatures below 4450°C and is used for metallurgical refractory, but is less resistant to molten steel and basic slags. It is not attacked by most acids and is used in the chemical industries.
SILK NOILS Japan, India, Italy, France	Silk fibers representing waste from textile industry.	Various silk cloths.
SILK, RAW Japan, Korea, Italy	Continuous silk filaments to skeins as reeled from cocoon of silkworm.	Medical sutures, bolting cloth, stencil silks used for screen printing, various miscellaneous uses.
SILK, WASTE Japan, India, Italy, France	Silk fibers representing waste from silk industry.	Various silk cloths.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
SILVER Mexico, United States, Canada, Peru	White metal characterized as intermediate between copper and gold in hardness; most ductile and malleable of all metals except gold; a better conductor of heat and electricity than all other metals; high resistance to corrosion; forms more insoluble salts than any other metal,	Manufacturing of photographic materials, silver solders and brazing alloys now used extensively in jet aircraft and space vehicles, optical goods, chemicals and antiseptics, dentistry and surgery, electrical contacts for light-duty circuits, high-efficiency batteries for aircraft and rockets, infiltration with tungsten carbide for rocket cones, coating for copper wire in rockets, coinage, bullion base for paper currency, bearings in aircraft and rockets, sterling silverware, electroplate, jewelry.
SPERM OIL Norway, England, Japan, Netherlands	Yellowish oil extracted from sperm whale.	In cutting and grinding oils for high-speed precision work; as textile fiber lubricant, in metal treatment, and rust preventives.
TALC,STEATITE BLOCK AND LUMP India, Italy	Talc is soft, hydrous magnesium silicate; steatite is variety of pure talc with low impurities suitable for manufacturing ceramic, single-piece insulator shapes for very high-frequency applications. Steatite may be in blocks which have been shaped by sawing or in lumps that have been cleaned.	Single-piece, electronic tube spacers and sundry precision insulators for very high-frequency electronic circuits, especially electronic transmitter tubes; insulators made from massive steatite are resistant to heat and continuous, high-frequency electronic paths.
TALC,STEATITE GROUND United States	Talc is soft, hydrous magnesium silicate; steatite is variety of high-grade talc with low impurities suitable for manufacturing ceramic insulator shapes for very high-frequency applications.	In producing shapes for steatite ceramics, 80 to 90% of ground steatite is mixed with about 5% of kaolin binder and flux (feldspar or alkaline earths), molded or extruded to shapes and dried. Shapes may be machined to final insulator design from extruded stock or mix may be molded directly to form final insulator shape; shapes are fired into finished shape known as synthetics in the insulator trade; has not replaced insulator shapes made from massive steatite.
TANTALUM Brazil, Mozambique	Hard, silver-gray metal extracted from tantalite and columbite.	In producing electronics, such as power tubes, capacitors, rectifiers. Also, in equipment for chemical industry, in surgery for bone repairs; for optical glass, cutting tools, and as carbide in other wear-resistant alloys.

(cont'd on next page)

TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
THORIUM India, Brazil, South Africa	Gray powder or heavy, malleable, radioactive metal changing from silvery-white to dark-gray or black in air.	With tungsten or nickel in electrodes in gas-discharge lamps and in conversion of fissionable uranium; to make incandescent (Welsbach type) gaslight mantle. Its compounds are used in luminous paints and in flashlight powders. Compounded with nickel to produce a high-temperature alloy.
THORIUM RESIDUE United States	Fine powder, white to gray or brown in color. Material in residue from processing of euxenite concentrates where columbium and uranium have been extracted.	In incandescent gas mantles, luminous paints, and flashlight powders. Also, in nuclear reactors for conversion of fissionable material and to a lesser extent in refractories, polishing compounds, chemical products.
TIN Malaysia, Indonesia, Bolivia	Silvery-white, lustrous, ductile, corrosion-resistant metal. Cassiterite is principal ore from which tin is derived by smelting.	In producing tinplate and terneplate; also, solders, bearing metals, bronze, casting alloys, foils, various chemicals.
TITANIUM SPONGE United States, Japan, England	Hard, corrosion-resistant, silver-gray, sponge-like metal only 56% as heavy as steel.	In producing titanium metal and titanium metal alloys requiring superior strength-weight ratios necessary for spacecraft and supersonic planes, surgical instruments, portable machine tools. Also, in chemical and paper-pulp industries.
TUNGSTEN United States, South Korea, Portugal, Bolivia, Communist China	Gray-white, heavy, high-melting, ductile, hard, metallic element derived from wolframite, scheelite, hubnerite, or ferberite.	For electrical purposes, such as lamp filaments, contact points, lead-in wires for power tubes; for alloying, to increase hardness of other metals in making carbides for cutting tools, abrasives, dies; for special shapes such as tungsten nozzles in missiles.
VANADIUM United States, Peru	Pale-gray metal with a silvery luster; readily alloys with iron and other metals.	Mainly by steel industry as alloy in producing high-strength structural steels, tool steels, and related products requiring toughness and strength at high temperatures.
VEGETABLE TANNIN EXTRACT, CHESTNUT Italy, France, United States	A solid brown tannin extract from the wood of the chestnut tree.	In the tanning of heavy types of leather, such as sole and belting.
VEGETABLE TANNIN EXTRACT, QUEBRACHO Argentina, Paraguay	Solid brown tannin extract from heartwood of quebracho tree.	In tanning leather; as an ingredient in petroleum well-drilling muds.

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TABLE 3-4. (cont'd)

Material and Sources	Material Description	Principal Uses
VEGETABLE TANNIN EXTRACT, WATTLE South Africa	Solid brown extract from bark of wattle tree.	In tanning heavy types of leathers such as sole or belting.
ZINC Australia, Bolivia, Canada, United States	Bluish-white, metallic element, easily fusible, somewhat brittle.	In die casting and galvanizing; alloyed with copper to form brass; electrogalvanic properties useful in protecting steel and iron from corrosion. Also in manufacturing batteries.
ZIRONIUM ORE, BADDELEYITE Brazil	Hard, brittle, lustrous, lumpy ore, grayish in color.	In producing ceramics, refractories, foundry facings.
ZIRCONIUM ORE, ZIRCON United States, Australia, B	Hard, fine sand, yellowish to brownish in color.	In producing refractories, foundry facings, zirconium metal.

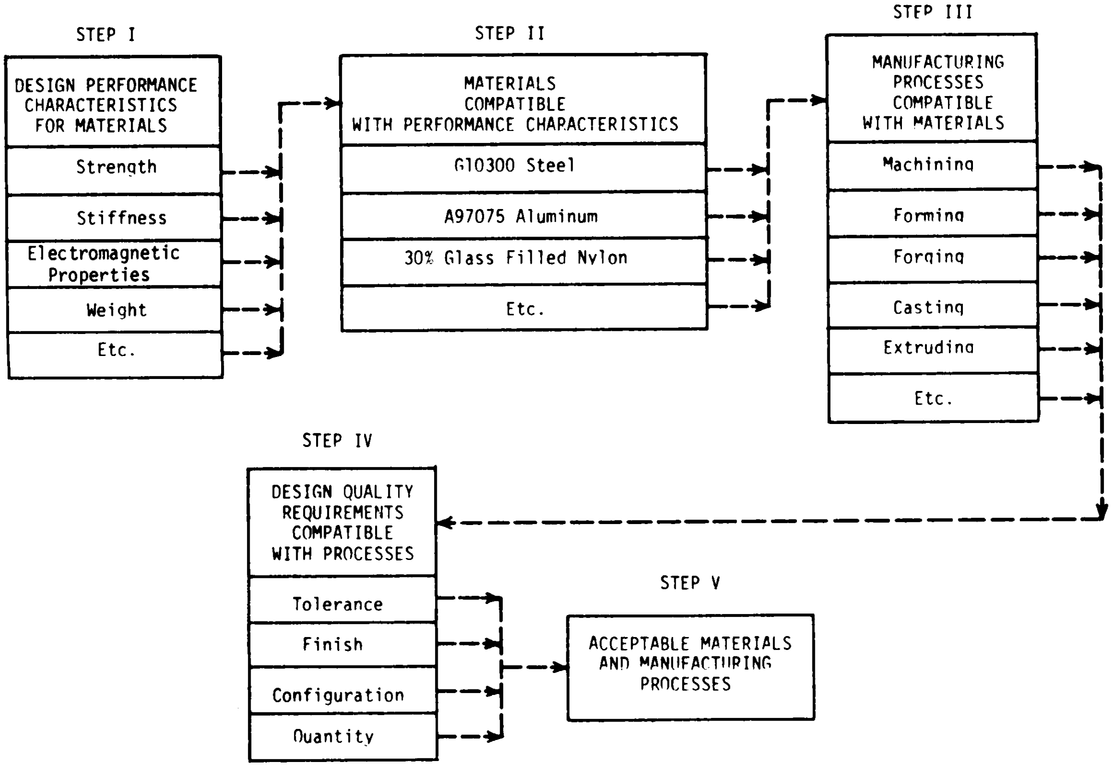

Figure 3-18. Interrelationship of Design, Material Selection and Manufacturing process Selection

When these characteristics (tensile strength, compressive strength, stiffness, etc.) have been identified as requirements, the materials are reviewed (step II) to determine which materials can satisfy the design performance characteristics. The resulting list of materials is reviewed (step III) to determine what manufacturing processes are compatible with each material. This list of processes is then checked against the design quality and quantity requirements (step IV), such as tolerance, finish, configuration, quantity, and schedule, to determine which of the manufacturing processes can meet those requirements. The remaining manufacturing processes (step V) are then listed in order of priority—cost, availabilities, and time.

In this manner the designer determines which manufacturing processes the specific design requirements will permit. The tolerances, 3 corners, draft angles, etc., used on the design should be as loose as possible to permit the maximum number of manufacturing processes and thus enhance producibility. The flow process shown on Fig. 3-18 is not, in most cases, a formalized procedure. The very nature of the interrelationships of the design process, material selection process, and manufacturing process selection make this a naturally imperative procedure that all design engineers must go through to achieve producibility.

3-5.2 MANUFACTURING PROCESS AVAILABILITY

A design engineer can go through all of the necessary steps to assure that his design is adequately presented to permit the maximum number of material and manufacturing process alternatives, and therefore, in every way possible the producibility of his design is enhanced. If the processes for which he has designed are not available at the time his design is ready to go into production, the design is not producible. This is not to imply that the designer is totally responsible for everything that could cause the manufacturing processes to be unavailable, but, there is a certain amount of responsibility for proper facility planning. Facilities may be unavailable for a number of reasons, but generally, they can all be summarized as either inadequate facilities or inadequate use of facilities. These conditions and their causes are shown in the subparagraphs that follow.

3-5.2.1 Inadequate Facilities

Facilities may be inadequate because of insufficient capacity or insufficient capability. In either case the insufficiency can usually be traced to the restrictiveness of or deficiencies in the design as designers often dictate the method by which their designs are to be produced. Dictating the production method restricts the freedom of potential producers, reduces the number of competitive producers who might otherwise bid, and often increases production costs. Consider an industrial complex that conducts its own research and engineering, prepares its own drawings, and does its own manufacturing. In-house drafting and engineering standards are used to facilitate these processes. Designs are predicated on in-house production facilities and capabilities and take advantage of shortcuts inherent in those capabilities. The designs produced in this set of circumstances, then, would not restrict production for that industrial complex. However, consider the restrictiveness imposed if the same drawings were presented to another manufacturer with his own standards, procedures, production facilities, and capabilities. To achieve maximum producibility, designs to be considered for competitive procurement must provide as much flexibility in the production processes as possible without degrading performance. Some examples of how the design influences the availability of production processes by limiting the number of choices are given in subpars. 3-5.2.1.1 through 3-5.2.1.4.

3-5.2.1.1 Restriction to Single Manufacturing Process

Frequently, the designer unintentionally restricts the manufacturing process to a single process through the misuse of tolerances. For example, an aluminum cast part with a tolerance of 0.005 mm per millimeter (0.005 in. per inch) must be investment cast since no other casting process can hold that tolerance economically. If the quantity being produced is in excess of 1000 parts, this becomes an uneconomical approach from the standpoint of time and money. If a cast part is dictated, the designer should examine every potential casting process and liberalize the design tolerances, draft angles, and other constraints to embrace as many different casting processes as possible.

3-5.2.1.2 Design Restrictions Prohibit Manufacturing

Occasionally, a design will describe a surface or configuration that cannot be produced by any process. More frequently, though, is the specification of quality requirements that cannot be inspected except by the most specialized techniques. Highly specialized processes are frequently not available on a universal basis. Consequently, in the interest of process availability, they should be avoided.

3-5.2.1.3 Design Not Conducive to Economic Processing

This situation usually results from excessively restrictive quality requirements. When this occurs, the manufacturer has no alternative except to process the design in accordance with the quality requirements and to sacrifice the economics of mass production techniques.

Consider a metal component for which the design specifies a tolerance of 0.03 mm (0.001 in.) to be turned on shafts in quantities of 10,000 or more. The best technique for accomplishing this is a numerically controlled lathe. However, if that tolerance could be relieved to permit a tracer lathe to be used (0.08 mm (0.003in.)), the cost of production could be halved. Production cost is a factor of the capital cost of the equipment, and the initial cost of a tracer lathe is approximately 25% that of a numerically controlled lathe. Of equal importance is the high availability of tracer lathes and the comparatively lower availability of numerically controlled lathes. The designer working in an environment that produces prototypes of the potential design on highly precision equipment before sending the design to a mass producer for quantity production must constantly be on guard to preclude the eventuality of creating designs not conducive' to economic processing in quantity.

3-5.2.1.4 Design Specifies Proprietary Process

There are a number of processes, particularly in the casting field, that are proprietary to a single vendor. The availability of such processes is usually limited to one or two licensed sources. **As** a consequence, the designer must know that it is absolutely imperative that proprietary processes be avoided on the design wherever possible.

3-5.2.2 Inadequate Use of Facilities

Although certain facilities and capabilities exist, they may not be available because of improper facility planning. These conditions are generally attributable to line balancing, scheduling, and loading deficiencies.

3-5.2.2.1 Line Balancing

Line balancing assures that the output of each individual assembly or manufacturing operation balances with the required input of each successive operation. Since some operations within a given line will require only half as much time as successive operations, this can create a situation in which half the employees are occupied only 50% of the time. Computer-aided line balancing techniques are available that can be applied to resolve problems of this nature; see Ref. 16.

3-5.2.2.2 Scheduling

Manufacturing processes often are unavailable due to poor scheduling of production requirements. The causes often are attributable to poor communication of the planned production requirements, which leads to a breakdown in facility planning. Also production processes are often unavailable because there is a lack of prior identification of critical resources. Before discussing these two potential problem areas, it would be best to understand the environmental factors that influence and control the manufacturing system. Fig. 3-19 shows

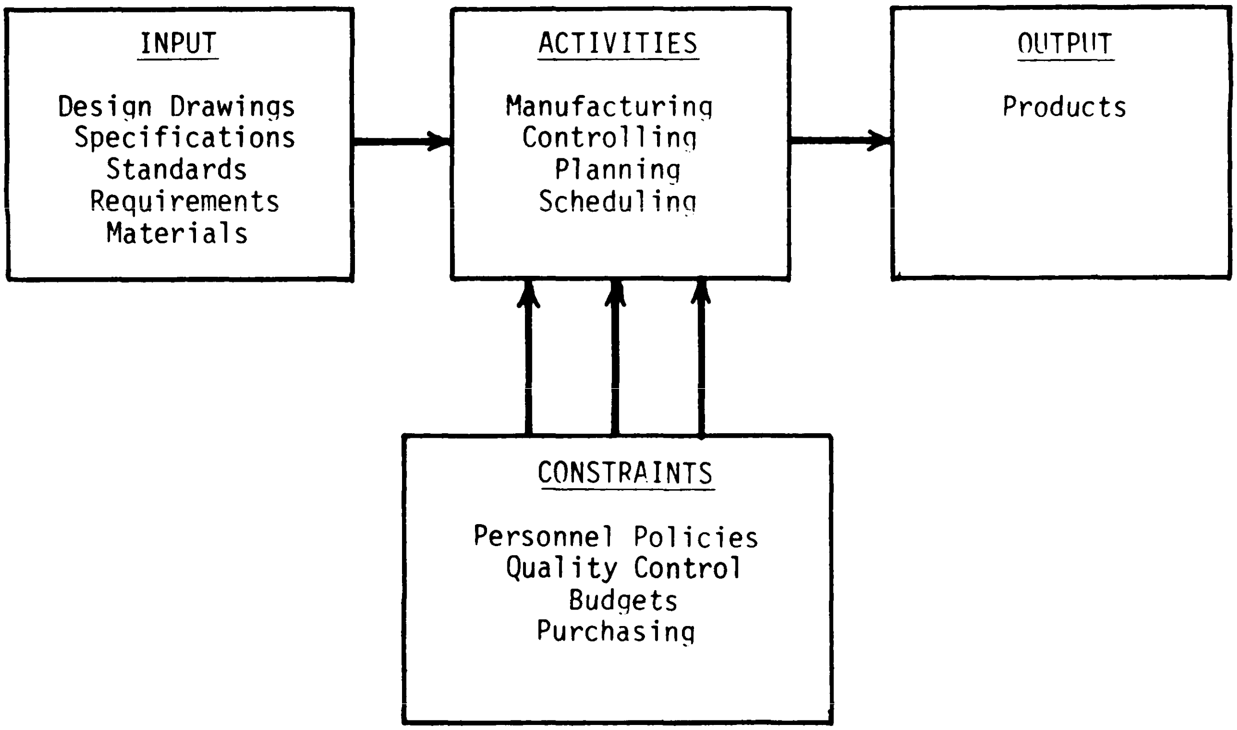

Figure 3-19. Manufacturing System Schematic

the schematic of a manufacturing system. By viewing this schematic diagram, it becomes apparent that the manufacturing function is subjected to many pressures from interested groups. The engineer interested in producibility must work closely with manufacturing in the planning and scheduling of his product.

3-5.2.2.3 Facility Planning

Assuring that the manufacturing process requirements (men and machines) for a given product are available in the planned production facility is an absolute necessity if good producibility is to be achieved. It is imperative that the engineer maintain a close and continuous liaison with manufacturing during the development cycle. Every change in a product during the development cycle could have a significant bearing on facility planning. Considering the constraints shown in Fig. 3-19, it is obvious that personnel policies and budgetary limitations imposed on the manufacturing activities would require close liaison to assure proper facility planning.

3-5.2.2.4 Group Technology

One new technique that shows great promise for facility planning is group technology. Group technology capitalizes on the benefits obtainable from the similarities of individual components in a total manufacturing requirement. Simply stated it is a systematic approach that organizes the individual components of all the manufacturing requirements into families of parts having similar attributes. Consequently, almost all the parts in an individual group require comparable manufacturing processes and tooling. The heart of group technology is a coding and classification system. In lieu of calling a class of parts by their generic names (i.e., washer, nut, burster tube), they are individually assigned specific identification numbers. The individual digits or groups of digits in the identification number are coded to represent the specific characteristics of each individual part. These specific characteristics include such things as geometric shape/configuration, dimensional size limitations, materials, tolerances, manufacturing processes, tooling, manufacturing cost, production rate, and source of supply.

A coding and classification system facilitates the introduction of a new part into manufacturing. When a new part is introduced, it is coded with its own descriptive identification number. Thus a quick data base search would reveal all similar parts previously stored in that family of parts. These parts would inherently have very similar (in many cases identical) manufacturing operations and tooling. Consequently, all of the historical data reflected in the characteristics of the identification number would be applicable to the new part being introduced.

Group technology is predicated on the premise that parts with the same or similar code numbers in the first series of digits will have similar manufacturing data. Obviously, the digits representing dimensional information, tolerance, and material may vary slightly without changing the manufacturing data. All coded parts with these digits falling within a prescribed range constitute a family or a group of parts. This group of parts will require the same machines to produce them, and these machines will constitute a machining cell. The cell would also have its own specifically identified group of special tools. When the data base of coding and classification numbers is complete, it contains a complete set of data on manufacturing requirements. A simple interrogation routine can then provide cumulative data on the total machine tool requirements for all of the manufacturing cells. New parts to be entered into the system can be coded, and impact analyses on the existing manufacturing base can be conducted.

Future manufacturing needs, i.e., mobilization planning, require only a change in quantity for parts already in the system or the addition of new parts to the system to determine the precise capital equipment investments needed to support the mobilization requirements. Likewise, corroboration of the planned capabilities and capacities of the producers are just as easily identified. Soon designers may find themselves providing the coding and classification number along with their completed designs. They may also code and classify their designs before reducing them to hard copy drawings. In this manner designers could screen the data base for existing products that may satisfy their design needs and could then forego the necessity of creating **a** whole new design.

3-5.2.2.5 Identification of Critical Resources

When facility planning and scheduling are completed, the engineer interested in producibility then asks the question, “What can go wrong that will have a serious impact on producibility?”. There are a lot of things that could go wrong; however, most of them would have little or no impact on overall producibility. Suppose, for example, a drill press broke down in the middle of production. Most shops have backup for this kind of equipment, and consequently, there would be little or no impact. If, however, the production is dependent on a five-axis, numerically controlled machine with no backup, the impact could be quite severe. Many engineers are finding simulation of the manufacturing line a quick and easy method for identifying critical resources, and there are a number of computer simulation programs available for this purpose (Ref. 16). Use of some does not require computer programming knowledge or special training. These simulations are ideal tools for laying out or checking production lines. Sensitivity to particular elements (men or machines) can be quickly checked by the simple procedure of a whole series of "what if" games. In this manner the impact of every possible failure can be tested and alternate plans quickly established, This is a particularly economical approach since it is accomplished before any irrevocable decisions are made.

3-5.3 MANUFACTURING PROCESS ALTERNATIVES

The most producible designs are those that offer, among other things, the greatest number of alternative manufacturing processes. Consequently, designers should strive to create designs that permit the greatest flexibility, yet result in an acceptable product. This means that the manufacturing constraints of recommended quality and quantity are established to embrace the largest number of manufacturing processes within the limits of a satisfactory product. Within these manufacturing constraints the various manufacturing processes provide some element of overlap.

3-5.3.1 Quality Overlap of Processes

One of the significant constraints precluding the use of alternate manufacturing processes is the capability of the various processes to produce parts of comparable quality. Fig. 3-20 shows some selected manufacturing process capabilities. Significant on this chart is the tolerance overlap of certain selected processes for plastics and metals. However, before deciding that an alternate process does exist to produce the same quality level for a product, the designer should further check to assure that the alternative process is compatible with the raw material. For example, if the required tolerance for a specific design were 0.25 mm (0.010 in.), it would appear, from Fig. 3-20, that die casting, extruding, or investment casting would all produce the desired tolerance. However, if the material were H41300 steel, a check of the manufacturing processes compatible with that material (see Chapter 4) would show that it is not extrudable. The only acceptable processes would be die or investment casting. The design engineer would then need to verify that the necessary draft angles and configuration constraints were also compatible before releasing the design for production.

3-5.3.2 Size and Quantity Overlap of Processes

The additional constraints of part size and quantity required would have to be verified. These are also shown on Fig. 3-20 for selected processes. From Fig. 3-20 it can be determined that a quantity of 50,000 plastic parts with a tolerance of 0.13 mm (0.005 in.) could be produced by either injection molding or extruding. However, if the part size were 0.30 m (12 in.) in diameter, a check of the part size column of Fig. 3-20 would reveal that extrusion could handle only parts up to 0.20 m (8 in.); therefore, injection molding would be the only acceptable process.

3-6 IMPACT OF PRODUCTION QUANTITY ON DESIGN DECISIONS

Long before the impact of production quantities on the selection of alternative manufacturing processes is determined, the design engineer should be considering the impact of production quantities on the design. Production quantity is a determining factor in establishing the production process, and the constraints of the production process should be consistent with the constraints of the design. Producibility can be further enhanced if ease of production is considered when establishing the basic design features.

Too frequently the term "designing for production" is misinterpreted to mean designing for high production. The impact of production quantities on design features is equally significant to the producibility of either high or low production quantities.

3-6.1 DESIGNING FOR HIGH PRODUCTION RATES

The opportunities for producibility improvements increase in direct proportion to the production quantity. Every production advantage gained in the design process is multiplied many times; therefore, every design engineer should become thoroughly acquainted with the high-rate production processes applicable to his designs. Only by this method can innovative concepts be employed that will take every advantage of the individual process to maximize producibility. The design engineer with the assimilated knowledge of design performance characteristics is in a unique position to capitalize on these opportunities. Only he can make the trade-off to maximize the producibility aspects of the design without impacting the performance characteristics. The paragraphs that follow provide some examples of how design engineers can design for high production rates.

3-6.1.1 Internal Corner Radii

The use of the largest possible internal corner radii for parts being machined in high production will greatly facilitate metal removal. Fig. 3-21 shows a part with an internal corner radius of 9.52 mm (0.375 in.). Manufacture of this part would probably be accomplished with a 50.8-mm (2-in.) milling cutter for roughing out the pocket at maximum metal removal rate leaving approximately 1.27 mm (0.050 in.) for a finish cut with a 9.52-mm (0.375 -in.) cutter to finish the surface with a cutter that matches the corner radius and provides a

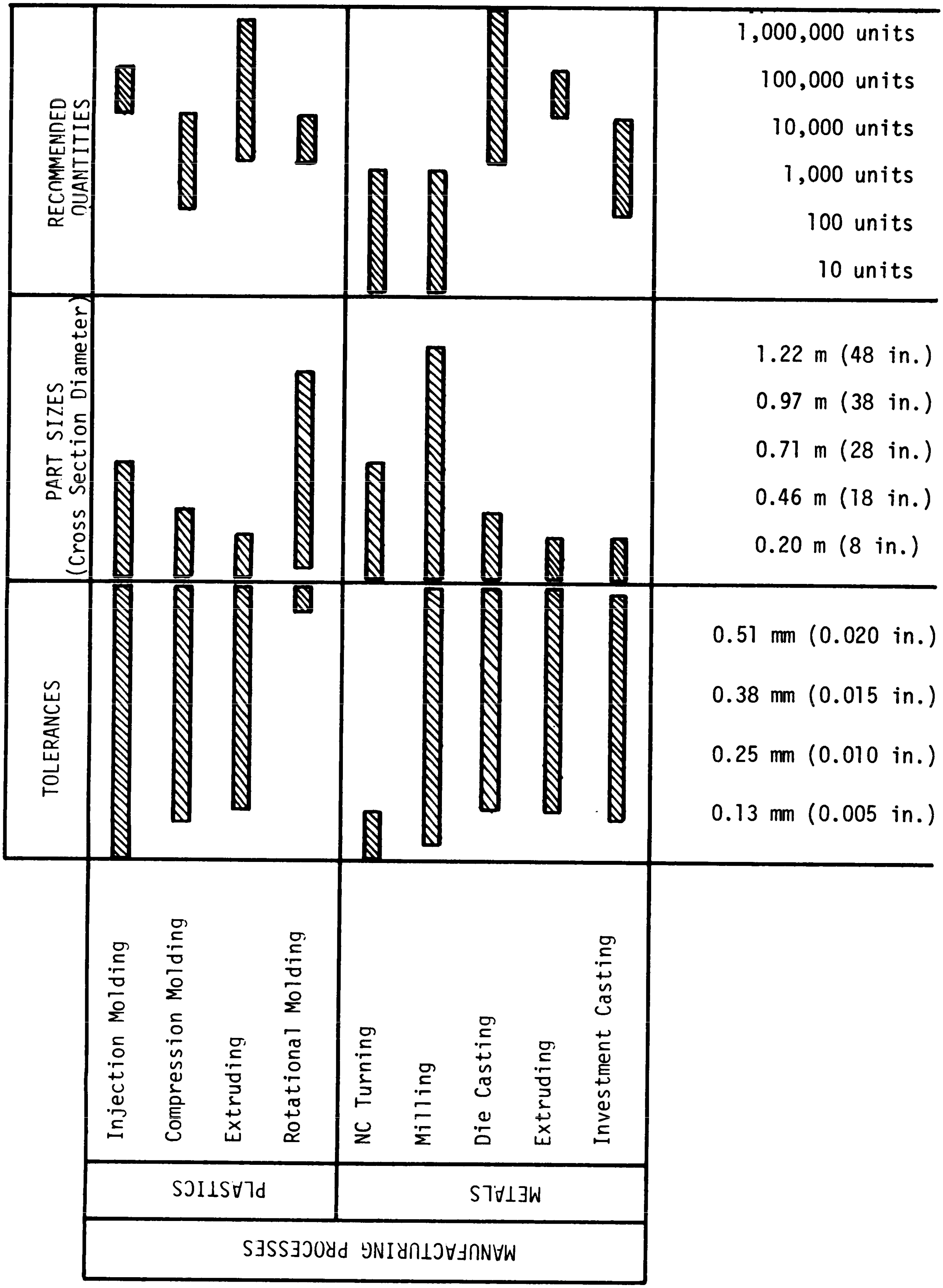

Figure 3-20. Selected Manufacturing Process Capabilities

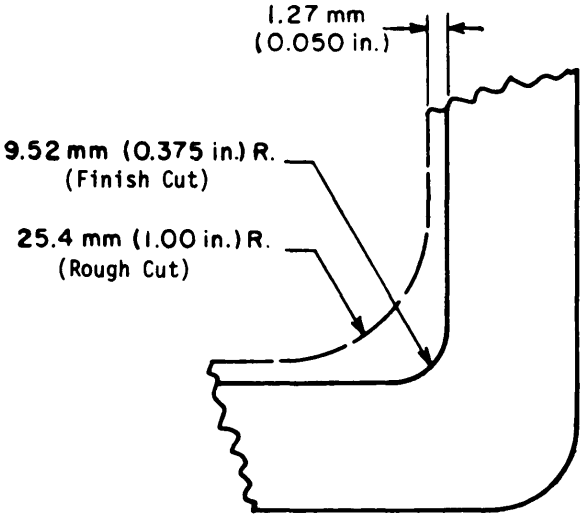

Figure 3-21. Internal Corner Radius

smooth blend between the radius and the straight edge. If, however, the design characteristics would permit the corner radius to be 25.4 mm (1 in.) in lieu of the 9.52 mm (0.375 in.), significant savings would be possible by permitting the maximum metal removal rate throughout the machining process while concurrently eliminating a tool change. If the total tool travel around the internal edge were 203 mm (8 in.), this savings could amount to 2.5 min per part. Given a production quantity of 10,000 parts, the savings would be 417 h—a significant improvement in producibility. However, tradeoff studies would have to be made to identify the effects of additional weight and volume on the performance requirements.

3-6.1.2 Material Consumption

Fig. 3-22 shows a spring clip functionally designed to meet a performance requirement. This part in a quantity of 500,000 would obviously be made on a punch press from a continuous strip of material. A punching tool would be fabricated to notch the front edge, leave the two tabs, and square the back edge by cutting off the tab remaining from the previous piece. The two holes would also be punched in the same operation. This would provide a completed part with each cycle. The total quantity of clips would consume 25,400 m (83,334 ft) of 25.4-mm (l-in.) wide strip material. That same spring clip designed for production as shown in Fig. 3-23 would provide significant producibility improvement. The back edge of the spring clip has been redesigned to permit the use of the tab that remains on the strip after the preceding clip has been punched. The holes were reoriented without any impact on the functional characteristics of the part. The design engineer is the only one in the unique position to know clearances with other parts, functional requirements, and the impact of relocating the attaching holes. There are obvious savings in tooling since only one end of the clip has to be cut. More important are the savings in the material. Since 13 mm (0.5 in.) of the total length of each part is salvaged from the previous part, there is a savings of 13 mm (0.5 in.) of the 25.4-mm (l-in.) wide strip material saved in each part. The total material used with this design is 19,050 m (62,500 ft) of 25.4-mm (l-in.) strip material. This is a total savings of 6350 m (20,834 ft) of strip material.

Figure 3-22. Spring Clip—Original Design

Figure 3-23. Spring Clip—Design for Production

3-6.1.3 High Production Rate Assembly

This subject is well covered in Chapter 7; however, there is a fundamental truth that the designer faced with high production rates should keep in mind. High production rates demand automatic assembly if producibility is to be maximized. The designer cannot accept the rationale that simply because his product was easily assembled in the prototype stage, it can be assembled easily in high production. If a printed circuit board is designed with component orientation that permits automatic component insertion, it is also possible to produce it by using manual component insertion. However, the reverse of that is not true. Printed circuit boards must be designed with automatic component insertion in mind.

3-6.1.4 High Production Rate Design

Every design should have two distinct phases if it represents a product that will be produced in high production quantities. In the first phase the designer's objective should be to satisfy the required performance characteristics. When this is done, the second phase should be started. This phase should be a redesign to optimize the capabilities of the potential manufacturing process. As can be seen in the examples in par. 3-6.1, there are, in most producible designs, elements of the design that have no bearing on the function of the product. These elements are created solely to take maximum advantage of the producibility opportunities presented by the manufacturing process.

3-6.2 DESIGNING FOR LOW PRODUCTION RATES

The opportunities for producibility improvements through an alternative production process at low production rates may not appear to be as prevalent as those available from the production processes for high production rates. This is primarily because tooling will not amortize over as many items. However, it can generally be stated that the magnitude of savings per individual improvement is greater. Low-rate production requirements will generally occur for one of two reasons. Either the limited quantity is all that will ever be desired, or it is a prototype quantity for testing prior to proceeding with high-rate production requirements. The designer should keep the manufacturing personnel informed of his reason for low-rate production because it can have a significant impact on how they react to the requirement. If the production quantity is all that will ever be needed', the approach will be to produce the limited quantity in the most economical approach possible and still meet the requirements, If it is a low-quantity buy for test purposes before proceeding with a high production rate requirement, the approach will be different. Every attempt will be made to use the low-rate production technique that most closely approximates the probable high production rate process that will subsequently be used. Some examples of designing for low-rate production are given in the paragraphs that follow.

3-6.2.1 Deep Drawing Thin Wall Shapes

Deep drawing, because of the high tooling cost for conventional matching dies, is normally not considered a potential manufacturing process for low-rate production. As a consequence, designers often try to design around potential candidate parts by designing for a spinning process or even a machined part. There is a low-rate production alternative to the high-rate conventional deep drawing process that is frequently overlooked. This process uses only the male half of the tool and forms the metal around that tool with rubber or rubber backed with hydraulic oil. These processes are known as marforming and hydroforming and are described in detail in Chapter 4. The processes are shown in comparison with the conventional deep drawing in 'Fig, 3-24.

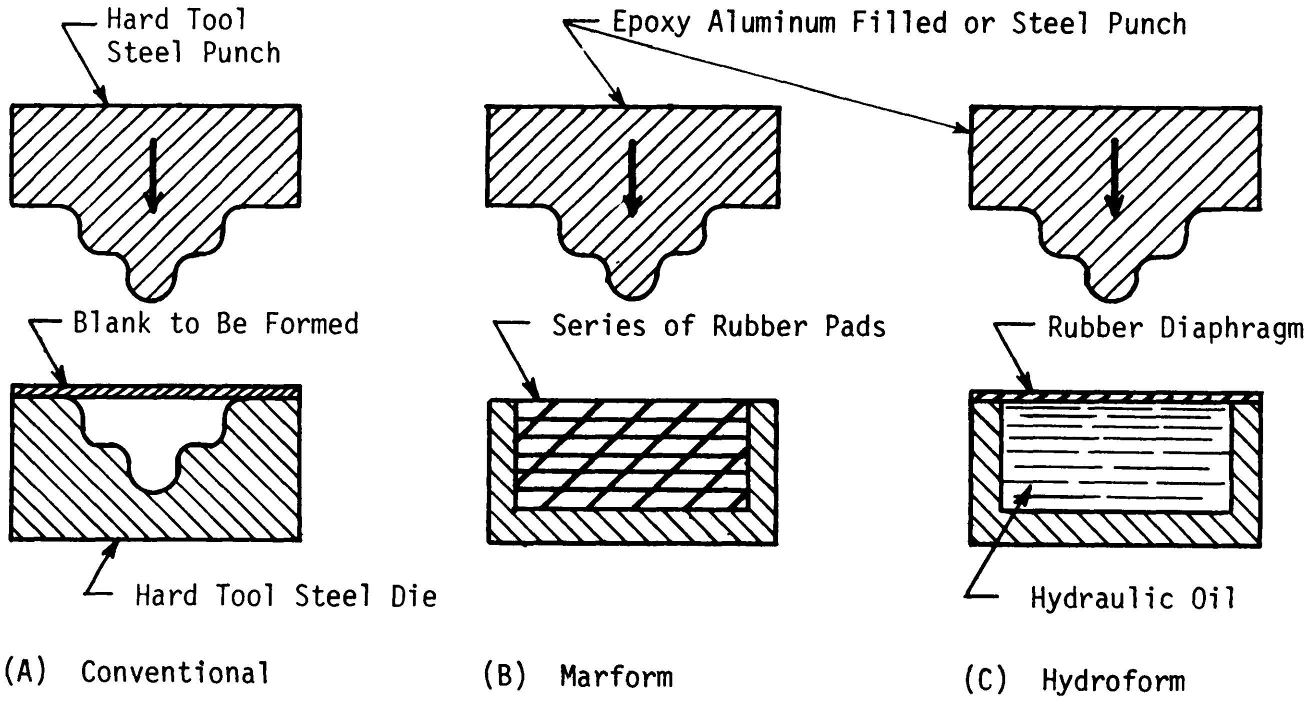

Figure 3-24. Comparison of Deep Drawing Processes

The marform and hydroform processes have slower production rates than conventional processes, but they provide closer tolerances and better definition of detail. They are capable of holding tolerances of ±0.05 mm (0.002 in.) to ±0.13 mm (0.005 in.) compared with ±0. 13 mm (0.005 in.) to ±0.38 mm (0.015 in.) for conventional deep drawing. Another advantage for these low-rate production drawing processes is their lower tooling cost; they require only the punch rather than the matching punch and die, which eliminates the more expensive part of the tool set. The female die, or the female half of the tool set, is usually about 60% of the total tool set cost. Added to this saving is the potential to use materials for the punch that are less expensive to machine. Fig. 3-25 shows recommended quantities and tolerances for different punch materials.

3-6.2.2 Designing for Numerical Control

Numerical control is one of the most viable of the low-quantity production techniques. It is ideally suited for quantities of from one to 2000 although these quantities may vary with the complexity of individual parts. A better understanding of numerical control operation procedures by the design engineers is essential to enhance the producibility aspects of many products produced by this new technology. This understanding is particularly true of the part programming function. This function translates part drawings into a format acceptable to the numerically controlled machine. The part programmer who translates the drawings into a machine-readable format literally redraws every part using an alphanumeric language. This new drawing is, quite simply, a listing of geometrical statements that describe the geometry of the part. Understanding how these statements are created permits the designer to correlate the design information more closely to the needs of the part programmer, which improves producibility. Additionally, understanding the capabilities of the programming function permits the design engineer to capitalize on numerical control and to reduce some of the detail work involved in the design function. A brief review of the more critical elements of importance to the design engineer is included here.

1. All part programming is done in a cartesian coordinate system. Consequently, all dimensions used in the geometric description are read from a zero origin point or from a geometric baseline element that has been located with respect to a zero origin point.
2. The part programmer uses geometric elements, such as points, lines, circles, and planes, in defining the overall geometric description.
3. The part programmer also has the ability to use algebraic equations to describe different geometric functions of the design. This is usually simpler and easier than any other method, particularly when describing an irregular curve or a surface.
4. The part programming system, while processing the data to create the punch tape, may compute the lengths of travel and feed rates of all machine tool motions required to produce the part and provide a total of the operational production time. An important aspect of this function is to minimize the number of tool motions

Figure 3-25. Punch Material Characteristics or changes of direction to minimize production costs.

5. The design engineer, when designing for numerical control, should assure that all dimensions are located from a zero origin wherever possible.

6. Whenever dimensional elements of a design are created from algebraic equations, the equations should be provided with the design for ease of programming.

7, Whenever comparative analyses of numerically controlled manufacturing are made, the program run time from the part program should be the basis for that analysis.

3-7 IMPACT OF EXPENDABLE AND NONEXPENDABLE ITEMS

Consideration of the factor of expendability early in the design can have a significant effect on design characteristics that will enhance producibility. This is not to imply that expendable items have a lower quality level. The significance is in the repairability of the item and the life expectancy of it. The designer should have complete awareness of these features to capitalize on the producibility considerations. For example, the life expectancy of an item is not a constant; it varies with time. In wartime the life span of even some costly items is such that they might almost be considered expendable. Consequently, the expected life span should be constantly reexamined in terms of the planned operational environment. In general, the possible expendability of a product must be constantly weighed against the density of issue. An expendable, high-density item may be treated quite differently from a nonexpendable, high-density item in terms of optimum producibility.

3-7.1 EXPENDABLE, HIGH-DENSITY ISSUE

Material in this category includes such items as protective clothing, ammunition, first aid kits, food rations, and other items of personal issue.

3-7.1.1 Material Considerations

The selection of raw materials used in the construction of equipment in this category can be significant to producibility and therefore should receive the highest priority of attention. In general the considerations that follow should be given to material selection:

1. *Minimum Cost.* This is always a desirable goal in trying to achieve producibility, but in this instance, it is especially important. Considerations should include not only the type of material but also the amount of material. Using thinner material and adding strengthening ribs can pay large producibility dividends. This can be very significant on high production rate items that can absorb the tooling cost in the large quantity and concurrently multiply minor material savings over the same large quantity.

2. Production Rate Compatibility. This, because of the large quantities involved, is very critical to producibility. The material selected must be compatible with high-rate production processes if optimum producibility is to be achieved.

3. Degradable Material. Some materials have a long-term effect on the environment while others degrade quickly and harmlessly and do not clutter or pollute the countryside. An expendable, high-density issue item is one that is normally discarded after use. The designer must consider the environmental effects of the discard when selecting the materials if the life cycle cost of the design is to be minimized. Life cycle costs, we now realize, include the cost of polluting the land or water with detritus.

3-7.1.2 Production Processes

The production processes for material in this category must be economical, high-rate processes. Inherently, this implies the need for high-quality production tooling and production processes amenable to automation.

1. *Production Tooling.* High-rate production processes invariably require the use of high-quality, special purpose tooling. These tools, such as deep draw dies, injection molds, master patterns, etc., are always made from high-quality tool steel, hardened and ground to provide the greatest tool life and the best product quality over long production runs. Although this type of tooling is the most expensive, when amortized over a large production run, the cost of it per part is minimal. Recognizing that the product is expendable, many repeat orders for the same item should be anticipated. Consequently, care should be exercised in tool management to assure subsequent availability.

2. *Production Process Automation.* When dealing with expendable products, the designer must be aware continually of the need to minimize the cost per part since none of the products are reclaimable. Further, when this expendable part is a high-density part also, even fractions of a cent per part can produce significant advantages to producibility. This usually means that rather than being labor intensive, the production process should be capital intensive. Manufacturing processes that maximize automation in processes, parts control, parts transfer, and parts orientation are preferred. An example of this is the high production of tin cans. The production rates are so high that production must be automated because human hands could not move fast enough to keep up.

3-7.2 EXPENDABLE, LOW-DENSITY ISSUE

Equipment in this category includes hand tools, training devices, and prototype ammunition. This is probably the most difficult area in which to achieve optimum producibility because it is typified by items that are manufactured in small quantities but that can be thrown away after use. The key elements in achieving maximum producibility here are the selection of the production processes and production planning.

3-7.2.1 Production Processes

The designer must be constantly aware that material selection, tolerance determinations, and design configurations carry with them certain implied manufacturing processes. Therefore, extreme care should be exercised in establishing these design features and parameters to assure that the implied manufacturing processes are the optimum for good producibility.

The particular attribute that should be sought in the production process is minimum tooling and setup cost. Low-density issue, though still of significant quantity, does not begin to approach the high-quantity production rates of high-density items. As a consequence, the production cost per item will be significantly higher. Since the items are expendable, replacement of the item is a definite consideration. Further, since the item is low-density, the frequency of reorders will probably be higher. This means that the production processes will be set up more frequently and that the tooling will be used over and over again. Therefore, the production process with the lowest setup cost will usually be the most economically producible.

3-7.2.2 Production Planning

Low-density, expendable items usually imply low-rate production processes, while high-density, expendable items imply frequent reorders. The previous paragraph discusses the need to select production processes with low setup costs. This paragraph discusses the need for planning the most economical batch size to produce.

Over 80’% of all manufacturing is done in batch operations. Typically, variable quantities, or batch lots, of various items are produced on the same line or facility. Determining the quantities of individual lot sizes of each item *is* often the only difference between good or poor producibility. Even when it is known that certain batch sizes produce a good result, one cannot be sure that some other combination of batch sizes might not result in greater producibility. Computer programs are available that can determine the most efficient batch size and sequence for an individual plant and product. They determine the batch sizes that will simultaneously meet the demand and minimize cost (setup costs and inventory carrying costs) Design engineers need to use these techniques in planning the production of expendable, low-density items to insure producibility.

3-7.3 NONEXPENDABLE, HIGH-DENSITY ISSUE

Nonexpendable materiel, such as rifles and machine guns, implies a high degree of repairability and maintainability. When this occurs with a high-density item, the implication is for a high degree of interchangeability of parts from a high production rate manufacturing process. The significant elements for the designer to consider are material selection, manufacturing process selection, and designing for simplicity.

3-7.3.1 Material Selection Processes

The information contained in par. 3-7.1.1, Items 1 and 2, is also applicable to material in this category. In addition, the designer should consider the potential impact on materials brought about by modular construction and repair. A printed circuit board, for example, may have only a bad component, but logistically and economically, it may be far more beneficial to replace the entire board rather than the component. This type of repair and rebuild can have significant effects on the repair parts requirements. This needs careful consideration by the design engineer to avoid degrading the producibility aspects of the design.

3-7.3.2 Manufacturing Process Selection

The designer must exercise care to assure that the design does not limit the application of mass production. Also the designer must allow tolerances compatible with interchangeability requirements inherent in repairable, nonexpendable items. This is one of the more critical elements of which the designer must be aware to assure maximum producibility.

3-7.3.3 Designing for Simplicity

The same rules of simplicity apply for this category of parts as for any other category. However, special emphasis should be given to designing for simplicity of assembly. Special assembly tools, not available in standard manual tool sets, should be avoided. Every designer should strive for the utmost simplicity in assembly tools.

3-7.3.4 Human Factors

Human factors must be considered in designing equipment of this type. For example it is desirable to design a part so that it may be assembled with its north end pointing north or south (fore or aft) in the assembly. If this is not possible, then great care must be taken in design to assure that there is no way the part can be inserted backward-even by forcing it. For components of such military items as individual weapons, it is also desirable to design for an orientation of some sort to permit proper assembly in the dark where feel is important.

3-7.4 NONEXPENDABLE, LOW-DENSITY ISSUE

Nonexpendable, low-density materiel includes such items as artillery weapons, depot maintenance tools, and mortars. The key items for the designer to consider are the longer service life and, consequently, the lower repeat orders along with the need for repair parts provisioning to support the longer life.

3-7.4.1 Longer Service Life

The designer needs a continuing awareness of the environment in which the design will operate. The production frequency of items in this category is a factor of the planned or predicted service life of the items. The service life of an item in peacetime may be an order of magnitude different from the life of the item in wartime. The item may get more handling in the disassembly, cleaning, and reassembly (conceivably improper) than in the use for which it was designed. As a consequence, these factors must be taken into consideration when planning the production processes. While certain manufacturing processes may be adequate for low-rate, infrequent production, they could be grossly inadequate for low-rate, frequent production (high setup cost, short tool life, for example). Concurrently, a design prepared in anticipation of low-rate, infrequent production could be totally inadequate for low-rate, frequent production. Therefore, the designer should be aware of these contingencies and provide for the proper alternatives in the design to assure producibility in every possible contingency,

3-7.4.2 Repair Parts Provisioning

Factors such as those discussed in the previous paragraph can have a like effect on repair parts. Under some conditions a nonexpendable, low-density item may be produced with low-rate production processes. When the consumption rate of repair parts is considered, this may be entirely different. The effect of initial production combined with a high consumption rate could make component part production a high-rate production process requirement. Again, the designer should assure the adequacy of the design for alternative production contingencies, consider the need for human factors, and conceivably for more wear due to handling and maintenance than to actual use.

3-8 QUALITY ASSURANCE CONSIDERATIONS FOR PRODUCIBILITY

In accordance with Ref. 17, quality assurance is a planned and systematic consideration in all designs to provide adequate confidence that the product conforms to the requirement. Inspection is the examination or testing of the product in accordance with a quality assurance plan. The inspection system requirements used to determine whether the quality requirements have been met are stated in Refs. 18 and 19. In the interest of enhancing producibility these generally include the amount of inspection, the aspects to be inspected, the methods of inspection, and the selection of quality level.

The first decision to be made is whether all of the units of the product should be inspected (100% inspection) or whether only a part of the units should be inspected (sampling inspection). The second decision will determine whether the sample is merely to be gaged or whether some portion of the sample is to be tested operationally to destruction.

3-8.1 ONE-HUNDRED-PERCENT INSPECTION

This method of inspection specifies that each unit is accepted or rejected individually for critical quality characteristics. For critical quality characteristics 100% inspection or relatively large sample sizes are usually required to assure the desired quality. However, in the interest of producibility 100% inspection should be specified judiciously. This is particularly true when inspection is expensive, such as in the case of large lots and in performance or environmental testing. Obviously, 100% inspection cannot be used when inspection is destructive, such as performance testing of explosive devices. In these latter cases a carefully worked out sampling inspection must be used.

3-8.2 SAMPLING INSPECTION

A sample consisting of one or more units of the total produced is selected at random and examined for one or more quality characteristics. This is usually the most practical and economical means for determining the conformance or nonconformance of a product, Sampling inspection has the advantage of flexibility with regard to the amount of inspection. The amount of inspection can be reduced for products of very high quality, or increased when the product quality begins to deteriorate. Sampling plans are developed on the basis of statistical techniques. Entire lots or batches are either accepted or rejected based on the results of sampling inspection. It should be understood that “accepted” and “rejected” in this situation indicate a statistical decision reached on the basis of the sampling plan and criteria used. The types of sampling plans include single sampling, double sampling, and multiple sampling. These plans are discussed in greater detail in Refs. 20 through 23.

3-8.2.1 Single Sampling Plan

In this method the results of a single sample selected for inspection from a lot are conclusive in determining the total acceptability of the lot. The number of sample units inspected is equal to the sample size given by the plan. This number is usually designated by the letter “n”. If the number of defdctives found in the sample is equal to or less than the acceptance number Ac or *a*, the lot or batch is considered acceptable. If the number of defects is equal to or greater than the rejection number *Re* or *r*, the lot or batch is rejected. A decision concerning the acceptability of a lot is reached on the basis of results obtained from taking a single sample of n units at random from the lot. For more detailed information on single sampling plans, see Ref. 24.

3-8.2.2 Double Sampling Plan

A double sampling plan involves sampling inspection in which the inspection of the first sample leads to a decision to accept, to reject, or to take a second sample. The inspection of a second sample, when required, then leads to a decision to accept or reject. Double sampling plans are operated in the following manner:

1. A first sample of n_1 units is selected at random from the lot and inspected. If the number of defects is equal to or less than the first acceptance number a_1, the lot is accepted. If the number of defects is equal to or greater than the first rejection number r_1, the lot should be rejected. If the number of defects is greater than the first acceptance number a_1 and less than the first rejection number r_1, the next sample step must be taken.
2. A second sample of n_2 units is selected at random from the lot and inspected. The number of defects found in the first and second samples are accumulated. If the cumulative number of defects is equal to or less than the second acceptance number a_2, the lot is accepted. If the cumulative number of defects is equal to or greater than the second rejection number r_2, the lot shall be rejected. Under certain conditions it may be more desirable to select both samples of a double sampling plan at one time, rather than to draw the second sample after the first sample has been inspected. Inspection of the second sample would not be required if the lot is accepted or rejected based on the inspection results of the first sample.

3-8.2.3 Multiple Sampling Plan

Multiple sampling is a type of sampling in which a decision to accept or reject a lot may be reached after one or more samples from the lot have been inspected, and the decision will always be reached after not more than a designated number of samples have been inspected. The procedure for multiple sampling is similar to that described for double sampling except that the number of successive samples required to reach a decision to accept or reject the lot may be more than two. For more detailed information on multiple sampling, the reader is referred to Ref. 25.

3-8.3 ATTRIBUTE INSPECTION METHOD

Inspection by attributes can best be compared with a “go no-go” gage. As a result of inspection, the unit is either accepted or rejected. No attempt is made to establish the level or degree of quality in a product; it is either defective or nondefective, within tolerance or out of tolerance, correct or incorrect, complete or incomplete, etc. Inspection by attributes is generally easier and less costly than inspection by variables and is generally used in conjunction with high-rate production where the cost of special gages can be amortized over the large quantity. However, inspection by this method fails to take advantage of the opportunities for inspection feedback into process controls. Trends of dimensional changes can be used to detect tool wear and to guide tool replacement and, therefore, to preclude the production of inaccurate parts.

In addition, it may be more economical to inspect for a particular dimensional characteristic on 100 units by using fixed gages than it is to measure 60 or 70 of the same units with standard measuring instruments. When inspection is by attributes, it is customary to group together all quality characteristics of equivalent importance and to establish one quality level for the group as a whole. The decision to accept or reject a quantity of product is then made by determining whether the units in the sample satisfy the one quality level for the entire group rather than for each characteristic individually.

3-8.4 VARIABLE INSPECTION METHOD

Under inspection by variables certain quality characteristics of the unit are evaluated on a continuous, numerical scale and expressed as precise points along this scale. This type of inspection determines the degree of conformance or nonconformance of the unit and is used whenever the quality of any given characteristic is determined in quantitative or measurable terms. Exampies include such characteristics as weight, tensile strength, dimensions, chemical purity, and burning time. A specific example follows.

A specification requirement on a type of hand tool specifies a Rockwell C-Scale hardness reading from 50 to 55. A hardness check on a sample of five hand tools picked at random yields readings of 53, 50, 52, 51, 50. These test results clearly show that the five sample units fall within the specification limits. The extent to which each sample unit is within the limits can be measureed, that is, these data not only shov whether the specification requirements have been met but also give an indication of the degree of variation within the quantity of product from which the sample was selected.

Variable sampling plans provide considerably more information regarding particular quality characteristics. For this reason they usually require smaller sample sizes for equivalent assurance. However, if a number of quality characteristics are to be evaluated on the basis of variables inspection, the cost of inspecting each unit in the sample on an individual characteristic basis may be so high that this factor greatly offsets the advantage of reduction in sample size.

3-8.5 SELECTION OF QUALITY LEVEL

A large variety of sampling plans is possible. Many acceptable quality level plans can be devised to protect the supplier from the rejection of high-quality products. Just as many limiting quality plans and average outgoing quality limit plans can be devised to protect the consumer from the acceptance of low-quality products. Some factors that should be considered in selecting a proper quality level and descriptions of the various quality levels are given in the paragraphs that follow.

3-8.5.1 Limiting Quality (LQ)

The lowest product quality that the consumer is willing to accept is LQ. Sampling plans may be devised to provide a specified LQ protection to the consumer. They can be used with a low consumer's risk for "isolated" lots or batches (one time or intermittent production) where very little or no control can be exercised over the production process. Plans of this type are designed primarily to provide protection to the consumer. A typical example of an LQ sampling plan is based on a statement by the consumer that he is willing to accept a maximum of 6.5% defective (LQ = 6.5%) no more than 5% (consumer's risk = 5%) of the time. A low probability of lot acceptance is usually associated with the LQ by the consumer.

3-8.5.2 Average Outgoing Quality (AOQ)

This is the average quality of outgoing product including all accepted lots or batches plus all rejected lots or batches after they have been effectively screened and defective replaced by nondefectives. The AOQ limit is the maximum AOQ for all possible incoming qualities for a given sampling inspection plan. Sampling plans selected to assure a desired AOQ limit are based on the assumption that rejected lots can and will be subjected to screening inspection. Plans of this type cannot be used where destructive-type testing is the only means of determining conformance to specified quality requirements. AOQ limit sampling plans are designed to protect the consumer with a specified risk. They offer a high probability of acceptance if the product quality is better than the required AOQ limit.

3-8.5.3 Acceptable Quality Level (AQL)

This is defined as the maximum percent defective (or the maximum number of defects per hundred units) that, for the purpose of sampling inspection, can be considered satisfactory as a process average. The sampling plans most frequently used by DoD are based upon the AQL, which is intended to assure that products of the AQL value will be accepted with a high probability of acceptance, i.e., a low supplier's risk. AQL sampling plans are designed to protect the supplier from having good lots rejected. The consumers' risks of accepting products of inferior quality are only indirectly considered.

3-8.5.4 Process Capability

The state of the art, or the capability of industry to produce the unit, may limit the selection of a quality level value. A review of suppliers' quality histories for a given product or similar products will provide an estimate of the product quality that can be reasonably expected under existing production capabilities.

3-8.5.5 Cost of Rework

If the installation of defective units early in the order of an assembly results in a large waste of time and materials during later processing or assembly, the quality level values set for these units should be tighter (lower numerical value) than might otherwise be expected. Selection of the proper quality level value depends on the type of product involved and the financial losses that might result. For example, it is much more expensive and time-consuming to locate and replace a defective resistor inside complex electronic equipment than it is to replace a defective external knob.

3-8.5.6 Cost of Inspection

Quality level values frequently have a direct effect on the cost of inspection especially when the quality levels are extremely high or low. If the quality level is very low (e.g., 650 defects per hundred units), only a very small sample will be required to determine acceptance or rejection of product. If the quality level is very high (e.g., 0.01 5% defective), a very large sample size may be required to determine acceptance or rejection of the product. An increase or decrease in the sample size, as determined in these cases by the specific quality level, may result in increases or decreases in the related inspection costs.

The quality levels specified for most inspection situations should not be considered as fixed or permanent quality requirements. They are subject to change with the concurrence of the technical agency initiating procurement. Flexibility and the capability to make changes in quality levels are necessary steps to proper administration of inspection systems or quality programs. A continuous review of quality levels should be made. Experience indicates that quality levels may be affected by changes to the specification, improvements in production machinery or equipment, development of new production or inspection techniques, consumer complaints, and other factors. Some actual examples of the cost of quality control are shown in Ref. 26; and a few of those are shown in Table 3-5,

3-8.6 SAMPLING RISKS

Regardless of the inspection plan used (sampling or 100% inspection), there is always a risk that a small percentage of defective units will be passed. Because of personnel errors, interpretation of quality tolerances, mis-

TABLE 3-5. EXAMPLE OF COST OF QUALITY CONTROL

Item	cost
Aircraft engines	5.6% of sales price
Airframe	2.7% of sales price
Engine forgings	11% of sales price

use of inspection equipment, or the incorrect conduct of tests, it is well recognized that there is always some risk that defective units may be missed. This is true under 100% inspection and even under 200 or 300% inspection. This is not to infer that such mistakes are not made under sampling inspection, but that even when circumstances dictate its use, 100% inspection incurs some risk of passing defective units. As a matter of information, studies have shown (Ref. 27) that 100% inspection under optimum conditions is only 85 to 95% effective. Therefore, it follows logically that sampling inspection can never guarantee that material it has passed is completely free of defects.

3-8.6.1 Statistical Considerations

The first consideration to be weighed in whether sampling inspection can be used is, “What would be the result of passing a defect?”. If the defect could cause a safety hazard, incur great loss, impair operating efficiency, or result in costly repairs, the conclusion probably would be that sampling inspection should not be used. Thus it would follow that even with its apparent limitations, 100% inspection should still be prescribed. There are certain risks inherent with inspection. In the case of sampling inspection there is, in addition to the error in human performance, a special kind of risk. In other words, with sampling there is always the risk (or chance) that good lots may be rejected and bad lots accepted. In general, the smaller the sample, the greater the risk. These risks may be explained as, “Assuming that a lot is some given percent defective, what is the chance (probability) that the lot will be accepted or rejected by the sampling plan ?“. When the given percent defective is in the region of good quality, interest will be centered on the chance that the lot has of being accepted, and when the given percent defective is in the region of bad quality, interest will shift to the chance that the lot has of being rejected. This ‘can be determined from the performance curve, or operating characteristic (OC) curve of the sampling plan.

The curve shown in Fig. 3-26 for the single sampling plan indicates the chance of accepting lots of varying quality. Due to variations in the sample, however, a sampling plan will sometimes yield results leading to an incorrect acceptance or rejection decision. That is, the sampling plan may reject a small percentage of good lots (commonly referred to as the supplier’s, or alpha, risk), and likewise, the sampling plan will accept a small percentage of bad lots (commonly referred to as the consumer’s, or beta, risk).

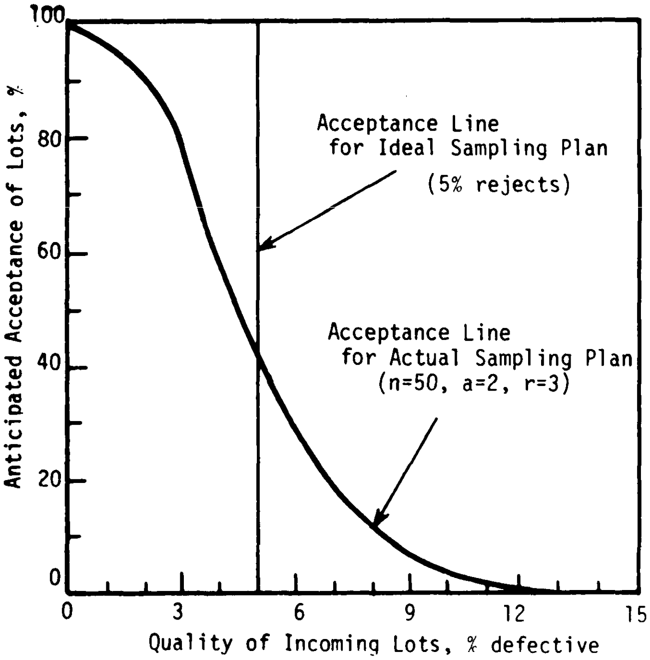

Figure 3-26. Comparison of a Theoretical Ideal Sampling Plan With an Actual Sampling Plan (Ref. 27)

3-8.6.2 Operating Characteristic Curves

The protection afforded by a sampling plan, that is, its capability to discriminate between varying degrees of good and bad quality, can be accurately calculated. The fact that these risks can be quantified makes it possible to state them statistically (numerically), usually in advance, and to describe, with a very high degree of mathematical accuracy, the quantities of product that can expect to be accepted if the quality standard is met, and the quantity rejected if the standard is not met. Such calculations, based on the mathematical theory of probability, provide the basis for the curve shown in Fig. 3-26. As in the case of the “ideal sampling plan”, performance of any sampling plan can be shown graphically by these curves. Fig. 3-26 compares the single sampling plan, with sample size n = 50 (acceptance number a = 2 or less, reject r = 3 or more), to the theoretical ideal sampling plan for which 5% rejects are acceptable.

The curve of Fig. 3-26 indicates the relationship between the quality of lots submitted for inspection and the probability of acceptance, and it is identified as the OC curve of the plan. These OC curves are a graphical means for showing the relationship between the quality of lots submitted for sampling inspection (usually expressed in percent defective, but may also be expressed in defects per hundred units) and the probability that the sampling plan will yield a decision to accept the lot (described as the probability of acceptance). In preparing the OC curve the percent defective of submitted lots is generally shown graphically on the horizontal scale and ranges from zero to some conveniently selected percent defective value representing very bad quality (but not exceeding 100%).

Along the vertical scale of the graph, the percent of lots that may be expected to be accepted by the particular sampling plan are shown—also ranging from O to 100%. Obviously, lots that contain 0'% defective will be accepted 100% of the time by any sampling plan, and lots which are 100% defective will never be accepted; consequently, the initial and terminal points (highest and lowest) on the graph can be plotted without the need for calculation. The points in between follow a smooth curve and are obtained from mathematical probability computation. Textbooks (Refs. 13, 16,20,21, 28, and 29) on statistical quality control and related procedures describe the exact procedures for constructing OC curves.

3-9 DESIGN SIMPLIFICATION FOR PRODUCIBILITY

Within the constraints of the design objective much can be done by the designer to enhance the probability aspects of the design. The element of planning is foremost in achieving this objective. The designer should examine each design with the primary thought of how it is going to be produced and mentally go through each step in that process to determine what can be done to simplify each one. Subsequent chapters in this handbook discuss design simplification at the component level. Beyond this the designer should examine the overall design with the same objective in mind. Recent developments, directions, and trends in manufacturing technology have shown an increasingly high level of interest in technologies oriented to this objective. Fig. 3-27 (Ref. 30) shows a comparison of funding levels of the DoD program in metals manufacturing technology. Note that the four most heavily funded technologies are forging, casting, powder metallurgy, and joining. These technologies are all concerned with providing the designer with the essential capabilities necessary for overall design simplicity. These capabilities are of particular interest in achieving processes that will permit near net

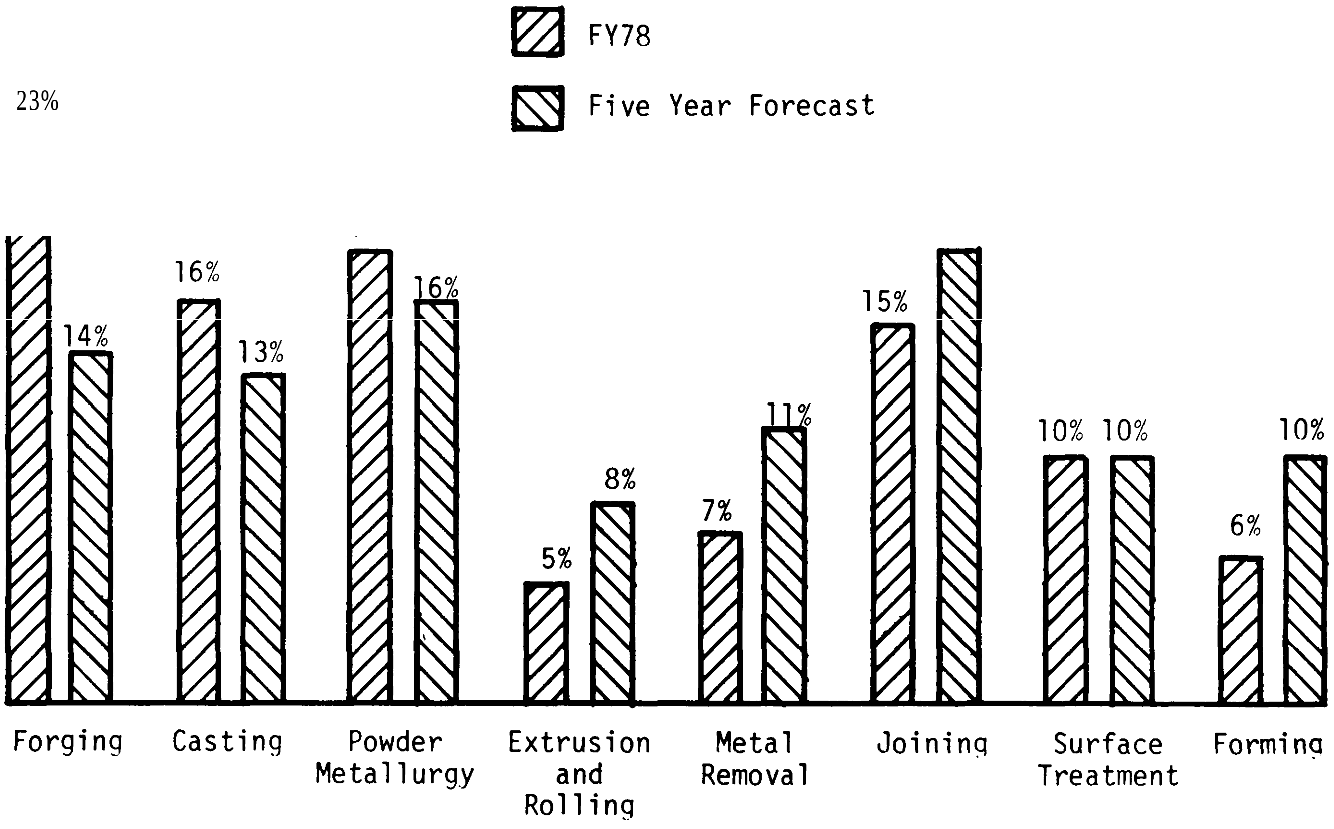

Figure 3-27. Funding Comparison of Metals Manufacturing Technology (Ref. 30)

shape components, reduced final assembly costs, and processes that will permit the designer to combine several components into one.

3-9.1 NEAR NET SHAPE

In recent years the phrase "near net shape" has come into being to describe forming processes that can efficiently produce components whose final shape is extremely close to the desired design requirement with minimal secondary processing. Historically, for example, conventional forging processes have left large amounts of metal to be removed by secondary machining operations. These were subsequently improved by proprietary processes that forged the part closer to its final shape and reduced the amount of secondary machining required to achieve the final shape. New processes are currently being developed that will further this concept of near net shape in the forming process and further minimize secondary processes. The philosophy of the concept is to put the material where needed in the first place, minimize the secondary material removal processes, and save the material and energy used in the removal process. However, it is possible that a near net shape process might cost more than machining a rough shape to final size and configuration. Therefore, the designer should be alert to this possibility and not necessarily assume that the near net shape process is the most economical. Always compare the cost of both methods before deciding on the optimum method.

3-9.1.1 Near Net Shape Forgings

Fig. 3-28 shows the advances that have been made in the area of new forging processes for near net shape components. Designers must maintain a continuous awareness of these emerging processes to assure design compatibility with the process constraints. Thus where design objectives permit, the design can be simplified and improved; higher producibility can be furthered.

3-9.1.2 Near Net Shape Casting

For many years low-quantity production has been capitalizing on the advantages of precision investment casting for achieving net shape components. This process, thoroughly described in Chapter 4, has limitations on part size and quantity. However, current efforts include the investigation of the possibility of increasing the size of parts handled by this process and the examination of automation possibilities to improve the efficiency on higher production rates. Also being investigated is hot isostatic pressing of cast parts to obtain higher production of more uniform parts.

3-9.2 REDUCED FINAL ASSEMBLY COSTS

Chapter 7 of this handbook describes the mechanical assembly of individual components into subassemblies. Of equal importance to producibility is the final assembly process of a complete system. Such simple items as wrench clearances and installation of fasteners can have significant detrimental effects on producibility in

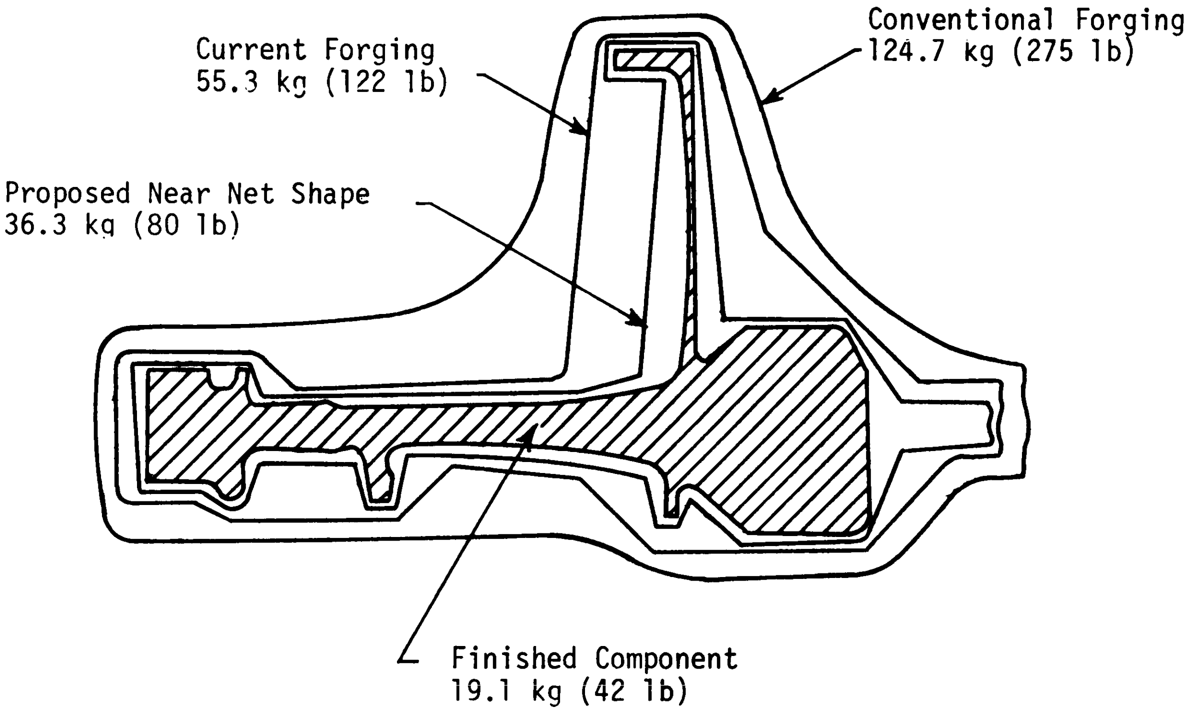

Figure 3-28. Net Shape Forging Advances

final assembly unless properly addressed in the design stage.

3-9.2.1 Wrench Clearances

Bolt heads and nuts are frequently located around the edges of parts, and these are often adjacent to other members of an assembly as shown in Fig. 3-29. Proper assembly requires the placement of a wrench on the fasteners to achieve the proper degree of tightness. In some instances these are located in such a manner that adjacent surfaces interfere with wrench clearances, as shown in Fig. 3-30. When these situations occur, the assembly operation will require the fabrication of special wrenches to achieve proper assembly or an engineering change to provide the necessary clearances. The proper clearances for each of the situations shown in Fig. 3-31 are thoroughly explained, documented, and dimensioned in Ref. 31.

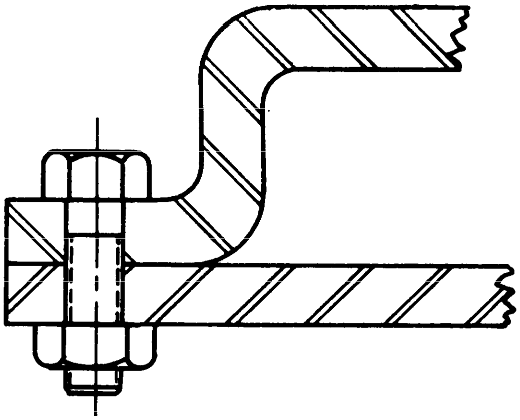

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Figure 3-29. Bolt Location (Ref. 31)

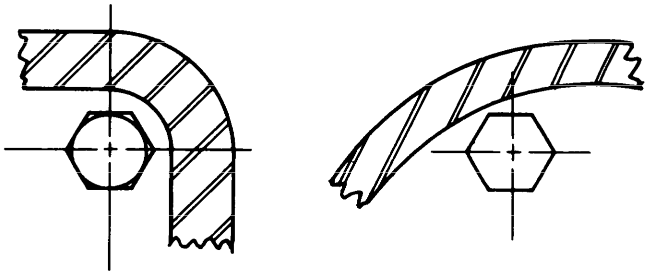

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Figure 3-30. Improper Wrench Clearances (Ref. 31)

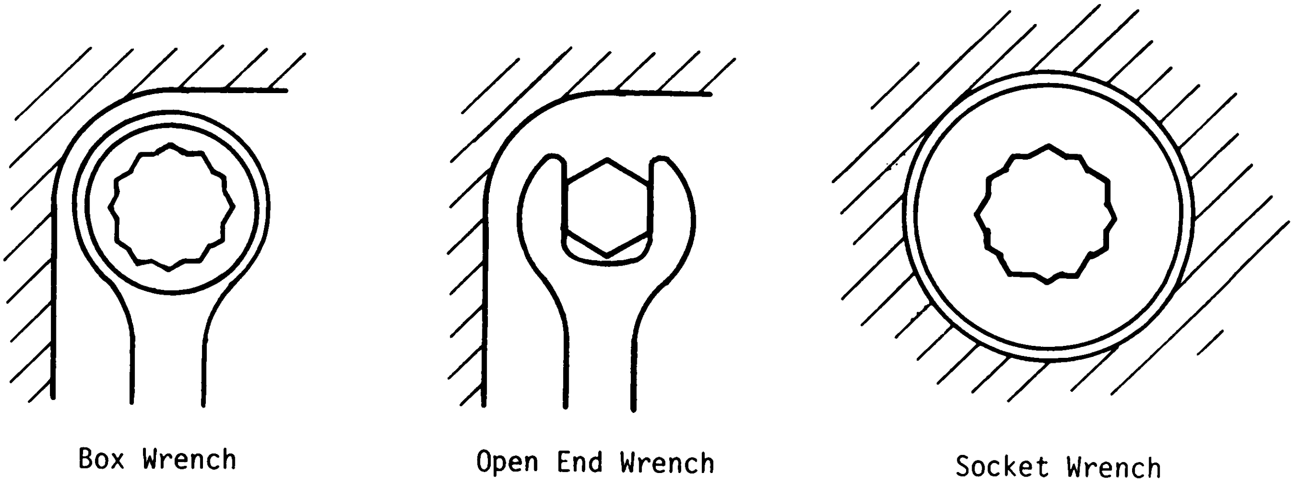

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Figure 3-31. Types of Wrench Clearances (Ref. 31)

3-9.2.2 Fasteners

Mechanical fastening is the major joining process in aerospace assembly applications. In two contemporary transport aircraft (one military and one commercial) more than two million fasteners are installed in each, which represents 4 to 7% of the total airframe cost. In high-performance aircraft fasteners are second only to engines in purchased airframe part cost. Fasteners are used not only in airframe applications but also in propulsion (where temperature requirements are, at the present time, around 925°C (1700° F)) with the attendant technical problems.

In view of the technical and economic role of fasteners, a proper assessment of mechanical fastening technology is warranted particularly with the increasing necessity for improved producibility. In such an assessment questions have to be raised pertaining to

1. Hole generation requirements with emphasis on the quality of the hole, its properties relevant to strength of the joint, and fatigue
2. Fastener selection and systems of installation; quality of the joint with respect to appearance, compatibility, corrosion, and damage to joined components
3. Mechanical fastening as a system whose cost drivers can be identified in terms of design and tooling requirements, lubrication, and secondary operations.

3-9.2.2.1 Problem Areas

The basic function of a fastener is simply to hold two or more pieces of material by mechanical restraint; typical examples of which are bolts, screws, and rivets. In spite of their relatively simple design, it is estimated that there are over a half million standard and three million special sizes, kinds, and shapes of mechanical fasteners in existence today. The reasons for this proliferation are easy to understand but somewhat difficult to justify. In the aerospace industry alone there are hundreds of aircraft types with numerous components made of different shapes, dimensions, and materials, and with a variety of requirements. In addition, it is estimated that there are 50 to 60 significant fastener suppliers with their own product lines, and there are about 300 procurement and performance specifications by military, federal, and general customer sources that affect fastener products.

3-9.2.2.2 Materials

For aerospace applications, fastener materials are generally titanium alloys, aluminium alloys, stainless steels, and alloy steels. Selection for a particular application depends not only on strength, weight, and cost, but also on corrosion resistance since galvanic corrosion between the fasteners and the structure must be avoided. The temperature of application is also important because of the effect of it on the properties of the fastener; one example is bolt tension relaxation in propulsion applications.

3-9.2.2.3 Cavity Preparation

The generation of a cavity in a structure to receive the fastener is one of the most important aspects of a successful joining process. The operation usually requires a machining process followed by secondary operations, such as reaming, deburring, countersinking, or cold working of the inner surface of the hole by various means. This is then followed by inspection of the hole for flaws and tolerances. The use of cutting fluids is also an important technical and economic factor in this process.

The state of the art in cavity inspection is not well developed; Table 3-6 shows the more promising inspection techniques. Most available techniques are capable of operating over a very narrow set of requirements. Eddy current probes have been used in small, deep holes in areas of metal that are more than 3.18 mm (O. 125 in.) from the bottom of the hole. In this manner, they are capable of scanning the bulk of the hole. Obviously, an area of great interest for these metals is the bottom of the hole, where stresses may be highest and eddy current probes cannot operate. Also this technique cannot be used on nonmetallic materials. Holes of about 6.4 mm (0,25 in.) in diameter appear to be the smallest practical size for which microprobe can be fabricated.

TABLE 3-6. HOLE INSPECTION TECHNIQUE

Technique	Advantages	Disadvantages
Eddy current	Low cost, good resolution	Proximity to edges
Visual/dye penetrant	Good resolution	Handling
Ultrasonics	Good resolution; can be automated	General surface finish
X ray	Viewing to edges possible	Health hazard and low penetration
Neutron radiograph y	Can locate cracks with fastener in place	Health hazard

Optical inspection with a borescope is capable of examining holes down to 3.18 mm (0.125 in.) in diameter. Dye penetrant will enhance the ability of the inspector to locate cracks, but application of penetrant techniques to large sheets is at best very awkward. A special ultraviolet source is needed with a borescope to activate the penetrant fluorescence.

Ultrasonics are useful for inspection of small cracks near the edge of a hole of any size, but the resolution of the difference between a crack and the edge of the hole is dependent upon the ultrasonic frequency used. High frequencies have good resolution but must be coupled into the material under test at a very smooth surface. The surface roughness must be less than the size of the defect to be detected. Many of the materials do not have adequate surface finish to permit high resolution. However, this technique may be useful for locating larger cracks in holes where fasteners may already be inserted.

X-ray and neutron radiography both hold promise of being capable of finding small cracks. X-rays are limited by their penetrating power while neutrons easily penetrate many meters of dense material. However, both techniques represent serious health hazards from the radiation. Neutron radiography does have the best capability of locating cracks and corrosion in assembled components.

3-9.2.2.4 Fastener/Cavity Interface

The fastener/cavity interface is important for two reasons. First, it is generally desirable to have an interface that produces residual compressive stresses at the circumference of the hole; this is conducive to increased fatigue life of the joint. The residual stress requires an interference fit, and lubricants may have to be used during insertion of the fastener. The selection of the proper lubricant is critical in reducing the forces required to install the fastener, in its role in controlling torque or the tension variability ratio, and in prevention of corrosion at the fastener/cavity interface.

The clearance at the interface also plays a crucial role, depending on the particular technical consideration. High interference is desirable for optimum fatigue performance. This has recently been studied more systematically for aluminum and titanium alloys in an Air Force Materials Laboratory program (Ref. 32). On the other hand, increasing the clearance between the fastener and the hole in the structure decreases the corrosion rate in the joint by lessening the chance that oxygen concentration cells will form, which cause crevice corrosion.

3-9.2.2.5 Types and Tooling

Factors such as the design, materials of the structure, and the fastener use determine the type and tooling of a fastener. No attempt can be made in this limited space to list the variety of fasteners available and the numerous components of an aerospace structure for which they are designed. The fact remains, however, that the proliferation of fastener types has to be examined seriously with respect to grip lengths, head, and head recess design, etc. All this also relates to the tooling required and the attachments that go with the tooling.

3-9.2.2.6 Fatigue

In spite of the complexity of the problem, it appears that inducing compressive residual stresses in the holes of the structure by various means is indeed technically desirable to reduce stress cracking. The methods used have been high levels of interference between the fastener and the hole and, less desirably, clamping the joined sheets so that they cannot move; the latter requires careful control of clamping loads. It appears that in terms of simplicity, performance, cost, flexibility, and minimized skill requirements, prestressing the hole by the sleeve cold working has certain advantages over other methods (Ref. 33).

3-9.2.2.7 Corrosion

The problem here is that, unless certain protective measures are taken, the fastener material acts as a cathode and the structure material as an anode; consequently, the structure begins to corrode. To determine materials for corrosion compatibility, the galvanic table (Ref. 34) can be used as a general guide. This, however, should be done cautiously since a number of other parameters also play a role in corrosion. As previously mentioned, clearance between fastener and structure is an important factor. The use of a lubricant in installing the fastener is another important factor. Some lubricants are good electrical conductors, thus encouraging galvanic corrosion. The presence of moisture is an additional factor. A number of techniques and materials (liquids, solids, coatings, and plating) have been used with varying degrees of success.

3-9.2.2.8 Costs

A typical breakdown of the total cost of mechanical fastening is material-40%, hole preparation— 16%, installation and inspection—34%, tooling—5%, handling (purchase and inventory)—5%. These figures will vary greatly, and detailed data are available on cost breakdown within each phase of the fastening system. From such data one can identify the areas in which cost savings may be achieved.

3-9.3 COMBINING COMPONENTS

Frquently, the opportunity to combine several parts into one component presents itself, but all too frequently, these opportunities are overlooked. However, with the advances occurring in manufacturing technology, these opportunities are becoming more prevalent. The designer should condition himself to examine every component design to determine the potential for combination of the component with an adjacent component in the next assembly. A few examples of how some designers take advantage of these opportunities are given in the paragraphs that follow.

3-9.3.1 Metal Forming

Metal boxes with tabs and louvered slots were among the first opportunities identified in this area. Fig. 3-32 shows an original design. A rectangular slot was

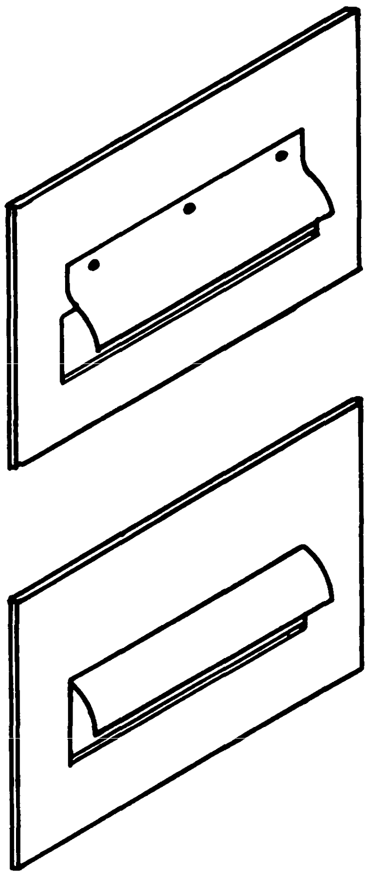


Figure 3-32. Louvered Slots

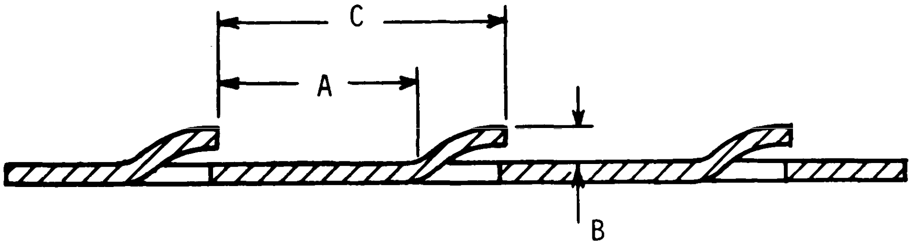
punched into the sheet metal; then a separate piece was stamped out and formed to serve as a louver cover. These covers were subsequently riveted together in a separate assembly operation. Subsequently, metal stamping and forming evolved to the point where the louver was stamped by simply punching three sides of the slot and simultaneously kicking the flap out and forming it to the desired shape. This required more expensive tooling, but with sufficient quantity to amortize the tooling, it became a far more producible component. This combined slitting and forming operation does have some constraints and limitations as shown in Fig. 3-33. The constraints provide for the minimum dimensions necessary to insure sufficient material to provide for the metal deformation characteristics.

3-9.3.2 Casting

As precision casting has evolved, the capability to produce thin-walled parts has displaced some forming operations. An example of this is the common electrical junction box, which used to be a formed box with separately attached tabs. Today the same box is made by a precision casting process as one complete, integral unit; the necessity of a separate assembly operation is completely eliminated.

3-9.3.3 Extrusion

Because of the unique flow characteristics of aluminum in the impact extrusion process, it is very adapt-



Dimension	Constraint (Minimums)
A	3.18 mm 0.125 in.) up to 1.59 mm (0.062 in.) material thickness 9.52 mm[0.375 in.) over 1.59 mm (0.062 in.) material thickness
B	2 times metal thickness
c	12.7 mm (0.5 in.) up to 1.59 mm (00062 in.) material thickness 31.75 mm (1.25 in.) over 1.59 mm (0.062 in.) material thickness

Figure 3-33. Combined Slitting and Forming Constraints

able to combining components. As shown in Fig. 3-34, this aluminum component was originally considered a two-piece construction. Subsequent redesign to suit impact extrusion tolerance constraints permitted the two components to be combined into one and consequently reduced the basic fabrication cost in addition to eliminating the assembly cost. The integrity of the structure also had beneficial impact on the reliability of the component.

3-9.3.4 Summary

Most of these opportunities for producibility improvement through combining components are only apparent in the assembly stage of the design. Consequently, careful attention should be given to this potential during the assembly design process.

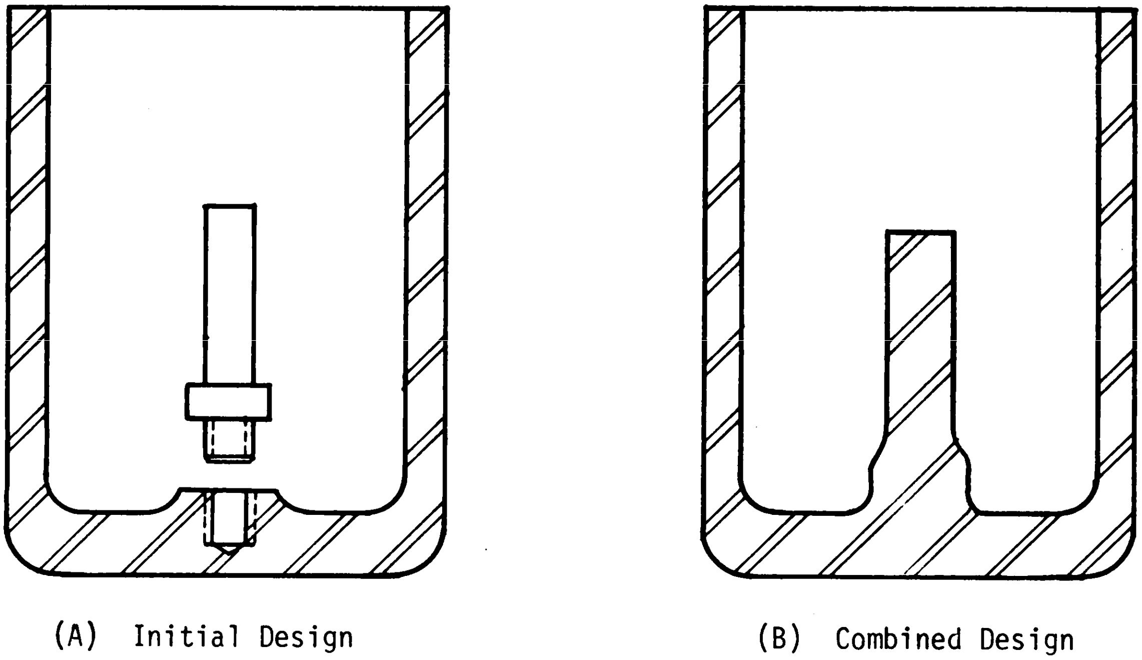


Figure 3-34. Impact Extruded Tube

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CHAPTER 4

PRODUCIBILITY CONSIDERATIONS FOR METAL COMPONENTS

This chapter is subdivided into a general introductory paragraph applicable to all metal parts and three additional major paragraphs devoted to sheet metal components, shaped/machined components, and structural components. Each major paragraph is complete in that each one provides data on related materials, manufacturing processes, and inspection. These paragraphs are arranged in a sequence comparable to the sequence in which design decisions are made. The fabrication of metal components is addressed, not the joining or assembly of those components. For information on joining or assembling see Chapter 7. This chapter concludes with a narrative description of the most common causes of producibility problems for metal components.

4-1 GENERAL PRODUCIBILITY CONSIDERATIONS

Some factors affect producibility of all products and are not limited to a specific category of parts; these are discussed in previous chapters. Similarly, there are common factors, discussed here, that affect producibility of all metal parts.

4-1.1 MAJOR MATERIAL CONSIDERATIONS

The variety of materials available today provides the design engineer with a wide latitude in the design process. Of course, the designer's primary concern is selection of a material with properties that meet the performance characteristics of his intended design. However, these properties also influence the producibility of his design, and this fact should receive equal consideration in the material selection process. Hypothetically, the property that makes the selection ideal for design performance characteristics could also make the design the least producible. Ideally, the material selection process should be a series of trade-offs of the various material properties to achieve the optimum design performance with the optimum producibility characteristics.

It is important to note here that all material designations in this handbook use the Unified Numbering System (UNS). Additional information on this system and further elaboration are included in Ref. 1.

4-1.1.1 Applications and Producibility

Specific materials have been found, as indicated by their continued use, particularly suitable for certain types of applications. Tables 4-1 through 4-11 were prepared so that the designer will have more pertinent producibility information on which to base a judicious choice of materials. Since the field of materials is now so vast, no attempt has been made to cover completely all materials. The "Remarks" heading includes statements of limitation and of special properties that may influence the use of the material. When the remark is one of caution, such as "Do not weld", it is to be interpreted as indicative of present good practice and does not necessarily imply that a certain process cannot be used without resort to special methods or without an appreciable sacrifice of certain desirable properties.

4-1.1.2 Material Selection Factors

During the initial material selection phase, the design engineer is more interested in the physical characteristics of a material than he is in its producibility aspects. These characteristics are readily available in a number of good reference books, such as Refs. 2,3, and 4. Since they are so readily available, these characteristics are not repeated here.

Each of the physical characteristics of material listed in the paragraphs that follow implies certain constraints or conditions relative to producibility. These characteristics influence the use of the material and have a decided effect on the producibility of products made from the material,

4-1.1.2.1 Ultimate Tensile Strength

The higher the strength of a material, the more difficult it is to draw or bend, i.e., high strength materials resist deformation. The low strength carbon steels are better for drawing. WARNING: High strength, high carbon steels may work harden and fracture during drawing operations. This is due to the heat generated in the draw, which causes a heat treat quench effect.

4-1.1.2.2 Elastic Limit

Stressing a material beyond its elastic limit permanently deforms it. Materials having a high elastic limit are generally more difficult to draw and form.

Text commences on p. 4-13.

TABLE 4-1. WROUGHT CARBON STEELS

Materials and Usual Forms Available	Applications	Remarks
G10100-G10150 Sheet, strip, rod, and wire.	Automobile body and fender stock, panels, deep drawings, sheet metal covers, and cold-headed parts, such as tacks and rivets.	Low-strength material not intended for primary components or structures. Poor machinability. Avoid threading. Does not respond to heat treatment.
G10200–G10250 (Machine Steel) Sheet, strip, bar, forging stock, and tubing.	For carburized parts and general structural parts requiring no special properties. Small unheat-treated forgings, low-strength shafting, wrist pins (low-power engines), cam shafts, fan blades, and tubing.	Poor machinability though somewhat better than G10100. Readily welded and brazed. Bends easily. Not generally heat-treated except for case hardening.
G10300-G10350 Bar, tubing, and forge stock.	Higher physical properties than lower carbon steels; for small- and medium-sized forgings, such as shackles, levers; cold-forged fittings, such as screws and bolts; and drive shafts and piston rods.	Responds to heat treatment in thin sections. Fair machinability. Do not carburize.
G10400-G10450 Bar and forge stock.	Forgings, such as crankshafts, connecting rods, starter ring gears, and brake levers; shafting, chain sprockets, and large gears.	Tough, wear resistant, and ductile. Shock resistant. Good hardenability. Small and intricate sections must be heat-treated with care. Generally best to avoid thin sections in design. For greater strength and toughness use G31400.
G10600-G10700 Sheet, wire, and forge stock.	Snap rings, clutch plates, Belleville washers, lock washers, cushion springs, valve springs. For springs not subjected to severe service. For large forgings.	Compared to other spring materials, these steels have low elastic limit and fatigue strength. Has better formability in pretempered condition than higher carbon steel does.
G 10950 Rod (called drill rod), sheet, strip, and wire.	Pins, retainers, flat springs, clips, washers, motor springs, hot-formed springs, dowels, shafts, and tools. Agricultural parts; harrow and seeder disks, and rake and binder bundle carrier teeth.	Drill rod available to accurately ground diameters ±0.13 mm (0.005 in.). Sheet in spring temper is readily punched and blanked. Complicated springs must be formed with material in annealed condition and then heat-treated. Avoid stress concentrations and cold-forming operations. Do not weld. Do not electroplate springs made of high carbon steel without special precautions to avoid embrittlement.
G11120 Free-machining screw stock, rod, and bar.	Screw machine products.	Unsuitable for parts subjected to shock, vibration, or fatigue. Not recommended for forming, bending, upsetting, or carburizing. Use where ease of machining and finish are prime considerations. Inherently brittle. For superior physical properties but similar free-machining characteristics, specifv SAE 1315*.

* UNS numbers have not been assigned to all materials.

TABLE 4-2. WROUGHT STAINLESS STEELS

Materials and Usual Forms Available	Applications	Remarks
S30200, S30400 Commercially called "18-8". Sheet, strip, bar, forge stock, and tubing.	For equipment dealing with corrosive products for heat exchangers, hospital, and food processing equipment, pipe and pipe fittings, screws, bolts, and shafting. Hard-drawn wire is used for springs, and aircraft and marine cable. Sheet stock in full hard temper is used in spot-welded structures.	Nonhardenable by heat treatment. Tensile strength and hardness may be increased by cold work. Nonmagnetic with high corrosion resistance, ductility, and toughness. Can be deep drawn and readily spot-welded. Do not use on wearing parts. Welds are strong and ductile, but must be made with care. For better machinability use type S30300. Type S30400 preferred for welded units.
S30300 Round, bar, forge stock, and stainless drill rod.	Shafting, valves, and pumps exposed to corrosive fluids. Aircraft instrument parts. Automatic screw machine products.	Good nongalling and nonseizing properties. High corrosion resistance. Free-machining stock. Nonmagnetic. Welding not recommended. Retains strength at elevated and subzero temperatures.
S41000 Sheet, strip, bar, rounds, tubing, and forge stock.	Valves and pipe fittings subjected to high temperatures (up to 850°C) or corrosive mediums, turbine blades, and pump parts. Parts for which paint is impractical. For decorative trim.	Good corrosion resistance. High strength. Hardenable by heat treatment. Magnetic. Good machinability. Welds are brittle and must be annealed. Good creep strength. Does not scale appreciably to 1033 K. Subject to discoloration unless passivated. For better free-cutting and nongalling qualities, use type S41600.
S41600 Bar, wire, and forge stock.	For parts requiring considerable machining, corrosion resistance, and high strength, but for which impact resistance is not important. For carburetor parts, screws, pump parts, and business machine parts.	Free-machining, heat treatable, magnetic, nongalling stainless steel. Do not weld or use where high impact resistance is required. Do not heat-treat after fabrication due to nonuniformity of properties obtained. (Readily machined when hardness is 270-340 Brinell.) Subject to discoloration unless passivated.

TABLE 4-3. WROUGHT ALUMINUM ALLOYS

Materials and Usual Forms Available	Applications	Remarks
A93003 Sheet, rod, extruded shapes and tubing in all temper conditions.	Piping, electrical conduit, and junction boxes. Applications involving deep drawing, upsetting, spinning, or welding. Fuel tanks, ducts, and decorative trim, Low-strength rivets. Not for primary structural applications. Widely used for unfired pressure vessels.	Low-strength, high corrosion resistance, soft, ductile, and readily welded. Can be brazed. Nonheat-treatable. Variations in properties obtained by cold work. For greater strength, but less formability and weldability, use A95052.
A92024 Sheet, rod, extruded shapes and tubing in various temper conditions.	Lightweight primary structures, frames, and fittings. Hydraulic fittings, hardware, rivets, and screw machine products.	High-strength, low-weight, heat-treatable alloy. Do not weld. Not commercially brazed. Readily spot-welded. Can be moderately formed in nonheat-treated state. In contact with heavy metals, as brass and bronze, is subject to galvanic corrosion. Can be refrigerated after quenching to stop room temperature aging and hardening and to prolong time for forming. For better physical properties use A97075.
A96053 Sheet, rod, tubing, wire, and shapes in various temper conditions.	Semistructural uses. Radio chassis, frames, household furniture, and architectural materials.	Good formability, weldability and corrosion resistance. Heat-treatable, but physical properties are about 60% of A92024. For slightly better formability, use A96061.
A92014 Extruded stock and forge stock.	High-strength, forged aircraft fittings and supercharger impellers; suitable for heavy-duty applications requiring lightweight forgings.	Strongest of forged aluminum alloys. Good forgeability. For greater corrosion resistance with reduced physical properties, specify A92017.
A97075 Sheet and extruded shapes.	For highly stressed members. For aircraft frames, coverings, and fittings. For parts subjected to high fatigue stresses.	Has better formability in the "W" (as quenched, not aged) condition than A92024. Must be quenched in water. Hardened, it has poorer forming qualities and notch sensitivity than A92024. Also has higher degree of springback than A92024. Can be welded by helium-shielded arc, but weld is not corrosion resistant and tends to be brittle. Spot welding satisfactory.
A95052 Sheet, plate, and tubing.	Extensively used for hydraulic tubing, aircraft fuel tanks, storm shutters, electronic panels, and fan blades.	Good tensile strength, very good corrosion resistance, good workability, weldability, and strength.
A96061 Sheet, plate, bar, rod, and tubing in all temper conditions.	Used for structural applications, boats, furniture, and transportation equipment.	Has good tensile strength, workability, and corrosion resistance. Good welding characteristics,
A92017 Bar and rod.	Good screw machine stock with good machinability. Particularly suitable for deep drilling:	Formability and corrosion resistance are good.

TABLE 4-4. WROUGHT ALLOY STEELS

Materials and Usual Forms Available	Applications	Remarks
SAE 23 17-2320* Bar and hexagon stock.	Gears, shafts, cams, pinions, universal joints, machine tool spindles, and pump shafts. Parts to be case-hardened requiring a tough core (piston pins and auto rear axle gears).	Principally for carburized parts in which only a small amount of distortion is permitted. Good machinability. Do not weld.
SAE 2512-2515* Bar and forge stock.	For carburized parts requiring high core strength and toughness. Wrist pins, king pins, transmission gears, cams, rock drill parts, general machinery gears, engine, and starter gears. Heat exchanger tubes.	When carburized, case has exceptional wear and fatigue resistance. Free from scaling and distortion during heat treatment.
SAE 2330* Bar, rod, and hexagon stock. Forge stock.	For highly stressed bolts, nuts, levers, turnbuckles, generator shafts, heavy-duty shafting axles, and rocker arms. Small parts subjected to torsion and fatigue. Large, heavy-duty parts where only simple heat treatment is practical.	Very high impact strength and toughness. Cold-drawn stock has fair machinability and bright finish. Deeper hardening than corresponding plain carbon steel. Little heat-treated distortion. Do not carburize or weld.
G31400 Bar, rod, flats, and square stock. Forge stock.	Aircraft, truck, bus crank shafts, and connecting rods; intake valves; excavating machine parts; and oil well tool joints; and steering knuckles. High-temperature valves and fittings. Suitable for wearing edges in contact with nonmetallic abrasives as in power shovels and farm machinery.	High impact and fatigue resistance. Suitable for parts subjected to heavy strains and vibration. Readily forged. Fair machinability. High creep resistance. Relatively low cost. Not recommended for machine parts subjected to heavy metal-to-metal wear.
G33106 Bar and forge stock.	For forged parts requiring hard wearing surfaces that are subjected to very heavy duty and high fatigue stresses. Used where reliability is essential. Aircraft engine gearing and shafts. Railroad truck, bus gears and roller bearings. Differential gears and broaches.	Extremely high fatigue strength and wear resistance. Very high core strength. Not readily machined. Careful forge and heat treatment required. Carburize for exceptional surface wear resistance. Air-hardening tendency adapts this steel to applications having large cross sections.
G41300 (Chrome-molybdenum steel) Bar, rod, sheet, and tubing.	Aircraft fittings as control sockets, brackets, and hardware. Structural frames of tubing. Widely used for welded units subjected to high stresses and not intended to be heat treated after welding. Used in autos for axles and steering knuckles.	Mildly air-hardening in thin sections. Readily welded. High impact strength. Good machinability after heat treatment. Shallow-hardening steel. Good physical properties with high ductility. Not recommended for parts of varying cross-sectional thickness.
G41400 Bar, rod, sheet, tubing, and forge stock.	Oil drilling, refining, and mining tools; and jaws, connecting rods, drill collars, shafting bolts, high-temperature valves, and screw fittings. Heavy-duty engine crankshafts, engine cylinder barrels, rear axles, spline drives, wrenches, hammers, aircraft forged fittings, and heavy-duty tubing.	High strength, wear, and fatigue resistance; suitable for high- and low-temperature applications. Suitable for large weldments because it can be deep-hardened. Good machinability. Weldability less than G41300. Suitable for parts of varying cross-sectional thickness.
G43400 Bar, rod, and forge stock.	Auto and aircraft engine, diesel crankshafts, and gears. Tractor rear axle drives. Medium-sized forgings that can be quenched and drawn. Heavy-duty shafting, machine tool arbors, and screwdriver blades. Large, heavy-duty gears.	For large sections. Deep hardening. High strength and fatigue resistance. Good machinability at high hardness. Weld with care. Hardens in air; requires careful heat treatment.

(cont’d on next page)

TABLE 4-4. (cont'd)

Materials and Usual Forms Available	Applications	Remarks
SAE 4640" Bar and forge stock.	Transmission gears and splined shafts with sliding members. For shafts and parts requiring high fatigue resistance and physical properties. High-strength studs. Medium-sized gears for moderate service.	Uniform properties with good machinability. Little heat-treatment distortion. High strength combined with very good ductility. Excellent wear resistance when cyanide dipped prior to quenching.
G61500 (Chrome vanadium steel) Round and forge stock.	For heat-treated forgings and machined parts of high strength and fatigue resistance. For parts where variation in section thickness precludes proper and uniform heat treatment. For gears, bolts, crankpins, worms, axles, and hot-work punches and dies, leaf and coil springs. Suitable for springs subjected to elevated temperatures, high stresses, and impact stresses.	High shock, wear resistance, and excellent ductility. Very little heat treatment distortion. Stock very uniform and free of defects. Fine grain structure. Poor machinability. Do not weld.

* UNS numbers have not been assigned to all materials.

TABLE 4-5. FERROUS CAST METALS

Materials and Usual Forms Available	Applications	Remarks
Cast iron	For machinery bases, housings, pipes, and fittings. For parts that may involve metal-to-metal wear. Precision bearings, engine cylinder blocks, piston rings, gears, flywheels, and pulleys. There are many specialized grades of cast iron for specific purposes to overcome objections to plain cast iron such as Mehanite-processed and nickel-, molybdenum-, and copper-alloyed cast irons.	Cheap, easy to cast. Low-strength material. Excellent machinability. Inherently brittle. Susceptible to growth if subjected to cyclic heating and cooling. Good atmospheric corrosion resistance. Excellent vibration damping characteristics. Does not seize or gall. Not generally welded except for repair work for which brazing is widely used.
Malleable iron	Automotive and agricultural equipment, such as housings, differential carriers, brake shoes, rear axles, miscellaneous brackets, steering gear housings, pedals, links, binder needles, and mower shoes. Railroad car castings, bridge railings, pipe, and rail fittings. Specify pearlitic, malleable iron for parts requiring hardness and wear resistance.	Moderate strength, good shock resistance. More ductile than cast iron though not as wear resistant. Excellent machinability. Not weldable. Unsuitable as a bearing except for low speeds with ample lubrication. For higher strength use steel forgings or castings. Good atmospheric corrosion resistance. Good foundry characteristics, but requires elaborate heat treatment.
Carbon steel	Used for economical castings of moderate strength in rolling mill frames, machine housings, connecting rods, links, and levers, and parts for heavy machinery. Medium carbon type steel most widely used where heat treating is required. Results in good yield strength and ductility. Low carbon types may be carburized for hard surfaces.	Lower carbon contents (less than 0.35% C) are readily weldable; higher carbon contents are welded with difficulty. Heat-treat for improved machinability and physical properties.
Nickel steel	For cast parts requiring toughness and resistance to impact and repeated stresses. For mining, excavating, mill, locomotive and ship castings, housing, and frames.	Has excellent physical properties at low temperatures. Suitable material for applications involving operation at subnormal temperatures. Weldable by all processes. Suited for castings of large section.
Chromium steel	For castings of good strength requiring hardness, and resistance to abrasion, high temperatures, and moderately corrosive conditions. For conveying equipment parts, rolling mill rolls, dies, crusher parts, and oil refinery equipment.	Good wear resistance. Arc welding generally preferred. When corrosive conditions are severe, cast stainless steel should be specified.
Molybdenum steel	For large, intricate castings that are difficult to heat-treat and that require considerable strength and growth resistance at elevated temperatures. For turbine and pump casings, engine blocks, and high--pressure and high-temperature valves and fittings.	Heat-treat to obtain good weldability and machinability.
Manganese steel	For cast parts requiring exceptional wear and abrasion resistance. For parts subjected to repeated impact stresses. Used in tractor treads, excavating buckets, wheels, mining tools, plow tips, railway couplings, mill rolls, sprockets, and crushers.	Hard to machine. Heat treatment improves machinability and greatly improves toughness and ductility. High-manganese type is nonmagnetic, Welding difficult; electric arc preferred. Do not use unalloyed high-manganese type where temperatures exceed 340°C (6500 F).

TABLE 4-6. WROUGHT MAGNESIUM ALLOYS

Materials and Usual Forms Available	Applications	Remarks
B107-76* Sheet, rounds, extruded shapes, and forge stock.	Low or moderately stressed, secondary aircraft structural parts, and oil fuel tanks. Furniture and household appliances. Use where welding and very light weight are required.	Good formability, weldability. Good corrosion resistance if properly finished. Excellent machinability. Formability best when heated, Not recommended for use above 200°C (400°F). Low abrasion resistance.
AM58*, 54*; Dow J-1* Sheet, rounds, extruded shapes, and press forge stock.	For extremely lightweight, moderately stressed secondary structures and structural fittings for which high physical properties are required and good formability and weldability are not, Aircraft frames, conduits, parts in textile machinery, engine cowlings, and bus and truck roofs.	Low stiffness with excellent machinability. Hardens rapidly with cold work. Formability greatly improved when heated to about 315°C (600°F). Poor abrasion resistance. In forgings, material has marked grain directional properties and low compression yield strength. Slight improvement in properties obtainable with heat treatment. Subject to galvanic corrosion when in contact with steel, brass, or bronze. Arc weld only. Readily spot-welded. Not recommended for use above 200°C (400°F).

* UNS numbers have not been assigned to all materials.

TABLE 4-7. WROUGHT COPPER AND NICKEL ALLOYS

Materials and Usual Forms Available	Applications	Remarks
C36000 Free cutting brass. Bar and shape stock.	Hydraulic fittings, electric terminal fittings, handles, and automatic screw machine work. Where low stresses are encountered and where a large amount of machining is required.	Low strength, fast machining, bright finish, and fair corrosion resistance. Poor malleability and ductility. Cannot be cold-worked. Welding not recommended.
C31400 Commercial bronze. Sheet strip and wire.	For stamped or drawn parts and for parts requiring extensive forming operations. For electrical sockets, conduits, and flexible cables.	Excellent cold-working properties. Fair machinability. Good corrosion resistance High ductility. Low strength.
C67500 Manganese bronze. Bar, plate, sheet, and forge stock.	For parts requiring great strength and shock and corrosion resistance. For bearings subjected to heavy-duty, slow-moving loads. For pump parts, valve stems, propeller blade bolts, and fittings.	High strength and toughness. Poor cold-working properties. Fair hot-working properties. Not recommended for metallic arc welding. Machinability 30% of free-cutting brass.
C27000 Yellow brass. ("High" brass) Bar and sheets in various tempers.	Soft temper for parts requiring deep drawing, spinning, or severe forming. Hard temper for fiat springs and parts requiring only simple forming operations. For electrical sockets, clips, cartridge cases, and eyelets.	Good strength and ductility, excellent cold-working properties. Fair machinability and corrosion resistance. Subject to season cracking. Can be welded and brazed. Do not hot-work.

(cont'd on next page)

TABLE 4-7. (cont'd)

Materials and Usual Forms Available	Applications	Remarks
C51000 Phosphor bronze. Sheet, strip, bar, and wire. Available in various tempers.	For contact springs, helical springs, fuse clips, electrical contractors, lock washers, clutch disks, and thrust washers. For small bushings, lead screw nuts, pump rods, bolts, valve stems, and gears. For parts subjected to corrosion and wear.	High strength and toughness; excellent fatigue corrosion, and abrasion resistance. Low coefficient of friction. Machinability is fair (20% of free-cutting brass). Do not hot-work. Fair weldability; arc welding recommended. Not subject to season cracking. For similar applications but better formability, use beryllium copper.
C65100 Silicon bronze. Plate, sheet, wire, rod, tubing, shapes, and forge stock. Available in various tempers.	Fastening and electrical hardware for outdoor and marine equipment; heat exchangers, vats, pressure vessels, turnbuckles, U-bolts and corrosion resisting chain. For hot- and cold-forged parts.	High fatigue resistance. Strength comparable to mild steel. Excellent corrosion resistance. Readily welded and brazed. Some types have poor machinability. Difficult to forge.
G61400 Aluminum bronze. Sheet, rod, tube, and forge stock.	Aircraft engine parts, such as propeller hub cones, bushings, valve guide, spark plug thread inserts, valve seats, and propeller blade bolts; and high strength, hard gears and forgings.	Excellent resistance to scaling oxidation at high temperatures and corrosive conditions. Lightweight. Good cold-working qualities. Some types have poor machinability. Welding not recommended. Readily hot-forged. Some can be heat-treated for improved physical properties.
C17200 Beryllium copper. Round, sheet, strip, wire, and forge stock.	Springs, vibrators, diaphragms, electrical contact brushes, siphon bellows, nonsparking tools, molds, appliance clips, and switch blades. For parts requiring extensive forming and spring qualities as well as good electrical conductivity. Accurate instrument springs.	Readily formed in annealed state. Can be heat-treated to spring tempers. Heat treatment must be done very carefully. High corrosion resistance. Cold-work hardens material readily. Arc weld and low-temperature braze only. Not readily machined after age-hardening. Grain direction for forming relatively unimportant.
N04400 Monel. Rounds, sheet, strip, tubing, wire. Available in different tempers.	Valve and pump parts, turbine blades, and laundry and food service equipment. Processing equipment. For marine and aircraft instrument parts. For parts requiring exceptional corrosion resistance combined with high strength, hardness, and impact resistance.	Do not use under severe abrasive or galling conditions. Fair machinability. For free-cutting quality, use N04405. Nonheat-treatable. Arc welding recommended. Cold-works readily when in soft temper.
N06062 Inconel. Plate, sheet, and strip, tubing, rounds, and wire.	For parts subjected to very high temperatures, corrosive fluids, and moderate stresses, such as aircraft engine exhaust manifolds, carburizing boxes, nitriding hoods, heaters, piping and fittings, and chemical processing vats and tanks.	Corrosion and oxidation resistant at high temperatures. Fair machinability. Readily arc-, gas-, or spot-weld. Nonmagnetic. High impact strength. Galling tendency. Good ductility and deep-drawing properties.

TABLE 4-8. SAND-CAST ALUMINUM ALLOYS

Materials Available	Applications	Remarks
A94043	Used for nonstructural aircraft fittings, and architectural and ornamental parts; pipe fittings, tank fittings, and marine castings. For intricate castings having thin sections and parts that must be pressure tight. Suitable for permanent mold castings.	Relatively low physical properties with excellent foundry characteristics. Good corrosion and shock resistance. Can be welded with special care. Not heat-treatable.
A01950	Engine crankcases, outboard motor parts, and machine bases; shop crane and trolley parts, and aircraft landing wheels. For parts requiring good strength and corrosion and shock resistance. Also good for permanent mold castings.	Heat-treatable. Moderate strength and ductility. Do not weld. For intricate, thin-walled castings where lower shock resistance is permissible, substitute A03560.
A92219	Heavy-duty castings, power shovel dipper parts, truck and railway *car* parts. For high-strength, structural aircraft fittings. Generally used only where high stresses are encountered.	Heat-treatable. Highest combination of physical properties of all aluminum alloy castings. Unsuitable for applications requiring pressure tightness or that are subject to elevated temperatures. Requires special foundry techniques. Difficult to cast intricate shapes and to obtain sound castings. Do not weld. Fair corrosion resistance. Good machinability.
AO3560	Used primarily for precision cast parts for which tolerances and intricate detail are required.	Heat-treatable, moderate strength, and ductility. Excellent foundry characteristics and can be welded.

TABLE 4-9. SAND-CAST COPPER ALLOYS

Materials Available	Applications	Remarks
C23000 Leaded red brass (ounce metal).	For hydraulic castings, such as pump bodies low-pressure valves and fittings. For intricate castings and for castings having thin sections.	Moderate strength, close grained. Good casting properties and machinability. Rich color. Low cost. Do not use at temperatures exceeding 200°C (400°F). Unsuitable for bearings.
C67500 Manganese bronze.	For high-pressure hydraulic valves and marine propellers and parts requiring strength and toughness. High-strength types suitable for gears, slow worm drives, lead screw nuts, and heavy-duty, slow speed bearings subjected to severe shock, such as turnable disks and bridge bearings.	Excellent corrosion and impact resistance. High strength. Cannot be welded or brazed. High shrinkage. Do not use in high-speed bearings. Wear-resistant under slow moving loads. High-tensile-type manganese bronze has higher strength and hardness.
C54400 Phosphor bronze.	Universal alloy for bearings and bushing applications at both low and high speeds and moderate pressures. Suitable for bearings subject to shock and vibration with inadequate lubrication. Use whenever resistance to wear due to friction must be minimized.	Nonseizing, nonscoring with low coefficient of friction. Good machinability (approximately 95% free-cutting brass). Poor weldability. For heavy-duty, slow-moving loads, use stronger varieties of manganese bronze.
C61400 Aluminum bronze Grades A and B.	For parts subjected to severe corrosion and elevated temperatures. For engine valve guides, air defense searchlight parts, furnace castings, and mill slipper bearings. Grade A is applicable to spur, helical, and bevel gears mated with hardened steel gears.	High strength. Good wear and repeated shock resistance. Hard. Maintains physical properties and resists scaling at high temperatures. Poor foundry characteristics and machinability y. Grade B is generally heat-treated. Under certain conditions is suitable for bearing or worm gear use.
C17200 Beryllium copper.	For heavy-duty brake and clutch drums, and high-strength aircraft fittings and brackets, such as gun mounts, safety tools, impellers, and marine propellers.	High "as cast" physical properties with good ductility. Heat-treatable. Very high impact resistance with high proportional limit. Good corrosion resistance. Good castability and machinability. Good electrical properties.

TABLE 4-10. SAND-CAST MAGNESIUM ALLOYS

Materials Available	Applications	Remarks
B80-65* Magnesium alloy.	When heat-treated, is used for moderately stressed structural castings of intricate design and for which light weight is first requirement. Aircraft engine accessory cases and landing wheels. Suitable for permanent mold castings.	Requires careful heat treatment. Good foundry characteristics. Poor abrasion resistance. Do not use at elevated temperatures. Suitable for pressure-tight castings. Do not arc- or gas-weld. Highest strength in T6 (heat-treated) condition. Excellent machinability. Good corrosion resistance.
B107-65* Magnesium alloy.	For moderately stressed, lightweight structural parts requiring good shock resistance and complicated parts that may have a tendency to warp during heat treatment. Aircraft structural supports, brackets, engine castings, and portable tool housings.	Highest strength when not heat-treated. Do not use if pressure tightness is required since it is subject to porosity. Poor abrasion resistance. Do not use at elevated temperatures. Do not arc- or gas-weld. Good corrosion resistance. Excellent machinability.

* UNS numbers have not been assigned to all materials.

TABLE 4-11. DIE-CASTING ALLOYS

Materials Available	Applications	Remarks
G30400, 30500,30700 Aluminum alloy (Alcoa 43, 13, 85)*.	Aluminum die-casting materials have good casting characteristics. Impact strength is inferior to zinc alloys. Aluminum alloys can be used at higher temperatures than zinc alloys. Used in household equipment, automobile parts and housings, junction boxes, and covers.	General purpose material. For parts where strength is unimportant, use G30400 and G30500. G30500 has high corrosion resistance and is suitable for large and intricate castings. G30700 has slightly better physical properties, Alcoa 218* is used where higher strength, corrosion resistance, and ductility are desired.
B80-76 Magnesium alloy.	Aircraft engine openings, covers, housings, brackets and instrument parts; and electrical conduit fittings, fans, and textile machinery parts.	Used where light weight is prime requirement. Excellent machinability. For intricate castings, substitute AM 230*.
C27000 Yellow brass.	The brasses have the highest physical properties of all the commonly die-cast materials. They have the worst casting characteristics. Die cost is high due to high melting point. Applied where weight is not a factor and where strength and rigidity are of first importance.	Yellow brass has good strength and ductility. For better castability, higher strength but lower ductility, use silicon brass. Yellow brass has best machinability.
SAE 921*, 903*, 923*.	Zinc-base die-casting materials generally have best castability. Physical properties are inferior to brass but superior to most other alloys. Low die cost. Not recommended for use in contact with steam or water unless properly protected. Housings for small machines; and handles, gears, cams, carburetor parts and locks.	SAE 921 has highest hardness; 903 has best dimensional stability and retains impact strength with age. SAE 921 and 923 have best corrosion resistance. 923 has best combination of strength, impact resistance, and dimensional stability.

* UNS numbers have not been assigned to all materials.

4-1.1.2.3 Yield Point

The higher the yield point, the more difficult it is to draw and form the material.

4-1.1.2.4 Yield Strength

For producibility, lower yield strengths are more desirable especially for drawing operations.

4-1.1.2.5 Modulus of Elasticity

The higher the modulus of elasticity, the more difficult it is to bend the material into a precise shape because of its tendency to spring back to original form.

4-1.1.2.6 Elongation

In general, materials with higher elongation will draw and form better.

4-1.1.2.7 Ductility

Usually considered in spinning, wire drawing, and extrusions. The higher the ductility, the better the flowability of the material. The environmental temperature of the material strongly affects ductility.

4-1.1.2.8 Malleability

Usually important in forging, cold heading, and thread rolling.

4-1.1.2.9 Hardness

In general, the harder the metal, the more difficult it is to machine. Exceptions to this are the gummy materials, such as some leads and soft coppers, which are very difficult to machine but easy to form.

4-1.1.2.10 Damping Capacity

A poor damping material may fail in fatigue. The avoidance of stress concentration points may increase the cost of the part because of the necessity for special operations, such as hand removal of tool marks.

4-1.1.2.11 Strength-to-Weight Ratio (STWR)

Generally higher strength-to-weight ratio (STWR) is a desirable feature in materials for military applications. Very high STWR as found in titanium and beryllium may be associated with high production costs, High STWR as found in glass-filled epoxy resins can be achieved with reduced production costs.

4-1.1.2.12 Notch Toughness

The higher the notch toughness, the less likely the material will crack during production.

4-1.1.2.13 Fatigue Properties

Under repeated stresses, well below the yield point, some materials will develop fatigue cracks and fail. Parts requiring repeated forming operations during production are susceptible to this factor.

4-1.1.2.14 Elevated Temperature Properties

Higher strength requirements at elevated temperatures increase producibility problems considerably. In general, heat resistant materials are the higher nickel alloys and the ceramics. These materials require slower machining speeds. reduce cutter life, and result in a higher scrap rate. However, new machining processes, such as electrical discharge machining and electrochemical machining, are helping to decrease these costs.

4-1.1.2.15 Lower Temperature Properties

High strength and lower temperature requirements in the middle low range (0 to — 40°C) pose few producibility problems. However, for metals used in the cryogenic range of 5 to 6 K, costs and producibility problems increase dramatically. Special vacuum degassing chambers, and welding and handling methods are required, Inspection costs are very high.

4-1.1.2.16 Corrosion Resistance

Corrosion resistant material generally costs more but poses fewer production problems. However, clad materials or special coatings could provide equivalent corrosion resistance at less cost. The designer should prevent surfaces having finishes of dissimilar metals from coming into contact with one another to avoid galvanic action (corrosion). Before using dissimilar metals in an assembly, the designer should check the table of galvanic couples in MIL-STD-171. Permissible couples represent a low galvanic effect.

4-1.1.2.17 Electromotive Potential

Care should be taken when specifying contacting materials having significantly different electromotive potential or galvanic effect. Insulating inert spacers may be required to separate the two materials. Use of inert spacers necessitates special handling and inspection procedures.

4-1.1.2.18 Electrical Properties (Resistance)

Care should be taken when specifying soft copper for good conductivity; it is very difficult to machine. Harder grades, considerably easier to machine, can be substituted and give approximately the same electrical performance. Higher resistance materials, such as the nickel-chromes, offer only a small increase in production difficulty.

4-1.1.2.19 Weldability

Welding of the copper and nickel alloys caused problems in the past, but new technologies, such as the laser beam and electron beam, are being used successfully in production. Aluminum sections as thick as 76 mm (3 in.) are being production welded.

4-1.1.2.20 Density

Designers frequently select a material for its density. However, when this is a critical factor, they should be aware of manufacturing processes that may alter this characteristic.

4-1.1.2.21 Specific Heat

The specific heat of a substance is the number of calories required to raise the temperature of 1 g of the substance 1 deg C. Since there is little variation in this property among metals, it would have little effect on producibility.

4-1.1.2.22 Coefficient of Thermal Expansion

Materials with a high thermal expansion can cause accuracy problems in machining because temperature changes cause expansion and shrinkage.

4-1.1.3 Cost Considerations

Initially, the design engineer is more interested in the properties of a material than he is in its cost. Since there is increasing interchangeability among materials, producers are promoting competition among ferrous metals and nonferrous metals. Each producer is defending his market and is seeking to enter the market of others. It is important to recognize that the decisions made by the designer regarding a material have a far--reaching effect; they contribute heavily to the ultimate end-item cost and can be a determining factor in the life cycle cost of the entire system.

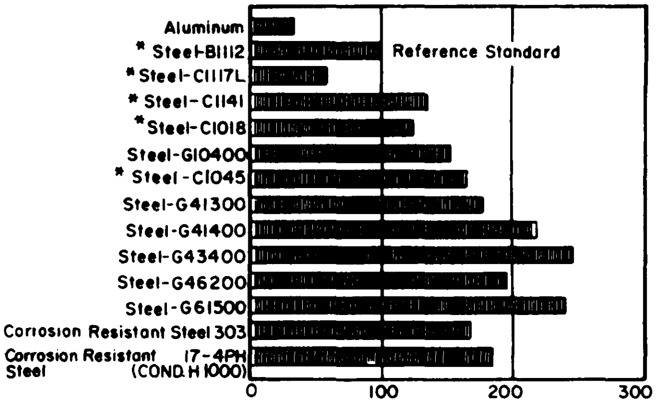
The selection of materials can affect cost in two ways—the cost of the raw material itself and the cost to manufacture with that material. Fig. 4-1 shows the relative cost of machining a part from various materials, and Fig. 4-2 shows the relative cost of the raw materials on a per unit weight basis.

4-1.1.4 Material Availability

Good producibility can be undermined by the poor availability of the resources necessary to produce the component; the raw material is one of those resources. A national shortage can make a material unavailable and stratcgically critical, or it may be locally unavailable in a particular shape, size, or form. Strategically critical materials are discussed in detail in Chapter 3.

4-1.1.4.1 Commercial Availability

Military equipment consumes a large volume of metals delivered to the hardware manufacturers. However, despite the wide requirements of the military user, it is the commercial market that determines the range and forms of alloys available. In addition, the available sizes have generally been set within each industry. Tablc 4-12 lists commercially available metallic alloys, their UNS numbers, availability, workability, formability, reducibility, and joinability.



* UNS numbers not assigned to all materials

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Figure 4-1. Relative Production Cost of Machined Parts (Ref. 5)

Since the capabilities of industry and individual suppliers vary, information on specific alloy grades and sizes should be obtained directly from potential suppliers.

4-1.1.4.2 Military Requirements

In certain instances the required materials are not commercially available. Therefore, in these instances it is necessary to place special orders for the required material. Since quantities are often small, special attention is necessary to assure that the material is available before ordering.

4-1.1.5 Material-Related Manufacturing Processes

Each time the design engineer specifies a material to be used, he knowingly or unknowingly specifies a manufacturing process. For example, some materials, such as 356 aluminum, are available only as castings. Therefore, whenever 356 aluminum is specified, the manufacturing process is specifically defined. Consequently, the material selection has a direct impact on the end product in terms of draft angles, radii, tolerances, and even the general shapes and configurations available from the implied manufacturing process. The design engineer must always consider the manufacturing process options available to him as a result of his material selection and the impact this process will have on potential production quantities. Production processes are most efficient with production-oriented materials. For example, a small quantity of steel parts could probably be machined efficiently from G10300. Yet, that same part in large quantities would gain significantly greater efficiency if made from a high lead content, free-machining steel.

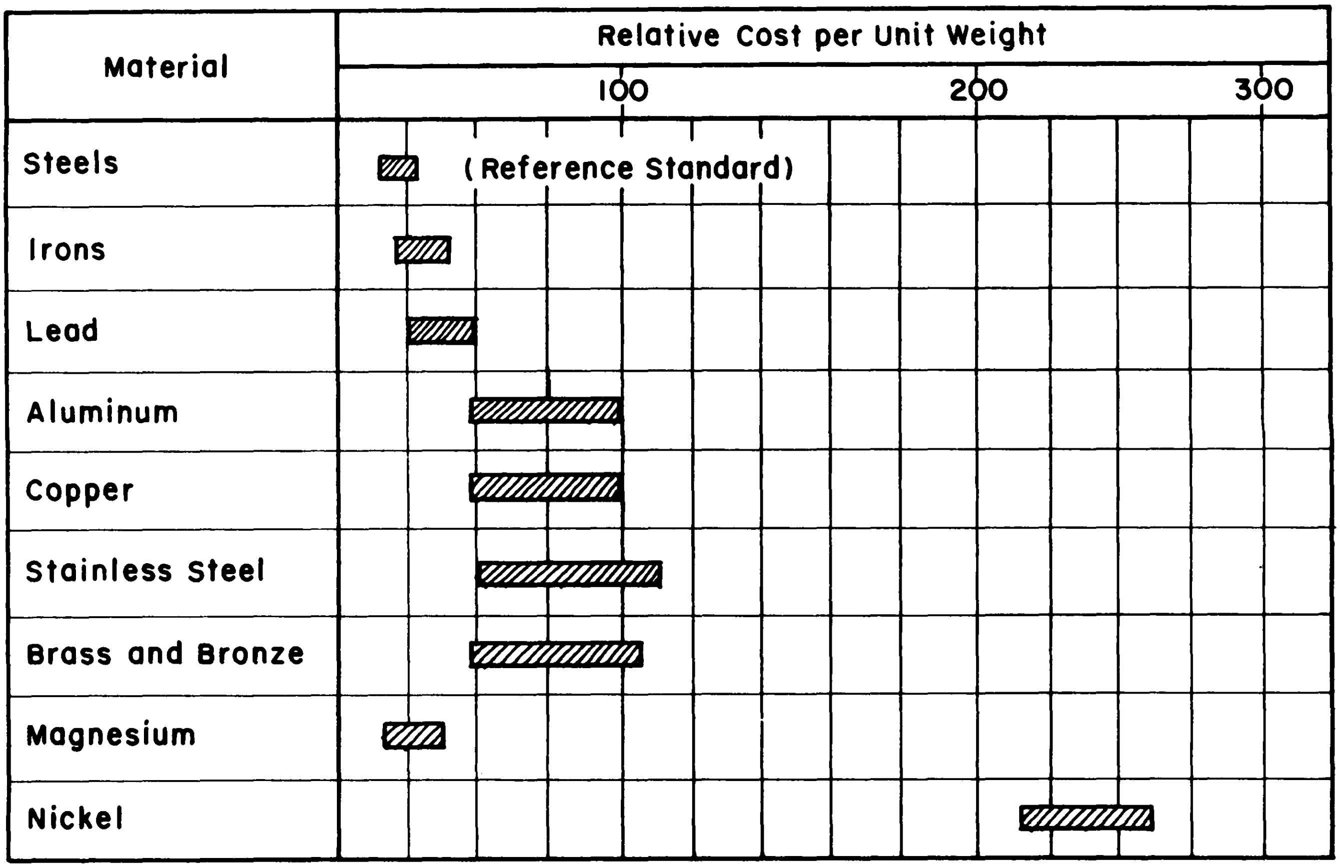

Figure 4-2. Relative Cost of Raw Material

It is obvious that the design engineer's job in material selection, initially thought of as just satisfying the performance characteristics, has changed significantly. Table 4-12 addresses some general material categories and their related suitability for various manufacturing processes.

4-1.2 MANUFACTURING PROCESS CONSIDERATIONS

The dictionary quite simply describes manufacturing as the making of goods or articles by hand or by machinery. For the layman that is probably adequate. However, for the design engineer with a concern for producibility, a better understanding is required.

Metal component manufacturing processes can be defined as those processes that transform raw materials into finished products or component hardware. This transformation is accomplished by a wide variety of processes. These are categorized as four types of primary manufacturing processes (forming, reduction or machining, fabrication or joining, and finishing), each of which has a subset of secondary manufacturing processes.

4-1.2.1 Primary Manufacturing Processes

4-1.2.1.1 Forming

Those processes that transform raw material through deformation or deposition of material into a desired shape or configuration are referred to as forming. These generally include rolling or bending, drawing, forging, and casting.

4-1.2.1.2 Reduction

Those processes that transform raw material into desired shapes or configurations through the removal of material by cutting, abrading, and grinding are referred to as reduction.

4-1.2.1.3 Fabrication or Joining

Those processes that join similar or dissimilar materials to create new components and achieve desired

Text commences on p. 4-26.

TABLE 4-12. METALLIC ALLOYS AND THEIR CHARACTERISTICS

Metal		Availability								Workability		Formability										Reducibility			Joinability								
Common Name and Identification Number	UNS Number	Strips	Sheets	Plates	Bar/Rod	Wire	Tube	Pipe	Shapes	Cold-Working	Hot-Working	Drawing	Forging	Casting	Extruding	Bending	Heading-Upsetting	Spinning	Thread-Rolling	Squeezing-Swaging	Metallizing	Shearing	Chemical Machining	Machinability Rating	Soldering	Brazing	Oxyacetylene Weld	Carbon-Arc Weld	Gas Shielded Arc Weld	Coated Metal Arc Weld	Spot Weld	Seam Weld	Butt Weld
Copper and Copper Alloys																																	
Oxygen free copper	C10200				X	X	X	X	X	E	E	X	X		X	X	X	X	X	X		X	X		E	E	F	F	G	N	N	N	G
Tough pitch copper	C11000				X	X	X	X	X	E	E	X	X		X	X	X	X	X	X		X	X		E	E	N	F	F	N	N	N	G
Phosphorus deoxidized	C12200				X		X	X	X	E	E	X	X		X	X	X	X	X	X		X	X		E	E	G	G	E	N	N	N	G
Sulfur Cu 147	C14700				X																												
Zirconium Cu 150	C15000				X	X																											
Beryllium Cu 172	C17200				X	X	X	X	X					X	X																		
Chromium Cu 182	C18200				X	X			X				X	X	X																		
Guilding 210	C21000	X				X				E	G	X				X		X		X		X	X		E	E	G	F	G	N	N	N	G
220 Commercial bronze	C22000	X	X	X	X	X				E	G	X	X	X		X	X	X	X	X		X	X		E	E	G	F	G	N	N	N	G
226 Jewelry bronze	C22600	X				X				E	G	X		X		X	X	X	X	X		X	X		E	E	G	F	G	N	F	N	G
230 Red brass	C23000	X	X			X	X	X		E	G	X		X		X	X	X	X	X		X	X		E	E	G	F	G	N	F	N	G
240 Low brass	C24000	X				X				E	F	X		X		X	X	X	X	X		X	X		E	E	G	F	G	N	F	N	G
260 Cartridge brass	C26000	X	X			X	X			E	F	X				X	X	X		X		X	X		E	E	G	F	F	N	G	N	G
268 Yellow brass	C26800	X	X	X	X	X				E	P	X		X		X	X	X	X	X		X	X		E	E	G	F	F	N	G	N	G
270 Yellow brass	C27000	X	X	X	X	X				E	P	X		X		X	X	X	X	X		X	X		E	E	G	F	F	N	G	N	G
280 Muntz metal	C28000	X	X	X	X		X			F	E			X		X	X					X		40	E	E	G	F	F	N	G	N	G
314 Leaded commercial bronze	C31400				X				X	G	P			X	X									80	E	G	N	N	N	N	N	N	F
330 Low leaded brass tube	C33000						X			E	P			X		X						X		60	E	G	F	F	F	N	F	N	F
332 High leaded brass tube	C33200						X			F	P			X								X		80	E	G	N	N	N	N	N	N	F
335 Low leaded brass	C33500	X		X	X					G	P	X		X								X		60	E	G	F	F	F	N	F	N	F
340 Medium leaded brass	C34000	X		X	X					G	P			X		X			X			X		70	E	G	N	N	N	N	N	N	F
342 High leaded brass	C34200	X			X				X	F	P			X	X				X			X		90	E	G	N	N	N	N	N	N	F
353 High leaded brass	C35300	X			X				X	F	P			X	X				X			X		90	E	G	N	N	N	N	N	N	F
356 Extra high leaded brass	C35600	X			X					P	F			X								X		100	E	G	N	N	N	N	N	N	F
'50 Free cutting leaded brass	C36000				X				X	P	F			X	X				X					100	E	G	N	N	N	N	N	N	F

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P = poor; N = not recommended;

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TABLE 4-12. (cont'd)

Metal		Availability								Workability		Formability										Reducibility			Joinability								
Common Name and Identification Number	UNS Number	Strips	Sheets	Plates	Bar/Rod	Wire	Tube	Pipe	Shapes	Cold-Working	Hot-Working	Drawing	Forging	Casting	Extruding	Bending	Heading-Upsetting	Spinning	Thread-Rolling	Squeezing-Swaging	Metallizing	Shearing	Chemical Machining	Machinability Rating	Soldering	Brazing	Oxyacetylene Weld	Carbon-Arc Weld	Gas Shielded Arc Weld	Coated Metal Arc Weld	Spot Weld	Seam Weld	Butt Weld
Copper and Copper Alloys (cont'd)																																	
365 Leaded Muntz metal	C36500			X										X																			
366 Leaded Muntz metal	C36600			X										X																			
367 Leaded Muntz metal	C36700			X										X																			
368 Leaded Muntz metal	C36800			X										X																			
370 Free cutting Muntz metal	C37000						X							X																			
377 Forging brass	C37700				X				X	P	F		X		X		X							80	E	G	N	N	N	N	N	N	F
385 Architectural bronze	C38500				X				X	P	E		X	X	X									90	E	G	N	N	N	N	N	N	F
442 Inhibited admiralty	C44200			X		X	X			E	F		X		X									30	E	E	G	F	F	N	G	N	G
443 Inhibited admiralty	C44300			X		X	X			E	F			X		X								30	E	E	G	F	F	N	G	N	G
444 Inhibited admiralty	C44400			X		X	X			E	F			X		X								30	E	E	G	F	F	N	G	N	G
445 Inhibited admiralty	C44500			X		X	X			E	F			X		X								30	E	E	G	F	F	N	G	N	G
464 Naval	C46400	X		X	X		X		X	F	E	X	X	X	X	X	X					X		30	E	E	G	F	F	N	G	F	G
465 Naval	C46500	X		X	X		X		X	F	E	X	X	X	X	X	X					X		30	E	E	G	F	F	N	G	F	G
466 Naval	C46600	X		X	X		X		X	F	E	X	X	X	X	X	X					X		30	E	E	G	F	F	N	G	F	G
467 Naval	C46700	X		X	X		X		X	F	E	X	X	X	X	X	X					X		30	E	E	G	F	F	N	G	F	G
485 Leaded naval brass	C48500				X				X	P	G			X	X									70	E	G	N	N	N	N	N	N	F
502 Phosphor bronze E	C50200	X				X				E	G		X							X		X			E	E	F	G	G	F	N	N	E
510 Phosphor bronze A	C51000	X			X	X	X		X	E	P	X			X	X	X		X			X			E	E	F	G	G	F	G	F	E
521 Phosphor bronze C	C52100	X			X	X			X	G	P	X			X	X						X			E	E	F	G	G	F	G	F	E
524 Phosphor bronze D	C52400	X			X	X			X	G	P					X						X			E	E	F	G	G	F	G	F	E
544 Phosphor bronze, free cutting	C54400	X			X				X	G		X				X						X		80	E	G	N	N	N	N	N	N	F
614 Aluminum bronze D	C61400		X	X	X					G	G	X				X						X			N	F	N	G		G	G	G	G
647 Precip. hard. bronze	C64700	Only forgings available											X																				
651 Low silicon bronze	C65100	X	X	X	X	X	X		X	E	E		X	X	X	X	X		X	X					E	F	G	G	E	F	E	G	E
655 High silicon bronze	C65500	X	X	X	X	X	X	X	X	E	E	X	X	X	X	X	X		X	X					G	E	G	G	E	F	E	E	E

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Copper and Copper Alloys (cont'd)																																	
675 Manganese bronze A	C67500				X				X	P	E		X	X	X										E	E	G	F	F	N	G	F	G
687 Alumium brass	C68700						X			E	F			X		X									E	G	F	F	F	N	G	F	G
706 Cupro-nickel	C70600	X		X	X	X				G	G					X									E	E	F	N	E	G	G	F	E
710 Cupro-nickel	C71000	X		X	X	X										X																	
715 Cupro-nickel	C71500	X		X	X	X	X			G	G		X			X									E	E	G	N	E	E	E	E	E
745 (65-10)	C74500	X	X		X	X			X	E	P	X	X		X	X	X		X	X		X	X		E	E	G	N	F	N	G	F	G
752 (65-18)	C75200	X	X		X	X			X	E	P	X	X		X	X	X		X	X		X	X		E	E	G	N	F	N	G	F	G
754 (65-15)	C75400	X	X		X	X			X	E	P	X	X		X	X	X		X	X		X	X		E	E	G	N	F	N	G	F	G
757 (65-12)	C75700	X	X		X	X			X	E	P	X	X		X	X	X		X	X		X	X		E	E	G	N	F	N	G	F	G
770 (55-18)	C77000	X	X		X	X			X	G	P		X		X	X						X			E	E	G	N	F	N	G	F	G
Carbon Steels—Hardening Grades																																	
C1030	G10300	X	X	X	X	X	X	X	X	E	E		G		G	G	G	G	G	G	G	E	E		G	G	G	G	G	G	G	G	G
C1040	G10400	X	X	X	X	X	X	X	X	E	E		G		G	G	G	G	G	G	G	E	E		G	G	G	G	G	G	G	G	G
C1060	G10600				X			X		G	G		G		G	G	G	G	G	G	G	G	G		F	F	F	F	F	F	F	F	F
C1080	G10800				X			X		F	G		G			X						X		44	P	P	P	P	P	P	P	P	P
C1095	G10950				X			X		F	G		G			X						X		43	P	P	P	P	P	P	P	P	P
C1137	N/A				X	X	X	X		F	G		F			X	X					X		75	P	P	P	P	P	P	P	P	P
C1141	N/A				X					F	E		F			X								95	P	P	P	P	P	P	P	P	P
C1144	N/A				X					F	G		F			X								74	P	P	P	P	P	P	P	P	P
Carbon Steels—Carburizing Grades		X	X	X	X	X	X	X	X	G	G																						
Carbon Steels—Free-Cutting		X								P		N	N	N	N	N	N	N	X	X	X		P	100	N	N	N	N	N	N	N	N	N
Carbon Steels—High-Strength Columbium Bearing		X	X	X	X	X	X	X	X																								
Carbon Steels—Vanadium		X																															

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Carbon Steels—High-Strength Low-Alloy (ASTM Types)	N/A		X	X	X				X	X	X	G	G	G	G	G	G	G	G	G	G	X	X	X	E	E	E	E	E	E	E	E	E
A94	N/A		X	X	X				X	X	X													X									
A242	N/A		X	X	X				X	X	X													X									
A440	N/A		X	X	X				X	X	X													X									
A441	N/A		X	X	X				X	X	X													X									
A374	N/A		X							X	X													X									
A375	N/A		X							X	X																						
Stainless Steels—Austenitic (AISI Type)																																	
303	S30300				X	X				G	F		F			X	X	X	X	X		X	X	75			P	P	P	P	P	P	P
304	S30400		X	X	X	X	X	X	X	E	E	X	X										X				X	X	X	X			
314	S31400		X	X	X	X		X	X	P	G					X			X			X	X	50			X	X	X	X	X	X	X
Stainless Steels—Martensitic																																	
403	S40300	X	X		X	X	X	X	X	P	G		X	X										40			F		F			X	X
410	S41000		X	X	X	X	X	X	X	F	G		X			X				X		X	X	54			X	X			X	X	X
Stainless Steels—Ferritic																																	
405	S40500		X	X	X	X		X		F	G	X	X	X		X		X				X		54				N		X	X	X	X
Stainless Steels—Age-Hardening																																	
Am350	S35000		X	X	X	X		X		G	E	X			X		X			X		X		40					G	G			
17-4 PH	S17400	X			X	X	X		X	P	E	X	X	X										40					F	P			
Alloy Steels—AISI Type																																	
1340	H13400	X			X					G	E		X	X																			
4063	N/A	X							X	P	G		X	X										55			P	P	P	P	P	P	P
4130	H41300	X	X	X	X	X	X	X	X	F	E		X	X			X		X			G	X	60			X	X			X	X	X
4040	H41400	X	X	X	X	X	X	X	X	P	E	X	E	X	X	X	X						X	62			X	X			X	X	X
4150	H41500	X	X	X	X	X	X	X	X	P	E	X	E	X			X							45			G	G	G	G	G	G	G

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Metal		Availability								Workability		Formability										Reducibility			Joinability								
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Alloy Steel—AISI Type (cont'd)																																	
4320	H43200	X	X	X	X	X	X	X	X	P	E		X	X			X			X				59			G	G	G	G	G	G	G
4340	H43400	X	X	X	X	X	X	X	X	P	E		X	X		X	X					X	X	55			G	G	G	G	G	G	G
4620	H46200	X	X	X	X	X	X	X	X	P	E		X	X		X	X					X	X	60			G	G	G	G	G	G	G
5140	H51400				X		X			P	E		X	X		X	X					X		60			G	G	G	G	G	G	G
6150	H61500	X	X	X	X	X	X	X	X	P	G		X	X		X	X			X		X		55			P	P	P	P	P	P	P
8620	H86200	X			X		X			P	G		X	X		X	X					X		63			G	G	G	G	G	G	G
8630	H86300	X			X		X			P	G		X	X		X	X							63			G	G	G	G	G	G	G
8640	H86400	X			X		X			P	G		X	X										64			G	G	G	G	G	G	G
8740	H87400	X			X		X			P	G		X	X		X	X			X				60			G	G	G	G	G	G	G
Alloy Steels—Ultrahigh Strength																																	
Scaife MX-2	N/A	X	X	X	X	X		X		G	G	E	X				X	X	X	X		X	X	62				X	X				X
Alloy 300M	N/A	X	X	X	X	X		X		P	E		X	X		X	X					X		45			X	X	X		X	X	X
Ladish D-6-A	N/A	X	X	X	X	X		X		F	G		X									X	X	50			X	X	X		X	X	X
Republic HP9-4-25	N/A	X	X	X	X			X		P	E	X	X			X	X					X							X				
Iron Base Alloys (Super)																																	
19-9DL		X	X	X	X	X	X	X		G	E		X			X				X		X		40	E	E	E	E	E	E	E	E	E
Unitemp 212	N/A	X	X		X	X		X		G	E					X						X											
W-545	N/A	X	X	X	X			X		G	E					X						X		25									
D-979	N09979	X	X		X					G	E					X						X											
AMS-5700	K66009	X			X					F	E																						
A-286	N/A	X	X		X	X	X	X		F	E		E			X	X					X		27									
V-57	N/A	X	X		X	X				F	E		E			X								25									
16-25-6	N/A	X	X		X					F	E		X											31									
Incolony 901	N/A	X								F	E		G											20									
Miltinet N-155	N/A		X	X	X		X			G	E		X	X										15	G	G	G	G	G	G	G	G	G

E = excellent; G = good; F = fair;
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(cont'd on next page)

TABLE 4-12. (cont'd)

Metal		Availability								Workability		Formability										Reducibility			Joinability								
Common Name and Identification Number	UNS Number	Strips	Sheets	Plates	Bar/Rod	Wire	Tube	Pipe	Shapes	Cold-Working	Hot-Working	Drawing	Forging	Casting	Extruding	Bending	Heading-Upsetting	Spinning	Thread-Rolling	Squeezing-Swaging	Metallizing	Shearing	Chemical Machining	Machinability Rating	Soldering	Brazing	Oxyacetylene Weld	Carbon-Arc Weld	Gas Shielded Arc Weld	Coated Metal Arc Weld	Spot Weld	Seam Weld	Butt Weld
Iron Base Alloys (Super) (cont'd)																																	
Refractaloy 26*	N/A							X		G	E		X											20									
S590	N/A			X						G	E		X											17	G	G	G	G	G	G	G	G	G
Titanium and Titanium Alloys																																	
Unalloyed**	N/A	X	X	X	X	X	X	X	X				X		X																		
5Al-2.5Sn**	N/A	X	X	X	X	X	X	X		F	G		X			X	X			X		X	X	F			G	G	G	G	G	G	G
5Al-5Sn-5Zn	N/A		X	X	X					G	F		X			X						X		F			G	G	G	G	G	G	G
8Al-1Mo-1V	N/A		X	X	X								X			X	X					X	X	F			G	G	G	G	G	G	G
7Al-4Mo	N/A				X			X		F	G		X			X	X						X		N	N	N	N	N	N	N	N	N
6Al-6V-25n**	N/A		X	X	X			X		G	F		X			X	X			X		X		F					X				
6Al-4V**	N/A	X	X	X	X	X	X	X		F	G		X			X	X			X		X	X				G	G	G	G	G	G	G
8 Mn	N/A	X	X	X						G	P				X	X	X			X			X	G						X			
13V-11Cr-3Al	N/A	X	X	X	X	X	X	X		G	G	X				X	X			X				F					X				
Magnesium and Magnesium Alloys																																	
B80-63	N/A	Foil billets	X	X	X	X			X			X	X	X	X	X	X	X	X	X		X	X	E			X	X	X	X	X	X	X
B90-65	N/A		X	X	X	X			X			X	X	X	X	X	X	X	X	X		X	X	E			X	X	X	X	X	X	X
Molybdenum and Molybdenum Alloys—TZM	N/A		X	X	X	X	X	Strip				X	X			X		X	X	X		X	X	E	X	X	X				X	X	X
Cobalt and Cobalt Alloys																																	
UMCO-50	N/A		X		X	X				E	E		X			X	X			X		Possible					G	G	G	G	G	G	G
Nivco	N/A	X	X	X	X	X				G	G													F									
S-816	N/A	X	X		X	X				P	G													P									
V-36	N/A	X	X		X	X				P	E	X	X			X	X			X				P			P	P	P	P	P	P	P
Haynes Alloy 25	N/A	X	X	X	X	X				E	E		X			X	X			X				F			X	X	X	X	X	X	X
Haynes Alloy L605	N/A	X	X	X	X	X				E	E	X	X			X	X	X	X	X		X		F			X	X	X	X	X	X	X
J1570	N/A	X	X		X					E	E	X																					

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N/A = not assigned

*Also springs.
**As clad sheets.

(cont'd on next page)

TABLE 4-12. (cont'd)

Metal		Availability								Workability		Formability										Reducibility			Joinability								
Common Name and Identification Number	UNS Number	Strips	Sheets	Plates	Bar/Rod	Wire	Tube	Pipe	Shapes	Cold-Working	Hot-Working	Drawing	Forging	Casting	Extruding	Bending	Heading-Upsetting	Spinning	Thread-Rolling	Squeezing-Swaging	Metallizing	Shearing	Chemical Machining	Machinability Rating	Soldering	Brazing	Oxyacetylene Weld	Carbon-Arc Weld	Gas Shielded Arc Weld	Coated Metal Arc Weld	Spot Weld	Seam Weld	Butt Weld
Aluminum Alloys																																	
EC (electric conductor)			X	X	X	X	X	X	X	E	E	X			X	X	X	X	X	X		X	X	G	E	E	E	E	E	E	E	E	E
1100*	A91100	X	X	X	X	X	X		X	E	E	X	X		X	X	X	X	X	X		X	X	G	E	E	E	E	E	E	E	E	E
1145*	A91145		X									X												G	E	E	E	E	E	E	E	E	E
1060	A91060		X	X			X			E	E	X				X	X	X	X	X		X	X	G	E	E	E	E	E	E	E	E	E
2011	A92011	X			X	X				E	E					X			X	X				E									
2014	A92014		X	X	X		X		X				X						X					E									
2017	A92017	X			X	X				E	E	X	X	X	X	X	X	X	X	X		X	X	G									
2018	A92018	Forging stock								G	G		X											E			P	P	P	P	P	P	P
2618**	A02618		X	X					X	G	G	X	X		X	X	X	X	X	X		E	E	E							X	X	X
2219	A92219		X	X					X			X	X	X	X	X	X	X				X	X	G					P		P	P	P
2024	A92024	X	X	X	X	X	X		X	G	N	X			X	X	X	X	X	X		X	X	G	N	N	N	N	N	N	N	N	N
3003*,**	A93003	X	X	X	X	X	X	X	X	E	E	X	X	X	X	X	X	X	X	X		X	X	G	E	E	E	E	E	E	E	E	E
3004	A93004		X	X			X	X		E	E	X				X	X	X	X	X		E	E	E			X	X					
4032	A94032	Forging stock											X											G			E		E				
5005	A95005	X	X	X	X	X			X	E		E				E						X	X	E	X	X				X	X		
5050	A95050		X	X	X	X	X			E		E				E	X		X	X		X	X	E	X	X				X	X		
5052*	A95052	X	X	X	X	X	X			E		E				X	X		X	X		X	X	E	X	X			R	X	X	X	X
5154	A95154		X	X	X	X	X		X	E	E	X	X		X	X		X	X	X		X	X	E			G	G	G	G	G	G	G
5454	A95454		X	X	X		X		X	E		X			X	X	X		X			X	X	E			G	G	G	G	G	G	G
5056	A95056	X			X	X				G	G	X				X	X					X	X	E			X	X	X				
5456	A95456		X	X	X		X		X	F	G	X			X	X	X		X			X	X	E				X	X	X			
5457	A95457		X							E	E	X				X		X				X	X	G			G	G	G	G	G	G	G
5083	A95083				X		X		X	F	G														X	X	X	X	X	X	X	X	X
5086	A95086				X		X		X	G	G	X		X	X							X	X	E			G	G	G	G	G	G	G
6151	A96151	Forging stock									E	X	X				X					X	X	E			X	X	X	X			

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*As foil also.
**As clad sheets.

(cont'd on next page)

TABLE 4-12. (cont'd)

Metal		Availability								Workability		Formability										Reducibility			Joinability								
Common Name and Identification Number	UNS Number	Strips	Sheets	Plates	Bar/Rod	Wire	Tube	Pipe	Shapes	Cold-Working	Hot-Working	Drawing	Forging	Casting	Extruding	Bending	Heading-Upsetting	Spinning	Thread-Rolling	Squeezing-Swaging	Metallizing	Shearing	Chemical Machining	Machinability Rating	Soldering	Brazing	Oxyacetylene Weld	Carbon-Arc Weld	Gas Shielded Arc Weld	Coated Metal Arc Weld	Spot Weld	Seam Weld	Butt Weld
Aluminum Alloys (cont'd)																																	
6053	A96053	X			X	X					E		X			X			X	X		X	X	E			X						X
6061	A96061	X	X	X	X	X	X			E		X	X		X	X	X	X	X	X		X	X	E			X	X	X	X	X	X	X
6063	A96063						X	X	X	E	F				X	X	X					X	X	E			X	X	X	X	X	X	X
6066	A96066				X		X		X	E	F	X	X		X		X		X			X	X	E			G	G	G	G	G	G	G
7001	A97001				X		X		X	E	E		X		X	X	X		X			X	X	E							X		
7075	A97075	X	X	X	X	X	X	X	X	E	E	X	X		X	X	X	X				X	X	E							X		
7178	A97178		X	X	X				X	G	G	X			X	X						X	X	E			X		X				
7079	A97079		X	X					X	E	G	X	X		X	X	X					X	X	E			X		X				
Nickel Alloys																																	
Nickel 200, 201	N02200																																
	N02201	X	X	X	X	X	X			F	E		X			X						X	X	F			X	X	X	X			
Duranickel 301		X		X	X	X		X		P	E		X			X	X			X				F			X	X	X	X			
Monel 4000	N04400	X	X	X	X		X		X	G	G		X			X	X							F			X	X			X	X	
Nickel Base Superalloys																																	
Inconel X-750	N07750	X	X	X	X	X	X				F		X			X				X		P	X	F							X	X	X
Hastelloy B	N10001	X	X	X	X	X	X			G	G		X	X		X	X					X		F	X	X	X	X	X	X	X	X	X
Hastelloy X	N06002		X	X	X	X				X				X		X	X					X		F									
Inconel/18	N07718			X		X										X						X	X	F						X			
Udimet 500	N07500	X	X	X	X				X	P	P		X											P			X	X					
Unitemp—Waspalloy	N07001				X			X	X		X		X										X	P			X	X					
Nicrotung		3-in. diameter melting stock								G	N	N	N	X	P	P	P	P	P	P	P			P									
Rene 41, R-41	N07041	X	X	X	X	X					X		X			X				X			X	F					X		X		
Unitemp 1753 M-252			X		X	X		X			X		X			X						P	P	P			F	F	F	F	F	F	F
IN-100	N06100													X																			

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TABLE 4-12. (cont'd)

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Low Expansion Nickel Alloys																																	
Ni36, Ni42, Ni4-50		X	X	X	X	X	X						X																				
Ni-span C-902	N09902	X			X	X																		P									
Precious Metals																																	
Gold	N/A		X		X	X	X	X	X					X									X		X	X	X				X	X	X
Silver	N/A	X	X		X	X	X		X	E		X	X	X	X	X	X			X	X	X	X		X	X	X				X	X	X
Platinum	N/A		X			X	X	X	X	G	P			X								X	X		X	X	X				X	X	X
Palladium	N/A		X			X	X	X	X	G	P	X		X		X	X	X				X			X		X				X	X	X
Rhodium	N/A		X			X			X												X	X											
Ruthenium	N/A	X			X				X	P	P		X			X					X												
Osmium	N/A									N	N			X																			
Iridium	N/A		X		X	X	X		X	G	G		X	X		X	X					X											
Exotic Metals																																	
Tantalum	N/A		X		X	X	X		X	G	P	X											X	F			X	X					
Tungsten	N/A		X	X	X	X	X	X	X	P	G												X	P			X			X	X	X	X
Mo-0.05 Ti	N/A		X	X	X		X	X		G	G		X			X								G			X			X	X	X	X
TZM (0.05Ti,0.01 Zr)	N/A		X	X	X		X	X		G	G		X			X	X							G			X			X	X	X	X
Tantalum 10-W	N/A		X		X					G	F																						
AVC-N-25Re	N/A	X		X		X	X	X																									
222 (10.5 W, 2.3 Hf, 0.01 C)	N/A				X			X																									
Tin and Tin Alloys																																	
Grade A tin	N/A		X					X	X	X		X		X		X		X							X								
Hard tin	N/A						X	X		X		X				X									X								
White metal	N/A		X							X		X		X		X		X							X								
Pewter	N/A		X							X		X		X		X		X							X								
1 (CY 44 A) 2,3	N/A	X			X	X								X																			

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(cont'd on next page)

TABLE 4-12. (cont'd)

Metal		Availability								Workability		Formability										Reducibility			Joinability								
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Tin and Tin Alloys (cont'd)																																	
YC 135 A	N/A					X								X																			
PY 1815 A	N/A					X								X																			
Tin-Lead-Antimony Alloys (cast)																																	
8,8 (YT 155A)	N/A				X	X																											
Y10A, 13, 15	N/A				X	X																											

E = excellent; G = good; F = fair; P = poor; N = not recommended; X = available or applicable but not rated; N/A = not assigned shapes, properties, and configurations are referred to as fabrication or joining. These generally include welding, soldering, bonding, riveting, and various mechanical connectors.

4-1.2.1.4 Finishing

Those processes that prepare the surface of a product for subsequent final surface treatment by precleaning and texturing and those processes that provide final surface treatment of the product are referred to as finishing. Finishing examples include chemical etching, plating, and cleaning. They might also include grinding, abrading, and polishing processes when these processes are used to provide a desired finish not a part of a reduction process.

4-1.2.2 Secondary Manufacturing Processes

The primary manufacturing processes describe in generic form the various methods by which raw metal is transformed into finished metal components. Each of these in turn has a subset of specific manufacturing processes known as secondary processes, which actually accomplish the metal transformation described in the primary processes.

4-1.2.2.1 Traditional Secondary Manufacturing Processes

Each of the secondary manufacturing processes and its relationship to the primary processes is shown in Table 4-13. Some of the processes are designed specifically for mass production runs, and some are ideally suited for short runs of small lot sizes. Consequently, the material and the process selections must bean iterative process if good producibility is to be realized. Table 4-14 shows the relative cost of some secondary processes, the unique factors contributing to cost differences, and most importantly, the optimum lot sizes for each process.

4-1.2.2.2 Nontraditional Secondary Manufacturing Processes

The secondary processes shown in Table 4-13 are well-established, traditional processes for transforming metal into a component. The designation “nontraditional processes” is applied to processes that are emerging or that have not been used extensively. These processes are sometimes labeled nonconventional. The terminology has a high degree of personal bias, depending on the experience of the individual and is

TABLE 4-13. MANUFACTURING PROCESSES

Primary Manufacturing Processes			
Forming	Reduction	Joining	Finishing
Traditional Secondary Manufacturing Processes			
Ausforming	Boring	Bonding	Carburizing
Casting	Broaching	Brazing	Silk screening
Cold-heading	Chemical milling	Soldering	Cleaning
Hot-heading	Chemical blanking	Cold welding	Surface blasting
Cold-roll forming	Drilling	Welding	Shot peening
High-energy forming	Electrochemical	Mechanical fastening	Deburring
Rubber pad forming	Electrical discharge		Heat treating
Marform forming	Electron beam		Knurling
Stretch forming	Flame cutting		Painting
Stretch draw	Grinding		Parkerizing
Deed draw	Hobbing		Electroplating
Electroform	Milling		Tumbling
Explosive form	Reaming		Brushing
Extruding	Shaping		Honing
Forging	Nibbling		Burnishing
Spinning	Piercing		Lapping
Hydroforming	Notching		Buffing
Metallizing	Slitting		Hydrohoning
Roll forming	Shearing		
Seaming	Punching		
Swaging	Tapping		
Thread rolling	Trepanning		
Thermoforming	Turning		
Tube bending			
Tube forming			
Wire drawing			

TABLE 4-14. MANUFACTURING PROCESS COST CONSIDERATIONS

Process	Raw Materials Costs	Typical Lot Sizes	Tooling Costs	Labor Costs	Finishing Costs
1. Sand casting	Low to medium	25 to 1000	Low	High—much hand labor required	High—cleaning, snagging, and machining required
2. Shell mold casting	Low to medium	25 to 10,000	Low to moderate	Relatively low	Low—often only a minimum
3. Permanent mold	Medium—nonferrous alloys used primarily	Large—best when requirements are in thousands, i.e., 1000 to 10,000	Medium	Moderate	Low to moderate
4. Plastics mold casting	Medium—nonferrous alloys only	High—10,000 or more	Medium to very high	High—skilled operators necessary	Low—little machining necessary
5. Investment casting	High—process suited to special costly alloys	Wide, although best for relatively small quantities, 100 to 1000	Low to moderate—depending upon whether a model is available	High—many hand operations required	Low—machining usually not necessary
6. Die casting	Medium	1000 minimum	High—more than for other casting processes—$300 to $5000 or more	Low to medium	Low—little more than trimming necessary
7. Drop forging	Low to moderate—steels up to high alloys	Large—10,000 or more best quantities, although less can be justified	High—great care needed in dies—cost from a few hundred to several thousand dollars	Medium—skilled labor needed for heater and hammer work	Medium—especially with ferrous metals due to scaling
8. Press forging	Low to moderate—equal to drop forgings	Medium to high production lots, 500 to 100,000	High—usually less than for drop forgings	Medium—less than drop forgings	Medium—same conditions as for drop forgings
9. Upset forging	Low to moderate—as with other forging processes	Medium to high production lots, 500 to 100,000	High—often because of number of impressions or difficult design	Medium—lowest of forging processes	Medium—often less than other forging processes
10. Cold headed parts	Low to moderate—chiefly steel wire	Large—not suited to small quantities, 10,000 minimum	Medium—up to a few hundred dollars	Low—almost completely automatic	Low
11. Extruded shapes	Moderate—primarily nonferrous metals, some alloy steels	Moderate—500-lb billet	Moderate	Moderate	Low

(cont'd on next page)

TABLE 4-14. (cont'd)

Process	Raw Materials Costs	Typical Lot Sizes	Tooling Costs	Labor Costs	Finishing Costs
12. Impact extruded parts	Moderate—primarily aluminum and other low cost, nonferrous metals	Wide range — 100 to 10,000	Medium—some dies less than $200	Low—skilled labor not needed	Low—often none
13. Roll formed shapes	Low to moderate—mostly low carbon steel sheet	High—should need 25,000 ft or more of one shape	High—several different rolls needed	Moderate	Low—cutting done automatically
14. Stamped and press formed parts	Low to moderate—ranging from carbon steel to stainless steel	Large—over 10,000 best, although new processes permit smaller quantities, 1000 minimum	High—$400 to $2000 for small parts, more for large	Medium—depending upon size and shape	Low—cleaning and trimming most frequent
15. Powder metallurgy	Medium to high—powders relatively expensive	Large lots best (10,000), but small runs might be necessary, 1000 minimum	Medium—from $150 to $2500	Moderate—some skilled labor needed	Low—machining seldom needed
16. Spinning	Low to moderate	Low—10 to 1000	Low—forms cost from $25 to $200 on ordinary work	High—skilled craftsmen needed	Low—restricted to cleaning and trimming
17. Screw machine parts	Low to medium—seldom used on high-strength alloys	Large—the larger, the better, over 1000	Medium—from $50 to $200 common	Low—one operator can handle several machines	Low—cleaning and deburring
18. Electroformed parts	Low to high—iron to silver	Small—best when few pieces are needed, 100 maximum	High—mold lasts indefinitely, but must be perfect	Medium to high—both skilled and unskilled labor needed	Low—no subsequent finishing
19. Sectioned tubing	High	Wide range—suitable for large or small quantities	Low—cutting done with simple tools	Low—skilled labor not needed	Low—generally
20. Welded, brazed, and bonded	Low to moderate	Small—although production brazing can handle large quantities	Low to moderate—simple jigs and fixtures	Medium to high—skilled labor needed	Medium—joints must be cleaned
21. Machining	Moderate—cutting away unwanted material makes high scrap rate	Small—1 to 50 where tooling cost cannot be justified	Low to moderate—simple jigs and fixtures	Medium to high—skilled labor needed	Medium—all parts hand finished

frequently limited to processes that have emerged since the early 1960's. A list of typical, nontraditional secondary manufacturing processes follows:

1. Electrical discharge machining
2. Hydrodynamic machining
3. Electrochemical deburring
4. Electrochemical discharge grinding
5. Electrochemical grinding
6. Electrical discharge sawing
7. Traveling wire electrical discharge machining
8. Laser beam machining
9. Laser beam torch
10. Chemical machining
11, Electrochemical machining
12 Numerical control machining
13 Computer numerical control/direct numerical control machining
14. Computer aided manufacturing
15. Plasma beam cutting
16. Rotary forging
17. Ultrasonic machining.

These processes are commercially available to a limited extent on a jobbing or service basis. However, new technology takes considerable time for acceptance, particularly among smaller job shops. Therefore, the designer should give consideration to the availability of these advanced processes. Subsequent paragraphs will discuss the more generic nontraditional secondary manufacturing processes. Others will be addressed under their appropriate chapters.

The nontraditional machining processes have relatively good application to all metals and alloys. This is in contrast to the traditional machining processes, which vary in their applicability because their capability to machine certain classes of alloys, e.g., the superalloys, is very low. Table 4-15 shows the material constraints of several of these nontraditional processes.

Fig. 4-3 illustrates the current status of the nontraditional processes with regard to the number of years they have been in research and development and in production, Brief descriptions of several nontraditional processes are given in the paragraphs that follow.

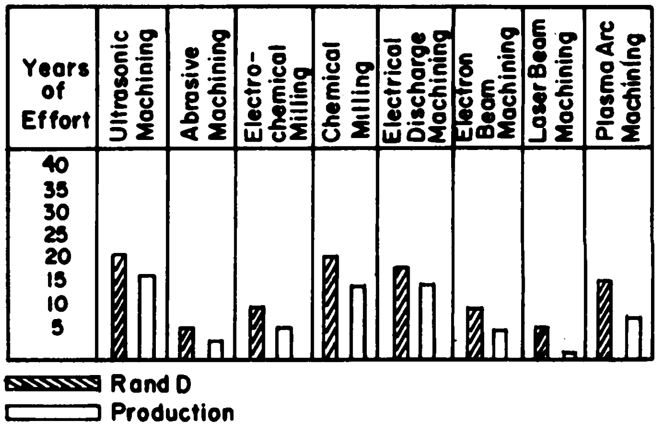

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Figure 4-3. Status of Nontraditional Machining Processes (as of mid-1970's) (Ref. 6)

TABLE 4-15. MATERIALS APPLICATIONS

Material	Ultrasonic Machining	Abrasive Jet Machining	Electro-chemical Deburring	Chemical Machining	Electrical Discharge Deburring	Electron Beam Machining	Laser Beam Machining	Plasma Arc Machining
Metals and Alloys								
Aluminum	P	F	F	G	F	F	F	G
Steel	F	F	G	G	G	F	F	G
Super alloys	P	G	G	F	G	F	F	G
Titanium	F	F	F	F	G	F	F	F
Refractories	G	G	F	P	G	G	P	P
Nonmetals								
Ceramic	G	G	N/A	P	N/A	G	G	N/A
Plastic	F	F	N/A	P	N/A	F	F	P
Glass	G	G	N/A	F	N/A	F	F	N/A

G = good
F = fair
P = poor
N\A = not applicable

4-1.2.2.2.1 Electrical Discharge Machining (EDM)

Electrical discharge machining (EDM), shown in Fig. 4-4, removes electrically conductive material with rapid, repetitive spark discharges from a pulsating dc power supply with a dielectric flowing between the workpiece and the tool. The shaped tool (electrode) is fed into the workpiece under servo control until a spark or discharge breaks down the dielectric fluid, the workpiece material is melted, partly vaporized, and expelled from the gap. Surface finish improves with increased frequency and reduced current. Material removal rate, surface roughness, and overcut all increase with a current increase or with a frequency decrease. Electrode materials frequently used are brass, copper, copper-tungsten, tungsten wire, and graphite. Erosion occurs on the tool as well as on the workpiece with tool-to-workpiece wear ratios ranging from 0.5:1 to 100:1 depending on spark waveshape from the power source, electrode material, and workpiece material.

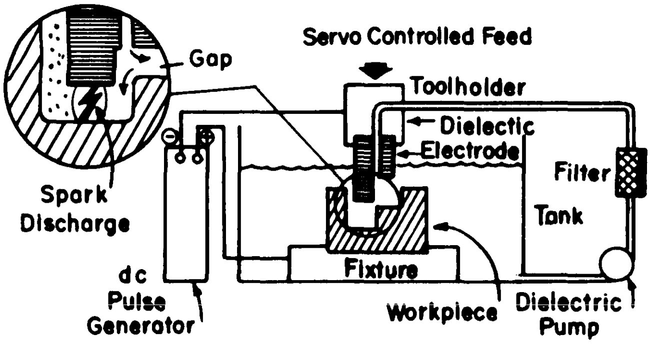

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Figure 4-4. Electrical Discharge Machining (Ref. 6)

EDM cuts any electrically conductive material regardless of its hardness, and it is particularly adapted for machining small, irregular slots or cavities. Because of the absence of physical contact, delicate structures can be cut successfully. Cutting is three-dimensional as the shaped electrode is fed into the workpiece. Because the sparks focus first on peaks and corners, burr-free cutting occurs. Multiple electrode, automatic dressing, automatic positioners, and numerical motion control all contribute to the versatility of EDM. Tool and die work is frequent, but mass production and even transfer line applications exist. Small and/or shaped holes at shallow angles to the workpiece surface are commonplace. A recast and heat-affected layer occurs on all materials cut with this process and should be removed or modified on critical or fatigue-sensitive surfaces.

4-1.2.2.2.2 Hydrodynamic Machining

Hydrodynamic machining, shown in Fig. 4-5, removes material by the impingement of a high-velocity fluid against the workpiece. The coherent jet of water—or water with a long-chain-polymer additive, such as polyethylene oxide—is propelled up to Mach 2 speeds. Direction and control of the 0.05- to 1.02-mm (0.002- to 0.040 -in.) diameter stream is through a sapphire nozzle. Standoff distance of the nozzle from the workpiece is important. Relatively small volumes of fluid are *used;* 3.8 to 7.6 min (1 to 2 gpm).

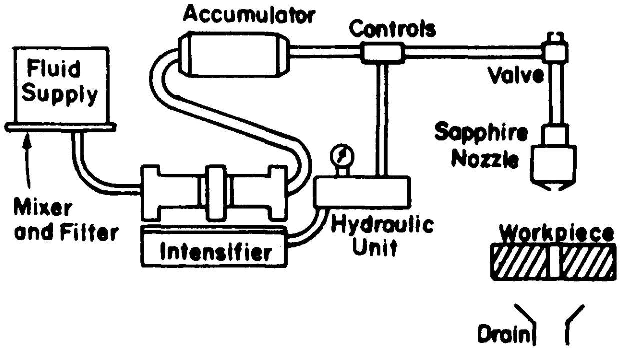

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Figure 4-5. Hydrodynamic Machining (Ref. 6)

The ability to cut soft nonmetallic materials in any position with a narrow kerf (except double-knit fabrics) leads to form-cutting applications. The absence of heat-affected zones allows the process to be used in the wood and paper products fields, such as cutting acoustic ceiling tile. Furniture forms of laminated paperboard, plywood, rubber, nylon, fiberglass, and fiberglass-reinforced plastics are also among the materials being cut.

4-1.2.2.2.3 . Electrochemical Deburring

Electrochemical deburring, shown in Fig. 4-6, was developed to remove burrs and fins or to round sharp corners. Almost any conducting metal can be deburred electrolytically. Most electrolytic deburring is done in seconds, whereas hand deburring would take minutes. Applications have included automotive connecting rods, gear teeth, blanking dies, valve ports, nozzle intersecting holes, and punch press blankings. Interior and hard to reach burrs or fins also can be removed with special, precise] y located electrodes.

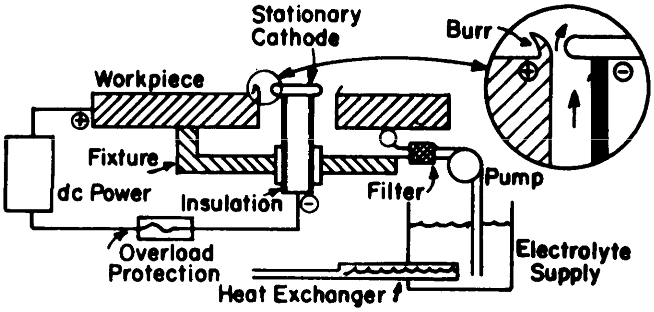

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Figure 4-6. Electrochemical Deburring (Ref. 6)

By controlled insulating of the cathode, effects on other exposed areas of the workpiece are reduced to negligible amounts. The highly focused action usually results in smooth finishes- better than 1.6 µm (63 µin.) and, with higher current densities, as smooth as 0.25 µm (10 µin.).

4-1.2.2.2.4 Electrochemical Discharge Grinding

Electrochemical discharge grinding, shown in Fig. 4-7, is a combination of two material removal processes, electrochemical and electrical discharge grinding with a slight modification of each. The principal material removal comes from an electrolytic action at low-level dc voltages; however, no physical contact occurs between the wheel and the workpiece. Electrical discharges from the graphite wheel are initiated from the higher ac voltage superimposed on the dc current. Sometimes a pulsating dc voltage is used.

Almost any electrical> conductive metal can be ground successful); dressing of carbide inserts is a good application. Plunger, surface, and form grinding are practical.

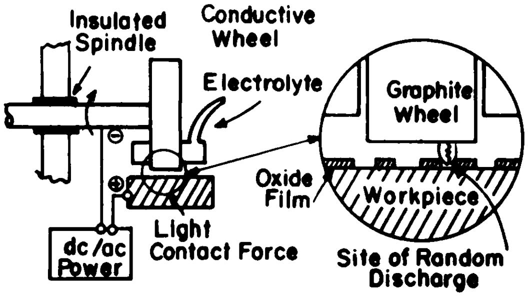

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Figure 4-7. Electrochemical Discharge Grinding (Ref. 6)

4-1.2.2.2.5 Electrochemical Grinding

Electrochemical grinding, shown in Fig. 4-8, is a special application of electrochemical machining in which the conductive workpiece material is dissolved by anodic action, and any resulting films are removed by a rotating, conductive, abrasive wheel.

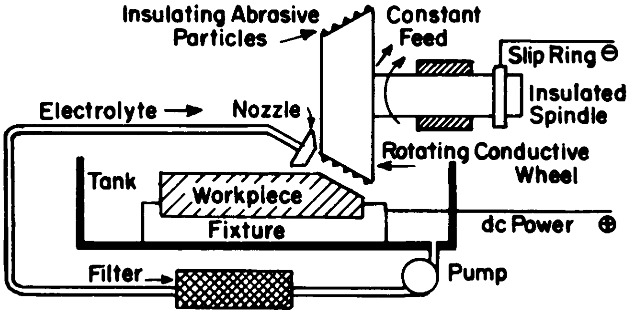

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Figure 4-8. Electrochemical Grinding (Ref. 6)

4-1.2.2.2.6 Electrical Discharge Sawing

As shown in Fig. 4-9, electrical discharge sawing is a variation of electrical discharge machining that combines the motion of the bandsaw with electrical erosion of the workpiece. The rapidly moving, 25 to 30 m/s (5000 to 6000 ft/min), 0.64-mm (0.025 -in.) thick special steel knife edge is guided into the workpiece by carbide-faced inserts. A 0.795-mm (0.0313-in.) kerf is formed, but no controlled gap is maintained between the saw blade and the workpiece as in EDM. No dielectric is used; therefore, there is continuous arcing from the low-voltage, high-current power source. Water flow quenches the arc and cools the workpiece. While the work is power fed into the cutting band, neither the band nor the work is subjected to major forces, so fixturing can be minimal. Precise adjustment of the feed rate must be made to be in exact balance, with the arc erosion rate.

Fragile cellular structures can be cut from aluminum, stainless steel, or titanium honeycomb. Thin-walled, heat exchanger tubular assemblies can be cut. No-burr cutting produces little or no rollover of edges on thin materials. Cuts up to 1015 mm (40 in.) have been made; however, only electrically conductive materials can be cut with electrical discharge sawing.

Cutting rates range from 2 to 85 mm/s (5 to 200 in. /rein). Flatness ranges from + 0.08 mm (0.003 in.)

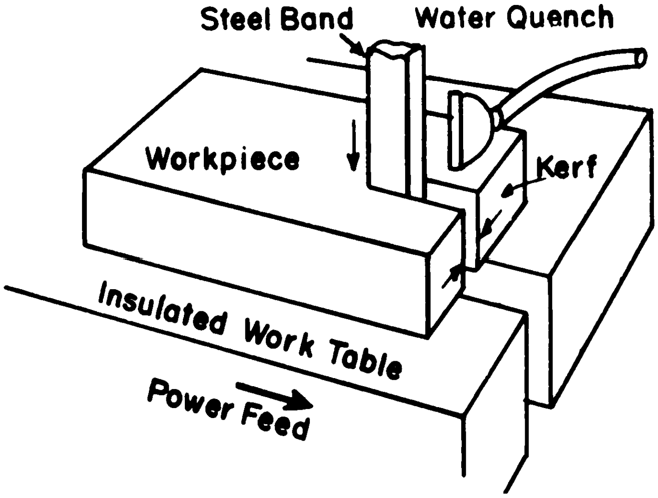

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Figure 4-9. Electrical Discharge Sawing (Ref. 6)

total indicator reading at the lower feed rates to ±0.41 mm (0.016 in.) total indicator reading at the maximum cutting rates. The finish is an electrically etched surface; however, the arcing leaves a recast, heat-affected zone below the surface.

Electrical discharge sawing machines are regularly available with throats up to 1210 mm (48 in.) deep for 660-mm (26-in.) workplaces.

4-1.2.2.2.7 Traveling Wire EDM

Electrical discharge wire cutting is a special form of EDM in which the electrode is a continuously moving conductive wire. It is often called traveling wire EDM and is shown in Fig. 4-10. The tensioned copper or brass wire of small diameter, 0.05 to 0.25 mm (0.002 to 0.010 in.), is guided to produce a straight, narrow-kerf cut. Usually, a programmed or numerically controlled motion guides the cutting while the width of kerf is maintained by the discharge controls. The wire is inexpensive enough to be used only once.

Extremely tight corners can be cut with almost no radius. Punches, dies, and stripper plates can be cut in any of the hardened conductive tool materials. Mirror-image profile work and internal contours from a starting hole are frequent, and stacking of sheets for multiple cutting is possible.

Cutting of 0.03- to 75-mm (0.001- to 3-in.) thick materials can be done. Thin parts can be cut at 1.7 mm/s (4 in./min). Positioning accuracy to ±0.005 mm (0.0002 in.) is normal in all metals.

Several manufacturers regularly build electrical discharge wire cutting equipment with numerical control, tracer controls, and all programming accessories. Equipment is also available with computer aided manufacturing or other mechanical programming for the wire motion as well as with standard EDM servo control for straight cutting.

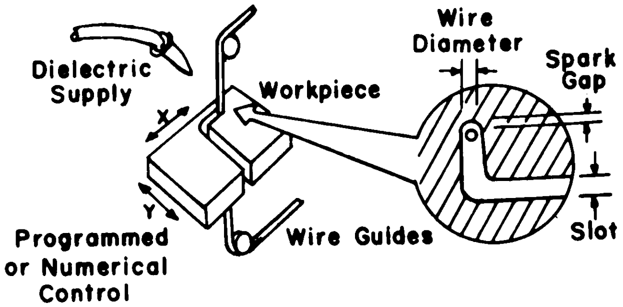

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Figure 4-10. Traveling Wire EDM (Ref. 6)

4-1.2.2.2.8 Laser Beam Machining

Laser beam machining, as shown in Fig. 4-11, removes material by melting and vaporizing the workpiece at the point of impingement of a highly focused beam of coherent monochromatic light. (Laser is an acronym for “light amplification by stimulated emission of radiation ”.)

Small, precision cuts or holes in thin materials can be produced. Scribing of ceramics can be done since there is no massive heat shock, mechanical contact, or large force between the tool and workpiece. This is not a mass material removal process; however, its operation in air at rapid, repetitive rates and its ease of electrical control commend it for mass micromachining production. Multiple pulses permit hole drilling up to 50:1 depth-to-diameter ratios, on 0.13-mm (0.005 -

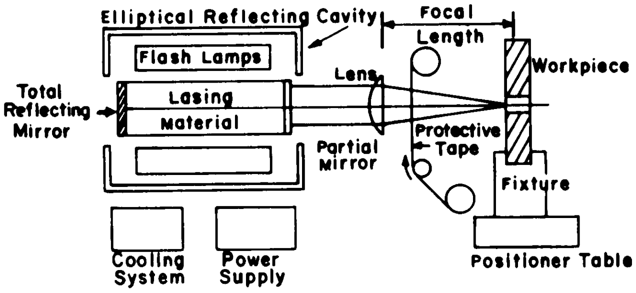

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Figure 4-11. Laser Beam Machining (Ref. 6) in.) diameter holes, which can be drilled through 2.54-mm (0.100 -in.) thick material. Shallow angles, 0.262 rad (15 deg), to the surface can be drilled. Other applications include engraving, resistor trimming, sheet metal trimming, and blanking. The same equipment can be used to weld, surface heat-treat, or to machine—all of which makes the laser a "universal" machine tool.

Several types of laser components or systems exist; however, very few are in practical use. The principal equipment concern is workpiece positioning and control. Integration of a numerical control (NC) table with focus beam intensity or standoff distance is common. Safety interlocked enclosures are commonly used. Bench-top equipment with a capacity of a few watts to computer controlled systems of a capacity of several kilowatts is commercially available.

4-1.2.2.2.9 Laser Beam Torch

Laser beam torch, illustrated in Fig. 4-12, is a material removal process that uses the simultaneous focusing of a laser beam and a gas stream on the workpiece. A continuous-beam laser is focused on or slightly below the surface of the workpiece, and the absorbed energy causes localized melting. The oxygen gas stream promotes the reaction as well as purging the molten material from the cut. Argon or nitrogen gas is used to purge the molten material and to protect the workpiece when organic or ceramic materials are being cut.

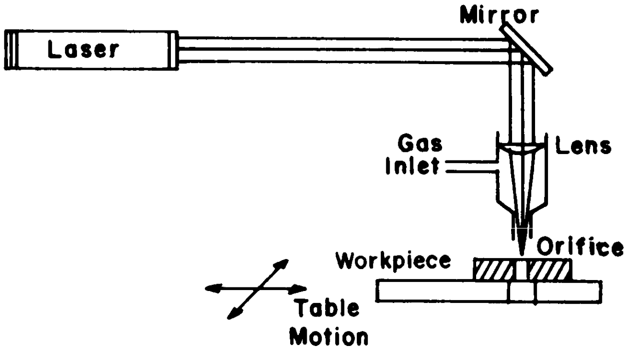

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Figure 4-12. Laser Beam Torch (Ref. 6)

4-1.2.2.2.10 Chemical Machining

Chemical machining, as shown in Fig. 4-13, is the controlled dissolution of workpiece material by contact with a strong chemical reagent. The thoroughly cleaned workpiece is covered with a strippable, chemically resistant mask. Areas on which chemical action is desired are outlined with the use of a template, and the mask is stripped from these areas. The workpiece is then submerged in the chemical reagent to remove material at an equal rate from all exposed areas. Next the workpiece is washed and rinsed, and the remaining mask is removed. Multiple parts can be machined simultaneously in the same tank.

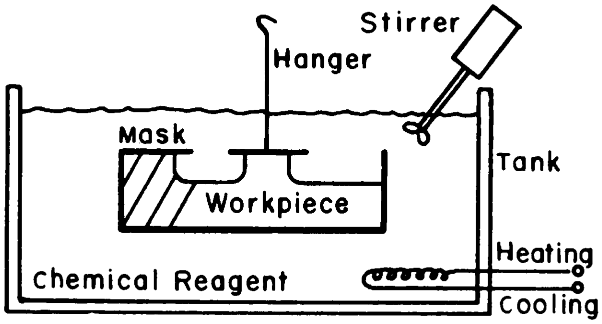

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Figure 4-13. Chemical Machining (Ref. 6)

Contour machining is accomplished by successively stripping masks and resubmerging the workpiece in the chemical bath. Etching of the workpiece proceeds radially from the opening in the mask, which results in an undercut as well as in a depth of cut. The ratio of distance etched beneath the mask to the distance etched into the workpiece (the etching factor) is typically 1:1, but it can be as high as 1:3. A controlled rate of immersion or withdrawal from the bath will produce tapered sections. The workpiece should preferably be oriented so that the grain is in the direction of the longest cut.

The chemicals are very corrosive and must be handled with adequate safety precautions; both vapors and effluents require suitable environmental handling.

Nearly all metals can be chemically machined; however, the depth of cut has a practical limit of 6 to 12 mm (0.25 to 0.5 in.). Large, shallow areas are especially suitable since removal is uniform and simultaneous. No burrs are produced, and no workpiece surface stresses are generated. Short-run, quick-change, low-cost tooling offers process flexibility. Thin sheets, formed sheets, and delicate cuts are particularly suitable with a maximum practical thickness for blanking of 1.59 mm (0.0626 in.). Sharp radii cannot be produced in the cutting direction.

4-1.2.2.2.11 Electrochemical Machining (ECM)

Electrochemical machining (ECM), as shown in Fig. 4-14, is the removal of electrically conductive material by anodic dissolution in a rapidly flowing electrolyte that separates the workpiece from a shaped electrode.

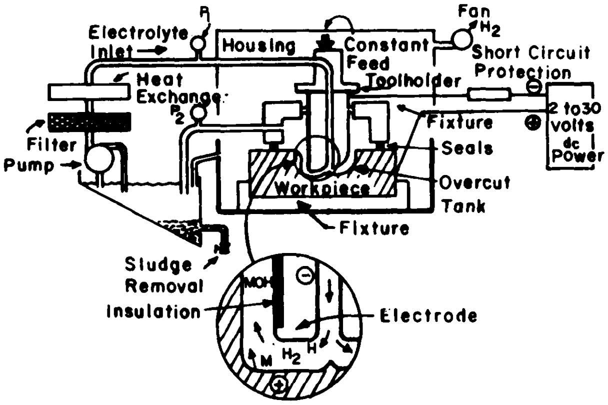

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Figure 4-14. Electrochemical Machining (Ref. 6)

The shape of the workpiece is nearly a negative image of the shape of the electrode that is advanced into the workpiece at a constant feed that exactly matches the rate of dissolution of the material.

To obtain tight tolerances, tool design must compensate for the variable current density that occurs with shape and electrolyte variations. Exact control of all critical parameters is needed for the best results. In "cutting", the metal ions are removed from the workpiece surface and hydrogen ions from the electrode.

ECM is best suited for mass production of complex shapes in difficult-to-machine materials. Small, odd-shaped and deep holes down to 3.18-mm (0. 125-in.) diameter can be "drilled" individually or multiply. The stress-free material removal eliminates distortion from machining but not necessarily from prior stress-inducing operations. The ability to cut simultaneously on the entire surface aids productivity. Tool design and development, except for the most simple shapes, are time-consuming and may require several "cut and try" cycles. Process control must be exact. Concentration of current density on edges of the workpiece provides automatic routing and absence of burrs. The workpiece must be thoroughly cleaned after electrochemical machining to prevent corrosion.

The material removal rate is independent of material hardness and is approximately 1639 mm^3 (0.1 $in.^3$) per minute per 100 A. Accuracy to ±0.05 mm (0.002 in.) is usual for cavities and to ±0.013 mm (0.0005 in.) for frontal cuts or for cuts made with highly refined tools. Internal radii of 0.18 mm (0.007 in.) and external radii of 0.05 mm (0.002 in.) are attainable. Deep cuts will have taper; 0.0254 mm (0.001 in.) per 25.4 mm (1 in.) is common with a 0.13-mm (0.005-in.) overcut gap. Surface finishes of 0.41 to 1.60 µm (16 to 63 µin.) are normal and improve with higher cutting rates. Mirror finishes in frontal cuts of nickel alloys are easily obtained. The side-gap areas are generally much rougher because of the lower current densities in these areas.

4-1.2.2.2.12 Numerical Control Machine (NCM)

Not a new technology, numerical control machines (NCM) were first introduced to the manufacturing world in the late 1950's; however, their adoption by the industry (less than 1.5% of the total US machine tool inventory) has been so slow it bears further discussion here. Additionally, there have been numerous misconceptions surrounding NCM technology from its inception.

The metal cutting technology is not new; it is the control technology applied to the traditional metal cutting techniques that is new. It has often been misconstrued as a mass production technique because of its automation orientation. NCM'S do not cut metal any faster than the traditional methods; they are constrained by basic mechanics and the cutting tool. However, NC does provide a degree of control never before possible for the cutting tool. This added control permits the tool to move much faster between cuts, but more importantly it permits the cutting tool to move to very precise locations (usually within 0.03 mm (0.001 in.)) while making a cut. Machinists operating a manual machine never plunge a cutting tool to within 0.13 mm (0.005 in.) of their finish cut and then make a final 0.13-mm (0.005 -in.) finish cut. Instead, they tend to creep up on their finish cut in numerous passes of the cutting tool and constantly check the part between cuts. It is not unusual to make 10 passes to reduce a 150-mm (6-in.) diameter bar to 142.88mm (5.625 in.) ±0.13mm (0.005 in.), whereas on NCM'S with positive control this could be done in two passes. The productivity advantage is obvious.

The significant contribution of NC to producibility is its capability to reproduce faithfully a dimension with a repeatability factor of less than ±0.013 mm (0.0005 in.). However, if quantity requirements are high enough, this can also be done on traditional production machines with very good hard tooling.

Understanding how NC works will help the designer to capitalize better on its advantages. In NC, the tooling is controlled by punched paper tape. This tape is generated by a part programmer. The part programmer translates the dimensions and configurations from a blueprint into a coded manuscript. This information is punched into an eight-channel tape to be read by the NC unit.

The NCM has an accuracy capability to within 0.03 mm (0.001 in.), but it should be borne in mind that this is the movement of a toolholder. The cutting tool is manually loaded into the holder. Obviously, very precise dimensions require very precise tool setting procedures. Here, as in other processes, tight tolerances cost more; therefore, the designer should specify only the level of tolerance required. However, if very tight tolerances are required, this is a very good process for producing them. Often this factor justifies using NC on a production run.

NC has been adapted to many different kinds of machines; a few of them are

1. Drills
2. Mills
3. Lathes
4. Machining centers
5. Inspection machines
6. Drafting machines
7. Flame burners
8. Punch presses
9. Sewing machines.

There are many others, and they are discussed in the appropriate paragraphs of this chapter. More recently some automated procedures, such as countercentrifugd chucks, robots, power feeds, and the adaptation of NC to traditional production machines (i.e., chuckers, turret lathes, etc.), have begun to bring NC into the production arena.

4-1.2.2.2.13 Computer Numerical Control (CNC) and Direct Numerical Control (DNC) Machines

These two techniques are merely extensions of NCM technology. NC was primarily a hard wired, special purpose logic unit; therefore, it was quite natural for it to evolve into a general purpose logic unit, computer numerical control (CNC). This general purpose unit can be used to perform independent calculations, store the results in memory formatted as NCM control data, and then transmit that data to the machine tool in the form of control commands—this eliminates the punched tape normally associated with NC. Concurrently, the logic device can accumulate operational data on the machine it controls. Direct numerical control (D NC) is a further extension of this concept and puts a number of machines under the control of a remote, general purpose computer. The remote computer provides data to the CNC unit where it is stored until needed to control machine motions. The CNC unit can provide the operational data on its machine to the remote computer for storage, accumulation, and management reporting on overall production progress.

4-1.2.2.2.14 Computer Aided Manufacturing (CAM)

This is a term that evolved from the use of computers in the control of NCM'S and even further back from the use of computers in the preparation of NC punched tapes. [Unfortunately, the connotation was so close that many began to think computer aided manufacturing (CAM) and NC were synonymous. However, the first people to successfully use and apply the computer outside of the formal automatic data processing environment were the NC users. They were, therefore, the initial developers of CAM. Some of these early developments using the computer to schedule and load the shops were picked up and used by shops without NCM. Some in fact were in technologies or processes where NC had never been used and probably never will be. Suffice it to say that NC is not a prerequisite for CAM use. NC helps defray some of the computer operating cost, but it is not a necessary prerequisite.

A rather simple definition of CAM is “the application of the computer in the manufacturing process”, Some of the more notable applications follow:

1. Production scheduling
2. Machine loading
3. Line balancing
4. Production line simulation
5. Computer aided estimating
6. Process planning
7. Facility planning.

For additional information on any of these applications, the reader should contact computer manufacturers, computer service bureaus, or software development firms. Ref. 7 is a very good book about this field.

The most recently developed application in this field is group technology, which is showing great promise as a new manufacturing concept. Group technology capitalizes on the benefits to be obtained from the similarities of individual components in a total manufacturing requirement. Simply stated, it is a systematic approach that organizes the individual components of all the manufacturing requirements into families of parts having homogeneous characteristics. Consequently, almost all the parts in a specific group require comparable manufacturing processes and tooling.

The heart of group technology is a coding and classification system. In lieu of calling a class of parts by its generic name (washer, nut, burster tube, etc.), the parts are individually assigned specific identification numbers. The individual digits or groups of digits in the identification number are coded to represent the specific characteristics of each individual part. These specific characteristics include

1. Geometric shape/configuration
2. Dimensional size limitations
3. Materials
4. Tolerances
5. Manufacturing processes
6. Tooling
7. Manufacturing cost
8. Production rate
9. Source of supply, etc.

A coding and classification system facilitates the introduction of a new part into manufacturing, and when a new part is introduced, it is coded with its own descriptive identification number. Thus a quick data base search reveals all similar parts previously stored in that family of parts. Inherently, these parts would have very similar (in many cases, identical) manufacturing operations and tooling. Consequently, all of the historical data reflected in the characteristics of the identification number are applicable to the new part being introduced.

Group technology is predicated on the premise that parts with the same or similar code numbers in the first series of digits will have similar manufacturing data. Obviously, the digits representing dimensional information, tolerance, and material may vary slightly without changing the manufacturing data. All coded parts with these digits falling within a prescribed range constitute a family or a group of parts that requires the same machines to produce it. These machines constitute a machining cell with its own specifically identified group of special tools. When the data base of coding and classification numbers is complete, it contains a complete set of data of manufacturing requirements. A simple interrogation routine can then provide cumu*lative* data on the total machine tool requirements for all of the manufacturing cells; new parts to be entered into the system can be coded, and impact analyses on the existing manufacturing base can be conducted. Future manufacturing needs, e.g., mobilization planning, require only a change in quantity for parts already in the system or the addition of new parts to the system to determine the precise capital equipment investments needed to support the mobilization requirements. Likewise, corroboration of planned producers' capabilities and capacities are just as easily identified.

In the not too distant future designers may well find themselves providing the coding and classification number along with their completed designs. They may also code and classify their designs before they are reduced to hard copy drawings. In this manner, designers could screen the data base for existing products that could serve their design needs, and they could forego the necessity of creating a whole new design. An excellent summary of group technology and coding and classification systems is available in Ref. 8.

4-1.2.2.2.15 Summary

In general, the comparative performance of some nontraditional machining processes is shown in Table 4-16.

4-1.2.2.3 Thermal Conditioning Processes

Thermal conditioning operations (or heat treating) change specific physical characteristics of the metal component. The affected characteristics include surface hardness, strength, and relief of residual stress—operations that are easily overlooked in the design stage and can be major contributors to producibility problems. Their impact on producibility is caused by the fact that in most cases they are the final operation performed on a metal component that is 95% complete. Recovery from failure at this point usually means scrapping a component that already represents a significant investment.

4-1.2.2.3.1 Heat Treating

Heat treatment is a process, which, through controlled heating and cooling, changes the properties of a metal. This handbook briefly considers some of the basic heat-treating principles and some of the properties that can be obtained by applying standard heat-treating procedures. Specific details on heat-treating processes are readily available in many good reference books, such as Refs. 9 and 10 and, therefore, are not repeated here.

Upon selecting a material for a specific part, the designer's first task is to insure that the material meets the intended service requirements. To do this, he must

TABLE 4-16. PERFORMANCE OF NONTRADITIONAL MACHINING PROCESSES

Process	Metal Removal Rate		Accuracy			
			Normal		Potential	
	m^3/s	(in^3\min)	± mm	(in.)	± mm	(in.)
Traditional turning	5.46×10^{-5}	(200)	0.13	(0.005)	0.03	(0.001)
Numerical control turning	5.46×10^{-5}	(200)	0.05	(0.002)	0.005	(0.0002)
Electrical discharge machining	1.4×10^{-6}	(5)	0.13	(0.005)	0.013	(0.0005)
Electrochemical machining	3×10^{-7}	(1)	0.13	(0.005)	0.013	(0.0005)
Laser beam machining	1.4×10^{-9}	(0.005)	0.13	(0.005)	0.013	(0.0005)
Plasma beam machining	2.7×10^{-6}	(lo)	2.54	(0.100)	0.3	(0.01)

first consider the composition, hardening qualities, and various external factors. Certain metallurgical characteristics will influence his decision. For example, it is necessary to temper martensitic steel to optimize its mechanical properties, which are relatively uniform over the full range of hardness. However, ductility and toughness increase as carbon content decreases. Thus if the designer specifies the shape of the part and its hardness, he has roughly established the other mechanical properties. The problem then becomes one of obtaining a tempered martensitic structure, free of internal stresses and combined with the lowest possible carbon content. Designing for heat treatment should try to minimize internal stresses in the part, which, if severe, will result in cracks and distortion. Some general rules of designing for heat treatment follow:

1. Insert radii or fillets at all reentrant angles or corners.
2. Eliminate blind holes, if possible, by continuing the hole through the part.
3. Strive to have sections of the part contain the same amount of metal so that the piece will heat and cool uniformly.

The simplest hardening procedure is cooling the heated steel to room temperature by quenching it in some cooling medium. Air, oil, water, and brine are the most common coolants. For optimum results, it is necessary that the quench bath have adequate and uniform heat extracting ability. Only under such conditions is uniformity in hardening achieved throughout a single part and from one part to the next. Consequently, the size and configuration of the part are an important consideration. The heat extraction rate varies widely depending upon the mass of the part, the amount of surface area available for heat transfer, and the volume and specific heat of the quenching medium.

Note that the actual achievement of temper conditioning in metals is primarily an age-hardening process. After age-hardening the materials lose most of their ductility. However, just prior to age-hardening the metals can be stored in a cold chamber, the aging process is temporarily inhibited, and the material maintains most of its ductility. For specific details on this procedure, refer to Ref. 10 or the supplier or producer of the metal.

4-1.2.2.3.2 Annealing

Annealing is used to soften, to relieve stresses, to homogenize, or to refine the grain structure of metal. Different types of annealing are possible, and the choice is dictated by the requirements of the situation. Several types of annealing are discussed in the paragraphs that follow:

1. *Full Annealing is* a softening process accomplished by holding the steel above the transformation temperature long enough to complete the transformation to austenite and then cooling it slowly to below the transformation range.
2. The *isothermal annealing* process provides better control (uniformity and fineness) over the formation of pearlite. It requires the extra step of holding the heated steel (after it is transformed to austenite) in a salt bath at a selected temperature below the transformation range until the pearlitic transformation has been completed. Provided the hardness is satisfactory, the pearlitic structure in carbon and alloy steel with 0.20 to 0.50% carbon exhibits good machinability characteristics.
3. *Spheroidizing* steel converts the carbide into globules through prolonged heating at or just below the critical temperatures, followed by slow cooling. The procedure varies with the type of steel, the size of the object treated, and the purpose. Spheroidizing may be applied to all classes of carbon steels, and it reduces hardness and improves shaping characteristics. In the steels above 0.60% carbon, spheroidizing improves machinability.
4. *Process annealing is* applied to cold-worked, low-carbon, and low-alloy steels. It is accomplished by heating the material to a temperature below the transformation range. This process is used primarily to soften a material between cold-working operations.
5. *Stress relieving,* also called heat soaking, is a process to relieve stresses induced by casting, quenching, normalizing, machining, cold-working, or welding. The process involves heating the part to a prescribed temperature and holding the part at that temperature for a prescribed period of time. This reduces residual stresses, improves dimensional stability, and restores ductility after cold-working.

4-1.2.2.3.3 Normalizing

The normalizing process heats steel to a temperature above the transformation range and cools it in still air, Normalizing cancels the effect of previous heat treatment or cold-working and insures that later reheating for hardening or annealing will produce a homogeneous austenite. In addition, normalizing, or normalizing followed by tempering, can be used as the final heat treatment in some applications of medium carbon alloy steels, such as H41300 or H86300 types. With these steels the alloy often has sufficient strength without quenching. Also normalizing can be used for parts too large for liquid quenching.

4-1.2.2.3.4 Surface Hardening Methods

There are several methods available to increase hardness along critical surfaces. These produce a hard surface and a softer interior. When applied to alloy steels, great core strength can be combined with extreme surface hardness, which results in a composite structure capable of withstanding certain kinds of stresses to a high degree. Where low or moderate core strength can be tolerated, cheaply fabricated, low-price carbon steels can be used in combination with the surface-hardened conditions. Surface hardening can be achieved using a variety of techniques. Heating of the entire part with subsequent rapid cooling is the most common, Various techniques to heat the surface locally are also used, i.e., flame, electron beam, and laser. Some of the specific techniques are

1. *Cyanide case hardening* (nitriding)—generally used for shallow case on small parts. Case depths obtainable: 0.03 to 0.3 mm (0.001 to 0.010 in.)
2. *Activated cyanide* case—case depths obtainable: 5.1 to 10.2 mm (0.20 to 0.40 in.)
3. *Salt bath carburizing* (nitriding)—case depths obtainable: 0.64 to 4.06 mm (0.025 to 0.160 in.)
4. *Pack carburizing*—case depths obtainable: 0.64 to 6.35 mm (0.025 to 0.250 in.)
5. *Gas carburizing*—case depths obtainable: 0.25 to 1.52 mm (0.010 to 0.060 in,)
6. *Flame hardening*—depth hardness obtainable: 0.76 to 6.35 mm (0.030 to 0.250 in.) or more
7. *Shot* peening—part is impacted with hardened metal balls of various sizes. While developing a residual surface compressive stress, the surface hardness also increases due to effects of cold-working. Effective depth:0.08 to 0.25 mm (0.003 to 0.010 in.) on thin pieces and up to 0.64 mm (0.025 in.) for thicker parts.
8. *Induction* heating—part is heated to quench temperature by use of induction coil and is quenched to martensite; the section is tempered to the desired hardness.
9. *Chrome* plating—parts may be plated with chromium to give a hard wear surface. The thickness may vary from 0.08 to 0.25 mm (0.003 to 0.010 in.).

For more detailed information on these processes, see Refs. 9 and 10.

One of the more critical factors of thermal treatment processes in the producibility of metal components is the resultant warpage in the product. In designing for heat treatment this factor should be paramount in the designer's mind.

4-1.2.2.4 Finishing Processes

Finishing operations are those operations performed for the purpose of obtaining the desired surface characteristics. Surface characteristics are generally of two types: those necessary to the proper function of the item, such as mating or bearing surfaces, and those necessary for corrosion resistance. Similar to thermal conditioning processes, finishing processes are very important for producibility since they are among the final operations performed on the metal component. These processes are addressed in this handbook as mechanical finishing and protective coatings.

4-1.2.2.4.1 Mechanical Finishing

Mechanical finishing methods include: grinding, tumbling, honing, lapping, superfinishing, electrochemical honing, and rotofinishing (also considered a cleaning process). Before considering these processes, the economic implications of obtaining a fine surface finish should be considered. The cost of production increases as the requirements for finer surface finishes increase.

Neither dimensional tolerances nor surface roughness should be specified to limits of accuracy closer than those that the actual function of design necessitates. Surface roughness root mean square (rms) is defined as the average deviation expressed in micrometers (microinches) from the mean surface.

Fig. 4-15 provides at a glance a general relationship of actual dimensional tolerance to surface roughness and the relationship to cost.

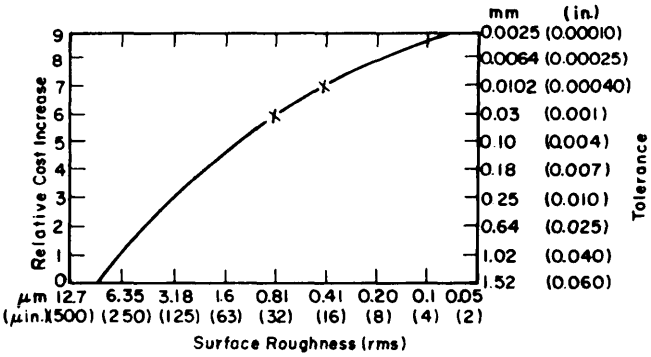

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Figure 4-15. Relationship of Surface Roughness to Tolerance and Cost (Ref. 5)

As shown in Fig. 4-15, it is obvious that there is a relationship between surface roughness and tolerance. It is not feasible to expect to hold a tolerance of 0.0025 mm (0.0001 in.) on a part that is to be machined to an average roughness of 3.18 µm (125 µin. rms). Likewise, a finish of 0.25 to 0.38 µm (10 to 15 µin.) for a surface merely intended to provide proper size for locating subsequent operations cannot be justified. A 1.02- to 1.52-µm (40- to 60-µin.) finish would be satisfactory and would cost approximately 25% less.

Besides showing the relationship between surface finish and roughness, Fig. 4-15 shows the relative cost increase as tolerances and surface roughness become finer. If a part is machined to a tolerance of ±0.01 mm (0.0004 in.), the chart indicates a finish of 0.41 µm (16 µin.) at a cost factor of seven. If the tolerance is increased to ±0.03 mm (0.001 in.), the chart indicates finish of 0.81 µm (32 µin.) at a cost factor of six. This is a 14.3% decrease in cost.

Fig. 4-16 shows the tolerance range of general machining processes. As can be seen, various processes overlap because of the ranges and sizes that the various processes can handle.

For example, it would be rather difficult to handle a 508-mm (20-in.) diameter hone, and therefore, other processes should be used to hold a tolerance of 0.038 mm (±0.0015 in.) as indicated in Fig. 4-16. Similarly, one does not build a 508-mm (20-in.) diameter drill only to use a boring tool to finish the inside diameter. The figure shows only the tolerance that can be held within the limits of the process.

Tables 4-17 through 4-20 are listings of recommended surface requirements covering a variety of design contingencies. Table 4-21 graphically illustrates the range of finishes that normally can be expected to result from various process operations. The influence of specified finishes on factors other than cost—i.e., production time, equipment availability, worker skills, etc.—must also be considered. Table 4-22 shows tolerance associated with interference fit.

The following data provide descriptions and relative producibility information on the various mechanical finishing processes:

1. *Honing is* a refined form of grinding. Surface finish quality approaches that achieved by lapping; however, honing is not an economical production operation. The principal difference between honing and grinding is that the abrasive stones have a large area of surface contact during honing; during grinding only line contact occurs. Stock removal is held to a minimum in the honing process. The tolerances for honing are shown in Table 4-21.

2. *Lapping is* another means of obtaining more accurate and smoother finishes than those possible with the finest grinding. It is a surface refining and stock removal process practical in production if no more than 0.013 mm (0.0005 in.) of material is removed. The mating surfaces themselves are used with a fine abrasive to insure an accurate fit. Since material removal should be held to a minimum, the preliminary grinding operations must be extremely accurate for lapping to achieve its accuracy potential. The tolerance variations total 0.0013 mm (0.00005 in.) typically. Surface roughness ranges between 0.013 and 0.05 µm (0.5 and 2 µin.).

3. *Tumbling or barrel finishing is* a finishing process in which the parts are put into a container with or without an abrasive and rotated. The processing done before barrel finishing ordinarily sets the tolerance limits since the overall reduction in dimensions should not exceed a few millimeters. Also surface finishes obtainable are determined by prior processing. For example, tumbling will improve a 12.7-µm (500-µin.) finish to 2.03 µm (80 µin.), a 1.52-µm (60-µin.) finish to 0.38µm (15 µin.), and a 0.38-µm (15-µin.) finish to 0.08µm (3 µin.).

4. *Grinding* is the primary method for surface finishing. There are several different types of grinding, and each is capable of providing various degrees of surface finish:

a. *Surface grinding is* accomplished by grinding wheels mounted over tables that move under the wheel in either horizontal or rotary passes. Tolerances for surface grinding follow:

(1) On surface grinders, flatness is held to within 5.08 to 7.62 µm (200 to 300 µin.) over 6.1 m (20 ft).

(2) On rotary table machines, flatness is held to 5.08 to 12.7 µm (200 to 500 pin.) parallelism to 10.16 to 12.7 µm (400 to 500 µin.), and length to ±5.08 µm (200 µin.).

Surface finish generally is dependent on the material being ground; however, 0.05 µm (2 µin.) can be obtained in production on hardened steel.

b. *Abrasive belt grinding* uses driven, endless, abrasive belts supported by suitable contact wheels, which provide opposing pressure to the workpiece to achieve stock removal. The tolerances for abrasive belt grinding are

(1) Flat surfaces, ±0.05 mm (0.002 in.) flatness and parallelism

(2) Center-less grinding operations, ± 13 µm (500 µin.) with fine grits, in production

(3) Finishes of 0.25µm (10 µin.) are typical.

c. *Cylindrical grinding* is a method of grinding the outside surfaces of cylindrical parts. Four movements are involved: the workpiece rotates on centers or a mandrel, the grinding wheel rotates, the grinding wheel moves in or out from the workpiece, and the workpiece traverses the wheel (on some large machines, the wheel may traverse the workpiece). Tolerances appropriate to the cylindrical grinding process are

(1) Cylindrical grinders, ± 3 to ± 13µm (100 to 500 pin.) on diameters

(2) Surface finish is dependent on work material, grinding wheel grit size, and other factors; 0.81 to 1.6 µm (32 to 63 µin.) typical for production.

d. *Centerless grinding* is a method of grinding the inner or outer surfaces of cylindrical parts; it is similar to cylindrical grinding except that the workpiece is not mounted on centers. Instead, it is supported by a work rest blade and a regulating wheel.

Text commences on p. 4-49.

Range of Sizes		Tolerances mm (in.)								
From mm (in.)	Through mm (in.)									
0.000 (0.000)	15.21 (0.599)	0.0038 (0.00015)	0.005 (0.0002)	0.008 (0.0003)	0.013 (0.005)	0.020 (0.0008)	0.030 (0.0012)	0.051 (0.0020)	0.076 (0.0030)	0.127 (0.0050)
15.24 (0.600)	25.37 (0.999)	0.0038 (0.00015)	0.0064 (0.00025)	0.010 (0.0004)	0.015 (0.0006)	0.025 (0.0010)	0.038 (0.0015)	0.064 (0.0025)	0.102 (0.0040)	0.152 (0.0060)
25.40 (1.000)	38.07 (1.499)	0.005 (0.0002)	0.008 (0.0003)	0.013 (0.0005)	0.020 (0.0008)	0.030 (0.0012)	0.051 (0.0020)	0.076 (0.0030)	0.127 (0.0050)	0.203 (0.0080)
38.10 (1.500)	71.09 (2.799)	0.0064 (0.00025)	0.010 (0.0004)	0.015 (0.0006)	0.025 (0.0010)	0.038 (0.0015)	0.064 (0.0025)	0.102 (0.0040)	0.152 (0.0060)	0.254 (0.0100)
71.12 (2.800)	114.27 (4.499)	0.008 (0.0003)	0.013 (0.0005)	0.020 (0.0008)	0.030 (0.0012)	0.051 (0.0020)	0.076 (0.0030)	0.127 (0.0050)	0.203 (0.0080)	0.305 (0.0120)
114.30 (4.500)	198.09 (7.799)	0.010 (0.0004)	0.015 (0.0006)	0.025 (0.0010)	0.038 (0.0015)	0.064 (0.0025)	0.102 (0.0040)	0.152 (0.0060)	0.254 (0.0100)	0.381 (0.0150)
198.12 (7.800)	345.41 (13.599)	0.013 (0.0005)	0.020 (0.0008)	0.030 (0.00012)	0.051 (0.0020)	0.076 (0.0030)	0.127 (0.0050)	0.203 (0.0080)	0.305 (0.0120)	0.508 (0.0200)
354.44 (13.600)	533.37 (20.999)	0.015 (0.0006)	0.025 (0.0010)	0.038 (0.00015)	0.064 (0.0025)	0.102 (0.0040)	0.152 (0.0060)	0.254 (0.0100)	0.381 (0.0150)	0.635 (0.0250)
Lapping and Honing		▨	▨	▨						
Grinding, Diamond Turning, Boring		▨	▨	▨	▨					
Broaching			▨	▨	▨	▨				
Reaming			▨	▨	▨	▨	▨	▨		
Turning, Boring, Slotting, Planing, and Shaping						▨	▨	▨	▨	▨
Milling							▨	▨	▨	▨
Drilling								▨	▨	▨

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Figure 4-16. Tolerance Range of Machining Processes (Ref. 5)

TABLE 4-17. NONMATING SURFACES

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
A. Clearance holes			x						
B. Clearances and reliefs									
1. Small				x					
2. Medium or large		x							
C. Cutoff length surfaces—sheared, sawed, etc.		x							
D. Datum surfaces									
1. Less than 0.03 mm (0.001 in.) tolerance					x				
2. Tolerance of 0.03 mm (0.001 in.)				x					
E. Nuts, bolt and screw heads, unthreaded shanks									
1. Finished (machined) bolts, screws				x					
2. Unfinished bolts			x						
F. Ends of bolts, pins, screws, and studs			x						
G. Screwdriver and wrench slots			x						
H. Chamfers, radii and undercuts				x					
I. Handles				x					
J. Tool runout-thread relief				x					
K. Exterior surfaces									
1. Housing cast		x							
2. Housing machined				x					
3. Guns through 30 mm				x					
4. Guns over 30 mm to 406 mm (16 in.)			x						
5. Painted surfaces, guns 75 mm to 406 mm (16 in.)		x							
6. Breechblocks					x				
L. Breech mechanisms									
1. Guns through 30 mm					x				
2. Guns larger than 30 mm to 125 mm				x					
3. Guns 125 mm to 406 mm (16 in.)			x						

TABLE 4-18. MATING OR CONTACT SURFACES-STATIONARY

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
A. Centralizing or location surfaces				X					
B. Clamping or mounting surfaces					X				
c. Housing, bracket, and pedestal-pads (base surfaces)				X					
D. Surfaces for copper gaskets and gasket seats						X			
E. Surfaces for soft, flat gaskets				X					
F. Gasket surfaces (minimum surface contact)					X				
G. Grooves for injection seats “				X					
H. Surfaces for O-rings						X			
I. Grooves for snap rings				X					
J. Counterbored surfaces									
1. Over 19.0 mm (0.75 in.) diameter			X						
2. 19.0 mm (0.75 in.) diameter and less				X					
K. Countersunk surfaces				X					
L. Spotfaced surfaces									
1. Over 19.0 mm (0.75 in.) diameter			X						
2. 19.0 mm (0.75 in.) diameter and less				X					
M. Dowel pinholes and taper pinholes						X			
N. Parts of breech mechanism					X				
o. Inside diameter of pinned hubs, collars, and spacers					X				
P. Lens, prism, and mirror mounting surfaces					X				
R. Spring seat surfaces				X					
s. Shafts and bores for ball bearings									
1. Up to 51 mm (2 in.) diameter						X			
2. Over 51 mm (2 in.) diameter					X				
T. Shoulder faces for shafts and housing (ball races)				X					
u. Surfaces contacting packing in glands and retainers					X				

TABLE 4-19. MATING OR BEARING SURFACES-ROTATING

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
A. Crankpins								X	
B. Pivot holes—pivot pins						X			
c. Bearings—ball track								X	
D. Bearings sleeve type (shaft OD*-bearing ID**)									
1. General						X			
2. Precision							X		
E. Shaft OD used with jewel bearing									X
F. Shaft OD used with oil seal or O-ring							X		
G. Piston pins									X
H. Friction differential faces								X	
I. Variable speed drivers—cone, disc, and cylinder faces								X	
J. Hub, collar, and shaft face bearing surfaces									
1. General					X				
2. Precision						X			
K. Pressure lubricated bearings									X
M. Propeller blades									X

*OD = outside diameter
**ID = Inside diameter

TABLE 4-20. MATING OR BEARING SURFACES-SLIDING

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
A. Gear teeth and screw threads									
1. DP* 10 or smaller									
a. General					x				
b. Precision						x			
2. Coarser than 10 DP*					x				
3. Heavy loads						x			
4. Worms							x		
5. Worm gears									
a. General						x			
b. Precision (lapped)							x		
c. For heavy loads						x			
6. Teeth of ratches and pawls				x					
7. Spline teeth					x				
8. Screw threads									
a. Chased			x						
b. Die or tap cut				x					
c. Milled									
(1) 10 or more threads per inch					x				
(2) Fewer than 10 threads per inch				x					
d. Ground threads and breech threads for guns							x		
e. Rolled threads								x	
B. Gibs and ways						x			
c. Sliding plates						x			
D. Sliding plate guides							x		
E. Slip clutch surfaces									
1. Metal to metal					x				
2. Metal to nonmetal						x			
F. Slip ring surfaces					x				
G. Valve stems and guide bushings							x		
H. Cylinder bores, pistons, and piston rods							x		
I. Surfaces of fluid seats									x
J. Valve seats								x	
K. Bearing seats bolts, nuts, screw heads				x					
L. Cam surfaces and followers									
1. Three-dimensional							x		
2. Groove									
a, General						x			
b. Precision							x		
3. Flat or disc lobe									
a. General						x			
b. Precision							x		
4. Throwout type					x				
M. Locking plungers (round or square end holes)					x				
N. Keys and keyways						x			
o. Breech and firing mechanisms of cannons							x		
P. Parts sliding in packings							x		
R. Dynamic O-ring seal surfaces									x
s. Dynamic T-seal (machined finish—no abrasive)							x		
T. Recoil mechanisms and equilibrators									
1. Antifriction metal							x		
2. Copper rings						x			

*DP = diametral pitch

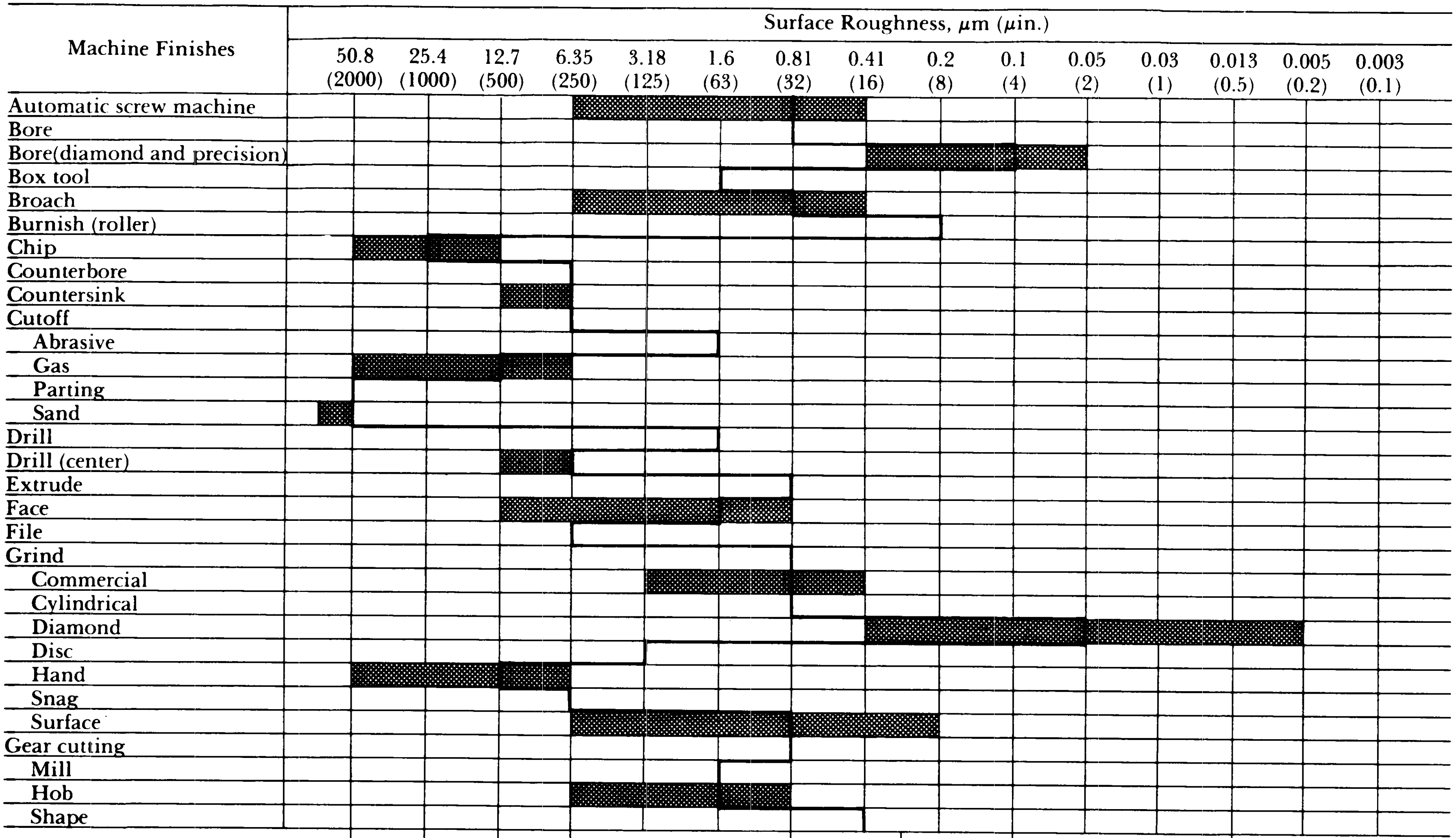
(cont'd on next page)

TABLE 4-20. (cont'd)

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
3. Silver rings							x		
4. Control rods-bronze buffer ends					x				
5. Control rods-steel-control diameter						x			
6. Internal bronze surfaces					x				
U. Propellant valves shafts							x		
V. Rifling in cannon barrels									
1. Lands									
a. Cannon over 30 mm up to 75 mm								x	
b. Cannon 75 mm up							x		
2. Grooves									
a. Cannon over 30 mm up to 75 mm							x		
b. Cannon 75 mm up						x			
W. Barrel chambers, lands, and grooves Guns through 30 mm						x			

* DP = diametral pitch

TABLE 4-21. INHERENT SURFACE ROUGHNESS AND PRACTICAL TOLERANCES OF VARIOUS PRODUCTION METHODS

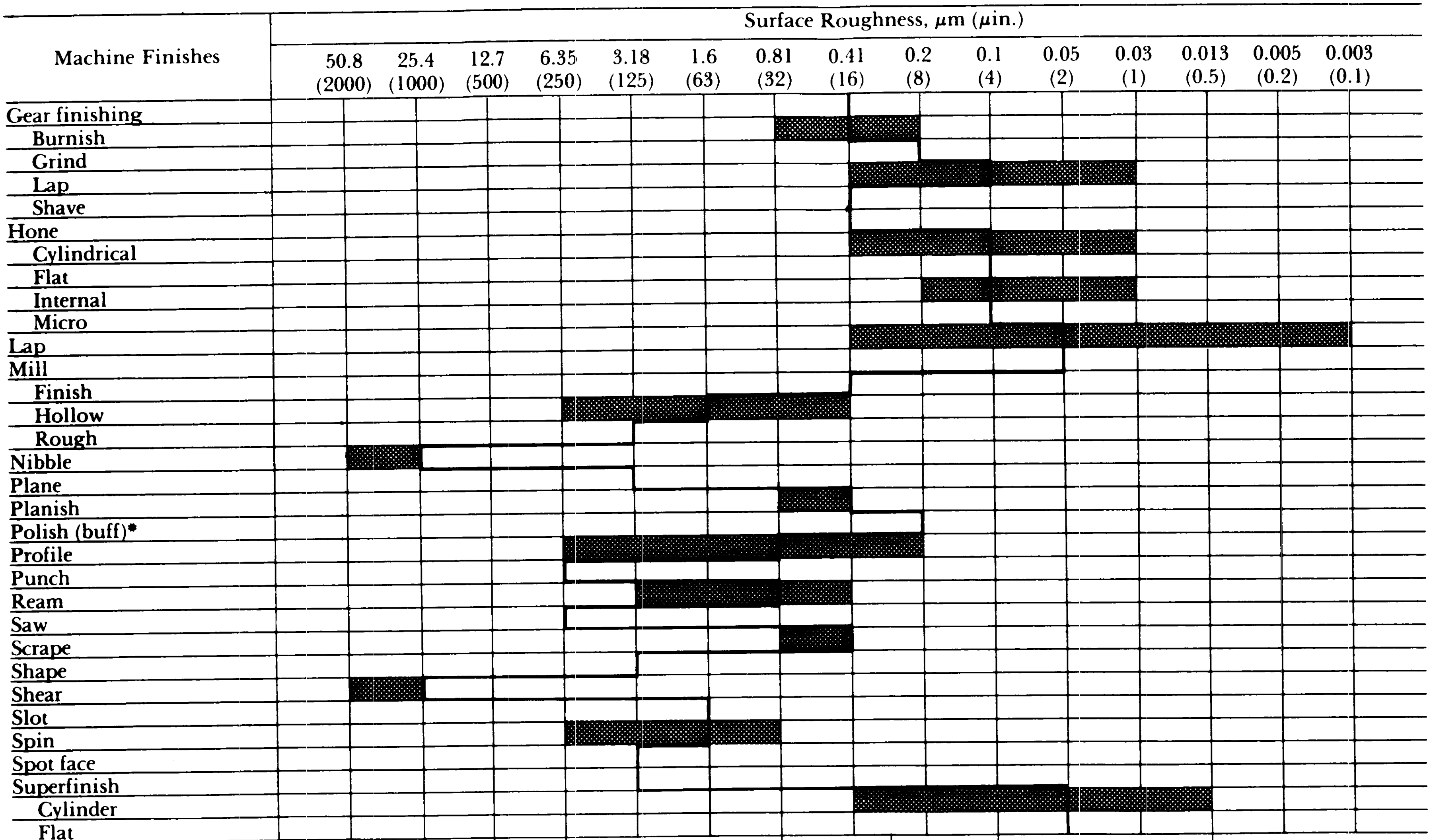


Normal practice tolerance for average size parts (+ or −), mm (in.)									
+	1.14 (0.045)	2.03 (0.08)	0.38 (0.015)	0.05 (0.002)	0.03 (0.001)	0.013 (0.0005)	0.0038 (0.00015)	0.002 (0.00008)
−	0.79 (0.031)	0.38 (0.015)	0.13 (0.005)	0.03 (0.001)	0.013 (0.0005)	0.0064 (0.00025)	0.003 (0.00010)	0.0013 (0.00005)

Left of heavy line: practical finishes at commercial costs.
Right of heavy line: obtainable finishes at increased costs.
Range of surface roughness for each process is indicated by shaded areas.

(cont'd on next page)

TABLE 4-21. (cont'd)



Normal practice tolerance for average size parts (+ or −), mm (in.)									
+	1.14 (0.045)	2.03 (0.08)	0.38 (0.015)	0.05 (0.002)	0.03 (0.001)	0.013 (0.0005)	0.0038 (0.00015)	0.002 (0.00008)
−	0.79 (0.031)	0.38 (0.015)	0.13 (0.005)	0.03 (0.001)	0.013 (0.0005)	0.0064 (0.00025)	0.003 (0.00010)	0.0013 (0.00005)

(cont'd on next page)

Left of heavy line: practical finishes at commercial costs.
Right of heavy line: obtainable finishes at increased costs.
Range of surface roughness for each process is indicated by shaded areas.

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*Dependent on previous finish, grit, and grade of abrasive.

TABLE 4-21. (cont'd)

Machine Finishes	Surface Roughness, μm (μin.)															
		50.8 (2000)	25.4 (1000)	12.7 (500)	6.35 (250)	3.18 (125)	1.6 (63)	0.81 (32)	0.41 (16)	0.2 (8)	0.1 (4)	0.05 (2)	0.03 (1)	0.013 (0.5)	0.005 (0.2)	0.003 (0.1)
Turn																
Smooth					▨	▨	▨	▨								
Rough																
Diamond								▨	▨	▨						
Protective and Mechanical Finishes																
Galvanize*			▨	▨	▨											
Oxide—black coat**																
Phosphate coat				▨	▨	▨										
Plate (0.0025 in. dep)*																
Plate (0.0005 in. dep)*								▨	▨							
Sheridize																
Mechanical barrel finish						▨	▨	▨	▨	▨	▨					
Natural Surfaces																
Cast																
Die						▨	▨	▨								
Permanent mold																
Precision					▨	▨	▨	▨								
Sand																
Shell mold					▨											
Coin																
Cold press (upset)						▨	▨	▨								
Draw (cold)																
Extrude				▨	▨	▨	▨	▨								
Forge																
Hone (liquid)				▨	▨	▨	▨	▨								
Hot press (upset)																
Peen (shot)		▨														
Normal practice tolerance for average size parts (+ or −), mm (in.)	+ −	1.14 (0.045) 0.79 (0.031)	2.03 (0.08) 0.38 (0.015)	0.38 (0.015) 0.13 (0.005)		0.05 (0.002) 0.03 (0.001)		0.03 (0.001) 0.013 (0.0005)		0.013 (0.0005) 0.0064 (0.00025)		0.0038 (0.00015) 0.003 (0.00010)			0.002 (0.00008) 0.0013 (0.00005)	

(cont'd on next page)

Left of heavy line: practical finishes at commercial costs.
Right of heavy line: obtainable finishes at increased costs.
Range of surface roughness for each process is indicated by shaded areas.

TABLE 4-21. (cont'd)

Natural Surfaces (cont'd)		Surface Roughness, μm (μin.)														
		50.8 (2000)	25.4 (1000)	12.7 (500)	6.35 (250)	3.18 (125)	1.6 (63)	0.81 (32)	0.41 (16)	0.2 (8)	0.1 (4)	0.05 (2)	0.03 (1)	0.013 (0.5)	0.005 (0.2)	0.003 (0.1)
Powder metallurgy																
Roll (cold)				▨	▨	▨	▨	▨								
Roll (hot)																
Swage			▨	▨	▨											
Weld																
Thread roll																
Normal practice tolerance for average size parts (+ or −), mm (in.)	+	1.14 (0.045)	2.03 (0.08)	0.38 (0.015)	0.05 (0.002)			0.03 (0.001)	0.013 (0.0005)		0.0038 (0.00015)			0.002 (0.00008)		
	−	0.79 (0.031)	0.38 (0.015)	0.13 (0.005)	0.03 (0.001)			0.013 (0.0005)	0.0064 (0.00025)		0.003 (0.00010)			0.0013 (0.00005)		

Left of heavy line: practical finishes at commercial costs.
Right of heavy line: obtainable finishes at increased costs.
Range of surface roughness for each process is indicated by shaded areas.

TABLE 4-22. INTERFERENCE FITS

AA Roughness Height Ratings	µm	12.7	6.35	3.18	1.6	0.81	0.41	0.2	0.1
	µin.	(500)	(250)	(125)	(63)	(32)	(16)	(8)	(4)
A. Push fit						x			
B. Keys and keyways					x				
C. Drive and press fits									
1. Holes and shafts to 51 mm (2 in.) diameter						x			
2. Holes and shafts over 51 mm (2 in.) diameter					x				

4-1.2.2.4.2 Nontraditional Finishing

Some recent developments in NC machining with a single point diamond cutter have shown an exceptional capability in achieving optical quality finishes. This technique employs the single point diamond tool in conjunction with a very lengthy program, usually compressed on magnetic tape. The program contains a large quantity of extremely small changes in feed rates and depths of cut. This is an economical process if precise optical quality finishes are required in small quantities.

One final note on mechanical surface finishes—it has been said erroneously that the finer the surface finish, the greater the degradation of producibility. If the surface finish specified is absolutely required in the design, then maximum producibility would be enhanced if the optimum process for achieving it were used. Producibility would be degraded only if the specified surface finish were greater than required by the design function.

4-1.2.2.4.3 Cleaning Processes

Generally, it can be stated that the quality of any coating is dependent on the precleaning. Accordingly, all protective coatings require some cleaning process that follows the manufacturing operations and precedes the application of the coating. It is important for the design engineer to be familiar with the more prevalent cleaning processes because of the potential impact on producibility, for example, the possibility y of entrapping chemical cleaning fluids that could ultimately react with the planned product environment. In this situation the design engineer might want to specify mechanical cleaning only.

How well a phosphate coating adheres depends on the cleanliness and preparation of the surface. Four steps are commonly required before plating: precleaning with a solvent, intermediate cleaning with alkaline solutions, electrocleaning, and acid cleaning. The last step conditions the surface, removes light oxide films from previous cleaning, and microetches the surface. One standing rule in electroplating that bears repeating is “The surface roughness you begin with is the surface roughness you will get.”.

Selection of a cleaning process is influenced by the type of soil to be removed; the degree of cleanliness required on subsequent operations; the base material to be cleaned; the fragility, size, and intricacy of the part; and the cost and ultimate purpose or use. The cleaning processes are broken down into mechanical, electrochemical, and chemical types. Each is discussed:

1. *Mechanical cleaning methods* include grinding, brushing, abrasive blasting, steam- or flame-jet cleaning, and tumbling.

a. *Grinding* cleans by wearing away dirt and usually takes part of the base metal with it. This method is commonly used to remove coarse irregularities as well as dirt from castings and other forms. Grinding is done with motorized grinding wheels on abrasive belts, both stationary and portable.

b. *Brushing is* an abrasive operation done with wire or fiber brushes mounted on a motor-drive wheel. Wire brushing may be uneconomical since further cleaning usually is required. However, almost any part that does not have precise dimensions and can be easily handled by the operator may be wire brushed. With stainless steel and aluminum, wire particles may become embedded in the surface and later corrode, which produces surface staining and the appearance of poor corrosion resistance. Use of stainless steel brushes will overcome this problem. When wire brushes are used on magnesium, close control of dust is necessary because of the explosive nature of magnesium dust.

c. The *abrasive blasting* method consists of bombarding a surface with an abrasive at high velocity. Many abrasives, e.g., sand, steel shot, steel grit or crushed shot, silicon carbide, cut wire, rice hulls, corn cobs, and alumina, may be used. Air is usually the transfer medium for the abrasive, but liquid can be used also.

The effects of the abrasive blast vary according to type and hardness of the abrasive, particle size of the abrasive, velocity at impact, and angle of impact with the surface. On metal, sand gives a matte finish that varies with the grit size and pressure used. Steel grit produces a matte finish that is similar to that produced with sand, and steel shot produces a bright finish.

Blasting produces a good bonding surface for paints and may be used for castings, forgings, stampings, welds, and heat-treated parts of all shapes and sizes. Guarding against possible dust explosions may be required.

d. *Steam- or flame-jet* cleaning is an economical, method of removing loose scale on large, unwieldy, ferrous metal parts; it is not suitable for cleaning nonferrous metals. In the steam-jet process, a jet of high--pressure steam is directed onto the surface and physically removes heavy scale. In the flame-jet process a jet of oxyacetylene flame is directed onto the surface and rapidly heats the scale, which breaks away from the base metal because of the differing rates of thermal expansion.

e. The *tumbling* operation consists of rotating a barrel containing small parts, either alone or with abrasives and lubricating (cushioning) liquids. Cleaning, deburring, abrading, work hardening, burnishing, or combinations of these may take place, depending on the type of barrel and media. The main advantage of this cleaning process is its low cost. Large volumes of small parts can be handled, and several treatments and rinses can be carried out in the same barrel, thus avoiding transferring parts from one piece of equipment to another.

2. *Electrochemical cleaning methods (electropolishing).* Most electropolishing methods are patented proprietary processes that represent a wide range of electrolytes and operating details. In general, the metal is made the anode at high current density in a concentrated acid bath. The action involves a rapid attack on the elevated spots in the rough finish and a minimum attack on the depressed ones. A smoothing or rounding off results in a brilliant finish. Electropolishing is applicable to most metals, with the exception of mild steel. The main advantage of this process is that it can be used to polish thin-sectioned or intricate shapes that are too cumbersome for mechanical wheel finishing or cleaning.

3. *Chemical cleaning methods.* The principal chemical cleaning methods are solvent cleaning, emulsion cleaning, alkaline cleaning, acid cleaning, pickling, descaling with sodium hydride, and paint stripping. Discussion follows:

a. *Solvent cleaning is* one of the most widely used methods of cleaning metal surfaces. The solvents include petroleum or coal tar hydrocarbons and chlorinated hydrocarbons used either as emulsions or as diphase systems. The types of soil most efficiently removed are unsaponifiable mineral oils and greases. Solvent cleaning is economical for high production work, particularly when the surface must be immediately ready for further treatment, and it can be used for any metal. Although parts dry rapidly after cleaning, solvent cleaning has these limitations: solid soils, saponifiable greases, and metallic soaps often are not removed; a residual oil film may be left on the surface; flammability and toxicity hazards are present; material costs are higher than for alkaline cleaning; and distillation is necessary to keep the solvent clean. The following methods are used in solvent cleaning:

(1) *Soak or tank cleaning.* All three forms of solvent—straight, emulsion, and diphase systems—may be used. The parts are immersed in the solvent, and some form of mechanical agitation is provided.

(2) *Spray decreasing.* The heated solvent—either straight or emulsified—is pressure sprayed on the surface. Spray degreasing is usually followed by rinsing with clean solvent or by alkaline cleaning.

(3) Vapor degreasing. The parts to be cleaned are suspended in the upper part of a vessel containing boiling solvent, usually a chlorinated hydrocarbon such as trichloroethylene. The solvent vapors condense on the surface and clean it as the liquid returns to the solvent reservoir. This method probably provides the most efficient and economical means of removing mineral oil and grease.

(4) *Ultrasonic cleaning.* This method uses ultrasonic vibrations in a liquid to obtain unusually rapid and thorough cleaning. It is based on the use of piezoelectric materials or transducers. The violent action thoroughly scrubs the metal surface while the liquid penetrates into deep crevices in the metal part and removes minute particles of insoluble soils, greases, oils, and metal chips, which are difficult to remove by other methods. Chlorinated solvents are commonly used in ultrasonic degreasers although alkaline solutions also can be used. Ultrasonic cleaning is rapid and produces a very clean surface, even for parts with complex shapes.

b. The *emulsion cleaning* process uses common organic solvents dispersed in an aqueous medium with the aid of an emulsifying agent. The cleaning process is conducted between room temperature and 80°C (180°F). The solvents used are generally petroleum base; the emulsifiers include polyethers, glycerols, polyalcohols, high molecular weight sodium or amine soaps of hydrocarbon sulfonates, and others. Emulsion cleaners are applied by spray and dip tank methods; dip tanks are preferred for small parts that must be placed in baskets, tubular parts, intricate castings, and other complicated shapes.

This method is not recommended for some parts unless it can be followed by some other method to remove trapped emulsion, which would impair subsequent finishing operations. Parts in this category include sand core brass plumbing fixtures, tubular parts for furniture, and parts with lapped and spot welded sections.

Emulsion cleaning is less costly than solvent cleaning because it uses relatively small amounts of expensive solvent and large amounts of water. It is safe to use with most metals if the pH remains below 10. Also it leaves a rust preventive film of oil on cleaned parts, which may or may not be advantageous.

c. *Alkaline cleaning,* in all of its forms, is probably the most widely used cleaning method. Alkaline compounds in aqueous solution are extremely effective for the removal of organic and water-soluble soils, vegetable and animal greases, and any solid dirt that may be embedded in a surface. It is the least expensive cleaning method for high production operations.

Alkaline cleaners work by detergent action and saponification to displace the dirt from the surface and suspend it in the solution. Fatty soils are saponified. Alkaline cleaning is done in soak tanks and by pressure spray. In some cases, heat or mechanical agitation is used and, for rapid action, an electric current. In cases where electrofinishing is necessary, other cleaning methods must be followed by alkaline cleaning. To eliminate traces of alkali, an alkaline-cleaned surface must be thoroughly rinsed or neutralized prior to most finishing operations since poor rinsing causes paints to deteriorate. Zinc, aluminum, lead, tin solders, and brass are attacked by strong alkaline cleaners; therefore, inhibited cleaners are required for these metals.

d. The *sodium hydride* process is a metal descaling process that avoids several disadvantages of conventional pickling and other methods. It is suitable for ferrous metals, copper, nickel, and titanium. It easily removes hot rolling, annealing, and heat treatment scale from both ferrous and nonferrous metals.

In the process, sodium hydride is generated by reacting metallic sodium and anhydrous ammonia. The immersion bath consists of fused sodium hydroxide, at approximately 370°C (700°F), containing approximately 2% sodium hydride. Descaling is carried out by immersing the metal part in the hot, molten bath. The sodium hydride reacts with the metal oxides, and the reduction takes place within a minute. Then the metal is removed, drained, and immersed in water. The generated steam mechanically loosens the reduced flaky metal. A water rinse and short acid dip remove any traces of remaining alkali and brighten the surface.

The process has these advantages: the base metal is unaffected; the bath attacks only the scale and makes it impossible to lose metal by overtreatment (an appreciable saving when processing expensive alloys); the same bath can be used for several metals; hydrogen embrittlement is impossible as the metal under treatment cannot absorb hydrogen (the tendency is to drive off any hydrogen present in the metal); the fluid bath penetrates deeply into minute recesses and complex shapes; a very clean surface is left because both oxides and organic soils are removed, and occasionally, the process can be combined with heat treatment.

The principal disadvantages are thin sections may buckle or warp at the temperature used (370°C (700°F)); it is uneconomical for light oxide films; it is not a useful process if the draw temperature of steel is less than 370°C (7000 F), and it is not suitable for low melting metals and alloys of magnesium, zinc, tin, aluminum, and lead because they are readily attacked by caustic soda.

e. Acid cleaning is commonly used on light soil and rust. Although acid cleaning involves pickling, these treatments must be considered distinct from straight pickling because acid cleaners are usually water solutions of phosphoric acid, organic solvents, acid-stable detergents, and wetting agents.

Acid cleaning is performed, either hot or cold, in soak tanks and spray systems. Cleaning results from emulsifying oils on the surface and dissolving or undercutting oxide films. A slight etch is usually left on the surface. Acid cleaning is unsuitable for removing heavy coats of grease, oil, and dirt because a deep etch would result from the long immersion time necessary for thorough cleaning. This process is used on ferrous metals, copper, and aluminum alloys, but it is seldom used on nickel, magnesium, lead, or tin.

f. *Pickling* is an acidic treatment for chemically removing surface oxide and scale from a metal. Wide variations are possible and depend on the type, strength, and temperatures, of the acid solutions used. The acid is selected on the basis of the metal to be pickled and on the type of foreign material to be removed.

A properly controlled pickling bath is much more efficient for scale and rust removal than is mechanical abrasion. However, pickling must be followed by a thorough rinsing and neutralizing. Hydrochloric and sulfuric acids, unless thoroughly removed, can cause organic finishing difficulties. Pickling is applicable to sheet, sand, and die-cast aluminum and its alloys; copper and its alloys; iron and steel; stainless steel; magnesium and its alloys; and nickel and its alloys.

The process has these advantages: the base metal is unaffected, the bath attacks only the scale, which makes it impossible to lose metal by overtreatment (an appreciable saving when processing expensive alloys), and the same bath can be used for several metals.

g. *Stripping or removing* old paint finishes is often necessary before applying new ones. It can be done by a combination of chemical strippers and mechanical action. The type of stripper used depends on the paint film to be removed. Strong, aqueous alkali solutions are used for paints based on drying oils and polymerized resins. In other cases, mixtures of organic solvents work well. A third type employs a mixture of alkalies, solvents, and wetting agents. Also flame is used occasionally to burn off paint.

All paint stripping requires some sort of mechanical assistance, usually brushing, to remove the loosened film. Even after thorough rinsing, the metal surface may require one of the other cleaning procedures. Stripping is usually a quick acting method of removing paint from old painted surfaces but, on occasion, may require long periods of time to attain best results. Some strippers are toxic and flammable; other strippers attack the metal surfaces. These processes can be more efficient if ultrasonic agitation of the stripping medium is used.

4-1.2.2.4.4 Protective Coatings

Since almost every situation presents the possibility that some form of corrosion will occur, appropriate means of protection must be routinely considered during the design process. The design engineer, developing military equipment that involves metals, must prescribe measures for protecting that equipment from corrosive attack.

Coatings are classified into three groups: metallurgical, electrochemical, and mechanical. The first group depends on metallurgical adhesion (flame spraying); the second depends on an electrochemical reaction for application (anodizing, electroplating, etc.), and the third depends on mechanical adhesion (paint, elastomeric coatings, etc.). Each group is described.

1. *Metallic Coatings:* There are four major types of metallic coating methods: flame spraying, weld deposition, diffusion, and hot dipped metal. Table 4-23 shows some of the properties of these coatings and their basic uses. The metallic coatings are

a. *Flame-sprayed coatings* are applied by spraying molten material onto a previously prepared surface. Their principal value is in increasing the wear resistance of metal parts; however, they are useful in building up worn and damaged parts, as well as in providing corrosion protection and heat and oxidation resistance. Flame-sprayed coatings can be applied to cast iron, steel, aluminum, copper, brass, bronze, molybdenum, titanium, magnesium, nickel, and beryllium. The coating materials that can be used with flame spraying include metals, ceramics, carbides, borides, and silicides.

b. *Weld deposition coatings* are applied to produce a hard, wear-resistant facing on less expensive base metals or on ones with special engineering properties, e.g., toughness. These facings are applied in thicknesses between 1.588 and 6.4 mm (0.0625 and 0.25 in.) by any standard fusion welding process.

Over 100 facing materials for use with weld deposition coatings are available. They have been classified by the American Welding Society and the American Society for Metals in order of increasing toughness or in order of decreasing abrasion resistance. Despite their name, hard facings are often applied for corrosion or thermal applications. Table 4-23 lists the major facing materials and their properties.

c. A *diffusion coating is a* surface alloying treatment for metal produced by changing the surface composition of the metal and thereby improving its properties. It is accomplished by heating metals to high temperatures while the surface is in contact with some appropriate substance. Diffusion coatings result in wear- and abrasion-resistant surfaces; however, they are also used to obtain corrosion- and heat-resistant surfaces.

d. The *hot dipped metal coating* process, generally applied to iron and steel, consists of dipping the material to be protected in a molten bath of a more corrosion-resistant metal. Aluminum, zinc, lead, tin, and lead-tin alloy are the principal materials applied by hot dipping as indicated by Table 4-23.

2. *Electrochemical coatings.* An electrolytic process of depositing metal on metals either to protect against corrosion or to increase the surface wearing qualities. The value of chromium-plating plug and ring gages has probably been more thoroughly demonstrated than any other one application of this treatment. Chromium-plated gages not only wear longer, but when worn, the chromium may be removed and the gage replated and reground to size. Table 4-24 gives an indication of some of the plating materials, cost, friction on steel, wear resistance, and Brinll hardness.

In designing a part that requires protective finishes on metal surfaces, the design engineer should use an established order of precedence for equivalent specifications covering materials, processes, or parts. The precedence is established to promote the use of the most economical, applicable, and widely accepted plating processes. The specification preference is as follows:

a. Federal

b. Military

c. Non-Governmental standardizing organizations, such as Society of Automotive Engineers (SAE), American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), and National Electrical Manufacturers Association (NEMA)

d. Contractor-prepared specifications.

The following subparagraphs discuss various metals and their use as coating materials and provide references to the appropriate Federal specification:

a. *Cadmium (Cd) is* a soft, white metal used primarily for corrosion protection. It is sacrificial to most base metals, i.e., corrodes first. Added protection is gained by adding a chromate coating over the cadmium plating. The chromate also provides improved adhesion of subsequent organic films, such as varnishes and lacquers. The Federal Specification is QQ-P-416, *Plating, Cadmium (Electrodeposited).*

TABLE 4-23. PROPERTIES AND USES OF COATINGS

METALS THAT CAN BE FLAME SPRAYED AND PRINCIPAL APPLICATIONS

Metal	Applications	Metal	Applications
Aluminum	Corrosion protection in industrial and salt atmospheres, electrical applications	Molybdenum	Hard wearing surfaces, bonding between substrate and sprayed ceramic coatings, buildup material
Babbitt	For bearing buildup	Nickel	Hard facing, corrosion-resistant coating
Boron	Neutron absorber	Platinum	Electrical contacts, high temperature electrical connectors
Cadmium	Corrosion resistance	Silicon	Wear resistant coatings
Cobalt	For hard facing	Silver	Electrical contacts
Copper	Electrical applications, aluminum, bronze, and phosphor bronze are used for general purpose wear applications	Stainless steel	Corrosion protection, wear resistant applications
Carbon steel	UNS G10100, G10250, and G10800 are used for rebuilding worn parts and wear resistance	Tantalum	High temperature applications
Hafnium	Neutron flux depressor	Tin	Electrical contact coating, food container coating
Iron	Magnetic applications	Titanium	Corrosion and oxidation resistance at high temperature 180°C (360°F)
Lead	Nuclear shielding, resistance against acids	Tungsten	Metal and nonmetallic parts exposed to high temperature as a means of fabricating intricate parts from tungsten
Magnesium	Corrosion resistance	Zinc	General atmospheric corrosion resistance
Manganese	Hard facing and wear	Zirconium	Nuclear applications

HARD FACING MATERIALS USED FOR WELD DEPOSITION

Material	Properties	Material	Properties
Tungsten carbide	Greatest hardness and best wear resistance	Nickel base alloys	Used where abrasion resistance plus resistance to heat and/or corrosion are required
High chromium iron	Best for metal to metal wear, inexpensive	Copper base alloys	Used where a combination of corrosion resistance and liquid erosion is needed
Martensitic iron	Good abrasion resistance, subject to internal stresses, and a tendency to crack	Martensitic steels	Good combination of low cost, hardness, strength, abrasion resistance, good impact resistance, and fairly high toughness
Austenitic iron	Less abrasion resistance than martensitic, less tendency to crack	Austenitic steels	Used for moderately abrasive applications or as a buildup material
Cobalt base alloys	Used where wear and abrasion resistance must be combined with resistance to heat and oxidation or corrosion		

HOT DIP COATINGS

Coating	Base Metal	Properties	Uses
Aluminum	Steel, cast iron	Protects equipment subject to corrosion and heat up to 535°C (1000°F). Minimizes high temperature oxidation and permits use of inexpensive materials for use in corrosive or high temperature applications	Oil refinery process piping, appliance parts, furnace heater tubes, brazing fixtures
Zinc	Steel	Combines high corrosion resistance with low cost. Effective life generally is in proportion to thickness	Nails, wire, tanks, boilers, pails, hardware, lighting standards

(cont'd on next page)

TABLE 4-23. (cont'd)

HOT DIP COATINGS (cont'd)

Coating	Base Metal	Properties	Uses
Lead	Steel, copper	High resistance to atmospheric corrosion and chemicals. Protective oxide film regenerates itself when damaged	Wire, pole-line hardware, bolts, tanks, barrels, cans, air ducts, outdoor gutters, flashing, and siding
Tin	Steel, cast iron, copper	Good resistance to tarnishing and staining indoors and in contact with foods. Sheet lends itself to stamping, drawing, rolling; readily soldered	Milk cans, food grinders, cooking pans, kitchen utensils, and electronic parts (Food cans generally are electrolytically tin-plated.)
Lead-tin alloy (terne)	Steel, copper	Provides some advantage of tin coatings at lower cost; ductility and good adhesion allow deep drawing; excellent paint-holding properties; good solderability	Roofing, gasoline tanks, oil filters, capacitor and condenser cans, connectors, and printed circuits

DIFFUSION COATING PROCESSES

Process	Base Metal	Surface Mixture	Use
Calorized	Carbon and low alloy steel	Aluminum compound or A1C1^3, vapor	Resistance to high temperature oxidation makes useful for furnace parts, chemical pots, air heater tubes
Carburized	Carbon and low carbon alloy steels	Solid, liquid, or gaseous carbon	Gears, cams, pawls, shafts
Cyanided	Carbon and low carbon alloy steels	Carbon and nitrogen	Gears, cams, pawls, shafts
Nitrided	Special steels for nitriding, medium carbon Cr Mo steel, stainless steel, some cast iron	Nitrogen in contact with ammonia	Gears, cams, pawls, shafts
Chromized	Carbon steels, alloy steel, cast iron, stainless steel, iron powder parts	Chromium	High resistance to wear, abrasion, and corrosion; high hardness. Aircraft, railroad, and auto parts; tools
Nickel-phosphorus	Ferrous metal	Nickel phosphorus	Pipe and fittings because of high corrosion resistance
Iron-aluminum	Cobalt, nickel, and iron base superalloys, carbon and stainless steel, some copper alloys	Iron-aluminum	Gas turbine blades and components subjected to high temperatures
Nickel-aluminum	Nickel base alloys	Iron-aluminum	Gas turbine blades and components subjected to high temperatures
Silicides and metal additives	Columbium, molybdenum, tantalum, tungsten	Silicides or metal additives	Aerospace components subjected to high temperatures, 1920 K (3000°F) for a short time
Siliconized	Low carbon, low sulfur steel	Silicon carbide and chlorine	Pump shafts, cylinder liners, valve guides, and valves
Sherardized	Ferrous metal	Zinc	Small parts that must resist atmospheric-corrosion, electrical conduit

TABLE 4-24. ENGINEERING FACTORS OF PLATING DEPOSITS (Ref. 5)

Material	Approximate Brinell Hardness	Wear Resistance	Friction on Steel	Process Cost
Cadmium	35-50	Poor	Fair	Medium
Chromium	800-1000	Excellent	Good	High
Copper	50-150	Fair	Poor	Medium
Gold	5-20	Poor	Good	Very high
Nickel	200-500	Good	Fair	Medium
Rhodium	260-400	Good	Good	Very high
Silver	50-150	Fair	Good	High
Tin	5-15	Poor	Good	Low to medium
Zinc	35-55	Poor	Poor	Low

b. *Chromium (Cr) is a* bright, hard metal that provides excellent corrosion resistance, wear resistance, and high strength. Brightness and type of finish depend upon preparation of the basic metal. The Federal Specification is QQ-C-320, *Chromium Plating (Electrodeposited).*

c. Copper (Cu) is a soft, ductile metal that can be plated from a large number of solutions. Dull to bright finishes are usually obtained. It is used principally as a stop-off for carburizing or brazing operations, as a barrier for subsequent plating layers, and as a substrate for metals that are difficult to plate. The Military Specification is MIL-C-14550, Copper *Plating (Electrodeposited).*

d. Gold (Au) is a soft, yellow metal having a high resistance to corrosion and oxidation. It has excellent electrical conductivity and high reflectivity to visible light. Wear resistance of the deposit may be improved by a nickel strike preceding the gold deposit. The Military Specification is MIL-G-45204, *Gold Plating (Electrodeposited).*

e. Nickel (Ni) is a bright, magnetic metal with high passivity. Nickel may be deposited in any condition from a highly stressed to a stress-free state. Because of its excellent bonding characteristics, nickel is often used as a strike deposit. The Federal Specification is QQ-N-290, *Nickel Plating (Electrodeposited).* Other specifications for nickel plating are provided in Ref. 5.

f. *Nickel-Phosphorous (Ni_2P) is a* bright, medium-hard deposit that can be either magnetic or nonmagnetic. The process plates uniformly on all surfaces. Corrosion resistance is better than that of nickel, and in the hardened state the deposit offers excellent abrasion and wear resistance. It is used to rebuild worn parts, for reflective coatings, and as undercoat for gold plating. The Military Specification is MIL-C-26074, *Coating, Electroless Nickel, Requirements for.*

g. Palladium (Pal) is used as a solderable coating, as a diffusion barrier between copper and gold, and on contacts requiring freedom from oxidation. Military Specification MIL-P-45209, *Palladium Plating (Electrodeposited),* specifies a minimum plating thickness of 0.0013 mm (0.00005 in.).

h. *Rhodium (Rh) is* a hard, silvery metal that provides excellent corrosion resistance. The metal has good solderability above 370°C (700°F) and has good resistance to wear. Thick coats are very brittle. Aerospace Material Specification AMS 2413, *.Silver and Rhodium Plating,* specifies a minimum plating thickness of 0.0005 mm (0.00002 in.).

i, Silver (Ag) may be deposited with a finish that can range from a slight yellow matte to a lustrous white. Solderability and electrical conductivity are excellent. Although it tarnishes easily, silver provides fair corrosion protection and the silver tarnish can act as an insulator when low current is used with silver-plated contacts. Its antigalling characteristics make it an excellent bearing material. Federal Specification QQ-S-365, Silver *Plating, Elect redeposited, General Requirements for,* suggests the following thicknesses: for terminals to be soldered, 0.008 mm (0.0003 in.); for corrosion protection of nonferrous basic metals, 0.013 mm (0.0005 in.); for electrical contacts, 0.013 to 0.28 mm (0.0005 to 0.011 in.). When silver is to be plated on steel, the required thickness, unless otherwise specified, should be 0.013mm (0.0005 in.), plus 0.013 mm (0.0005 in.) copper or nickel, or any combination of both not to exceed 0.013 mm (0.0005 in.) preplate.

j. *Tin (Sri) is* a soft, white, ductile metal with high luster when flowed onto a suitable surface. It has excellent corrosion resistance and solderability. Tin also has excellent antigalling and antiseizing properties. Pure tin deposits are subject to “tin disease” at temperatures below 0°C (32°F). Small additions of antimony and bismuth prevent this tin disintegration at low temperatures. The Military Specification is MIL-T-10727, *Tin Plating, Electrodeposited or Hot-Dipped, For Ferrous and Nonferrous Metals.*

k. *Zinc (Zn) is* a white metal that can be deposited in either dull or bright coat, and it offers excellent corrosion protection since it is sacrificial to most basic metals. Conversion coatings on zinc enchance its corrosion protective properties. These coatings may be applied in a variety of colors from clear to yellow to olive drab. The Federal Specification is QQ-Z-325, *Zinc Coating, Electrodeposited, Requirements for.* Other specifications for zinc plating are provided in Ref. 5.

1. *Hard-coating treatment of aluminum (Al) alloys (anodizing). The* primary purpose of this process is to increase surface hardness and resistance to abrasion and corrosion. The treatment forms a dense aluminum oxide and is used for aluminum and aluminum alloy parts. Careful consideration should be given to the use of the hard-coating treatment on highly stressed parts because of the resultant lowering of the endurance limit. Also the use of it should be weighed carefully if the parts have sharp corners and edges where chipping may occur. The Military Specifications for surface treatments and finishes for aluminum include MIL-A-8625, *Anodic Coating, For Aluminum And Aluminum Alloys,* and MIL-C-5541, *Chemical Conversion Coatings On Aluminum and Aluminum Alloys.*

3. Chromate coatings are simple and economical to apply; they provide a corrosion-resistant surface film, an excellent base for paint, and may be a decorative finish. They are applied on aluminum and aluminum alloys, zinc and cadmium plate, zinc castings and galvanized metal, and, to a lesser extent, on copper, tin, magnesium, silver, and chromium. These coatings may be applied by dipping, brushing, spraying, swabbing, and electrolysis. Chromate coatings are self-healing in that scratches and minor abrasions are protected by a bleeding of the chromium coating onto the damaged area. The coatings can be dyed a variety of colors. In the undyed state they vary from clear and highly polished to a flat black (depending on treating method used, substrate material, and thickness of the coating).

4. *Mechanical coatings.* Elastomeric, vitreous enamel, and paint coatings are among the commonly used mechanical coatings. Each is discussed:

a. *Elastomeric coatings* may be applied to most metals. In addition to being elastic, they offer a wide range of interesting protective properties. The five major elastomer types used in coating are polychloroprene (neoprene), chlorosulfonated polyethylene (hypalon), urethane, polysulfide, and fluoroelastomer. Combinations of these are sometimes used, one as a primer and the other as a top coating. This enables the designer to take advantage of the best properties of each. The typical properties of elastomeric coating materials are listed in Table 4-25. Elastomers are usually applied manually by spraying, brushing, rolling, etc. For production line use of the process, they can be applied by dipping.

b. *Vitreous or porcelain enamel coatings* may be applied to metals including cast iron. They provide a hard, glass-like surface with excellent resistance to

TABLE 4-25. GENERAL PROPERTIES OF ELASTOMERIC COATINGS (Ref. 5)

	Neoprene	Hypalon	Urethane	Polysulfide	Fluoroelastomer
Acid resistance	G	G to E	P to F	F	E
Adhesion	G to E	F to G	G	G	F to G
Alkali resistance	F to G	E	P	F	P
Electrical	F to G	F to G	F to G	F	F to G
Heat resistance	G to E	G to E	G	F to G	E
Oil resistance	G	G to E	E	E	E
Ozone resistance	G to E	E	E	G	E
Permeability	G	G to E	F	E	E
Solvent resistance	F	F	F to G	G	G
Toughness	G	F to G	E	F	F to G
Water resistance	G to E	G to E	G	G	E
Weatherability	G to E	E	G to E	G to E	E
Temperature limit approximate °C	90	135	105	100	230

P = poor; F = fair; G = good; E = excellent

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atmospheric corrosion and most acids. A wide variety of colors, color combinations (speckled, stippled, etc.), and a variety of finishes are available. These coatings are applied by a process of spraying the coating on and then baking.

c. *Paint, varnish lacquer, and related coatings.* Paint probably offers the most versatile type of coating for protecting metals against corrosion. Generally, a properly applied paint coating offers much higher corrosion resistance than an inorganic finish, such as a plated coating or a bare surface coating. Therefore, whenever the nature of the part and its intended usage allow, it should be painted. Four types of transparent coatings in use are varnish, shellac, lacquer, and linseed oil. Pigmented coatings include oil-type paints, varnish enamels, lacquer enamels, sealers, undercoatings, and some stains.

4-1.3 TEST AND INSPECTION

This paragraph describes the major techniques for testing and inspecting metal components to assure that they conform to the technical data package requirements. Test and inspection affect producibility in a very basic manner. Because test and inspection are frequently overlooked in the production process, these aspects of manufacturing may contribute greatly to poor producibility. It is generally assumed that test and inspection will provide the designer with the assurance that the metal component conforms to the drawings and specifications. However, for this to happen the designer must be continually aware of how the product will be inspected and that it can in fact be inspected. To do this, an understanding of the basic test and inspection tools is necessary. There are two fundamental types of inspection: one assures that the basic raw material conforms to the drawings and specifications, and the other confirms that the configuration of the finished component also conforms.

4-1.3.1 Material Test and Inspection

The paragraphs that follow describe some nondestructive testing procedures; all of them are suitable for revealing material defects often encountered in manufacturing. Only a summary of the basic advantages and limitations of the most sensitive nondestructive tests is presented here for general consideration. Detailed information relating to the procedures, limitations, hazards, interpretation, and reference standards appropriate to the proper selection of nondestructive testing methods can be found in inspection guides, specifications, and industrial publications.

4-1.3.1.1 Magnetic Particle Testing

Magnetic particle testing, although not a thorough inspection, provides rapid visual indication of discontinuities at and below the surface to a depth of one-third or more of the thickness of the part. It is limited to those materials that will support magnetism (ferromagnetic materials). Only limited areas can be inspected at each application, and orientation of application is necessary since defects parallel to the magnetic field may be missed. Parts can be damaged by arcing or heating, and caution must be exercised in applying the technique. The visual reaction is the attraction of fluid particles or dry powder to the magnetic leakage field directly over the defect or discontinuity.

4-1.3.1.2 Radiography

Radiography (with an adequate energy source) offers relatively unlimited penetration. It provides a reasonably accurate shadow image of the interior of a material. Surface preparation is not critical, yet the process allows a high degree of sensitivity. Permanent images are readily obtainable, and a wide choice of equipment is available. Neutron radiography, a similar, less expensive process, is also often used. It is done in real time without the necessity for X-ray development and reading.

Both sides of the material must be studied, and careful alignment of the source and the registering media is required. The technique is unable to detect material weaknesses not caused by density differences; it will not resolve fine cracks, laminations, or segregations unless they are within a few degrees of the incident beam. Radiography methods and processing are critical, and interpretation of the results requires a knowledge of materials, techniques, and standards. Detailed information relating to procedures, limitations, and personnel hazards are highly dependent on the particular equipment being used and should be checked and verified through appropriate equipment specifications and equipment manufacturers.

4-1.3.1.3 Ultrasonic Testing

Ultrasonic testing, which has a material penetration ability corresponding to the sound transmission index of the material, provides rapid visual indications of laminations, cracks, or other discontinuities presenting an interface perpendicular or angular to the axis of the transmitted sound beam.

Ultrasonic tests are limited to situations requiring the examination of objects that can be fluidly coupled to the generating surface. Surface preparation is also critical for surface contact methods. The search unit must conform to the test surface, and an adequate couplant must be employed, or the test objects must be adapted for immersion in a liquid. Ultrasonic testing fails to resolve discontinuities parallel to the sound beam, Both sides of the material must be essentially parallel, or extensive experience must be gained with parts that can be sectioned, to establish the standard pattern for that part.

Ordinary ultrasonic tests of metals lose indications within the first 15.88 mm (0.625 in.) of transmission and occasionally lose indications beyond the first major defect. Special techniques have been developed that reduce these limitations. However, experienced interpretation of the test results is mandatory. Images can be photographed or test data recorded for test documentation purposes.

4-1.3.1.4 Penetrants

Penetrant tests, which disregard material size or shape, develop high contrast indications of discontinuities that are open to the surface of the material. Orientation of application is not necessary.

Penetrant tests are limited to the detection of surface discontinuities. Surface preparation is quite critical, and the test procedures must be carefully controlled to avoid developing false indications. Penetrant tests inspect one side of the material only with each application, and indications must be photographed if they are to be recorded.

Fluorescent penetrant is a method whereby detection is accomplished only by backlight, and only surface ruptures or discontinuities are revealed.

4-1.3.2 Component Test and Inspection

The paragraphs that follow describe some procedures and tools for the test and inspection of components. Only a summary of some basic procedures normally found and used in most metalworking shops is presented here. Detailed information relating to these and numerous other special tools and techniques can be obtained in inspection guides and from industrial suppliers of inspection equipment.

4-1.3.2.1 General Shop Measuring Instruments

The most common shop measuring instruments are the rule and combination set, depth gage, vernier caliper, vernier height gage, micrometer, and the telescoping gage. Descriptions of these basic instruments can be found in any number of good reference books, such as Ref. 9. However, for more accurate inspecting and measuring, some basic methods and precision measuring machines and instruments are described in the paragraphs that follow.

1. Bench *micrometer.* For accurate shop measurements to 0.03 mm (0.001 in.), a bench micrometer, as shown in Fig. 4-17, may be used. This machine is set to correct size by precision-gage blocks, and readings may be made directly from the dial on the headstock, Constant pressure is maintained on all objects being measured, and comparative measurements to 0.0013 mm (0.00005 in.) are possible. Precision measuring machines employing a combination of electronics and mechanical principles are capable of an accuracy of 0.003 mm (0.0001 in.).

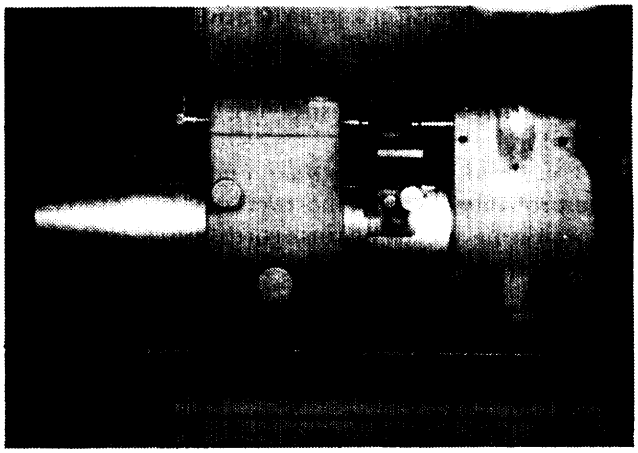

Figure 4-17. Bench Micrometer

2. *Optical instruments.* Numerous optical instruments have been devised for inspecting and measuring because of their extreme accuracy and ability to inspect parts without pressure or contact. A microscope for toolroom work is shown in Fig. 4-18. An object viewed is greatly enlarged, and the image is not reversed as in the ordinary microscope. To be measured, a part is first clamped in proper position on the cross-slide stage. The microscope is focused, and the part to be measured is brought under the crossline seen in the microscope. The micrometer screw is then turned until the other extremity is under the crossline, and the dimension is obtained from the difference in the two readings. The micrometer screws operate in either direction and read to an accuracy of 0.003 mm (0.0001 in.).

Fiber optics can be used as an inspection tool by lighting hard-to-see places and by enabling viewing through a flexible probe. The Bausch and Lomb Flexiscope* has a fiber optic probe equipped with a light and a viewing head. The probe is 610 mm (24 in.) long and can be bent around corners having a radius of less than 50 mm (2 in.). The cooling water passages in automotive cylinder blocks, for example, can be inspected visually using this equipment by “snaking” the probe into the cored areas.

3. *Sine bar.* A sine bar is a simple device used either foraccurately measuring angles or for locating work to a given angle. Mounted on the centerline are two buttons of the same diameter at a known distance apart. The distance on most sine bars is either 127 or 254 mm (5 or 10 in.). For purposes of accurate measurement the bar must be used in connection with a true surface.

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*The Bausch and Lomb Flexiscope is used only as an example of the capability of fiber optics. This discussion does not constitute an indorsement of the Bausch and Lomb Flexiscope.

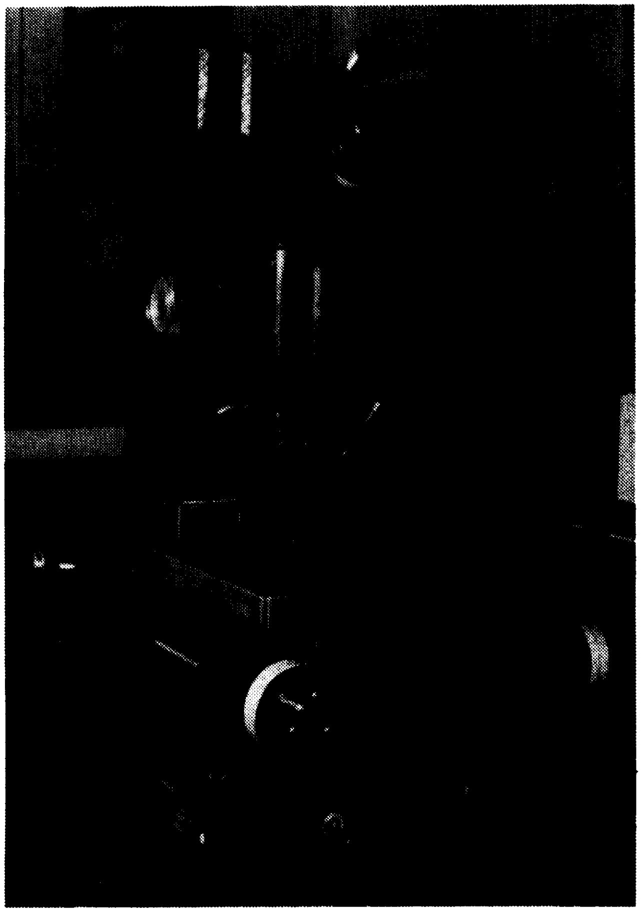

Figure 4-18. Toolmaker's Microscope

The operation of the sine bar is based on the trigonometric relationship that the sine of an angle is equal to the opposite side divided by the hypotenuse. Measurement of the unknown side is accomplished by a height gage or precision blocks. In Fig. 4-19a sine bar is set to check the angle on the end of a machined part.

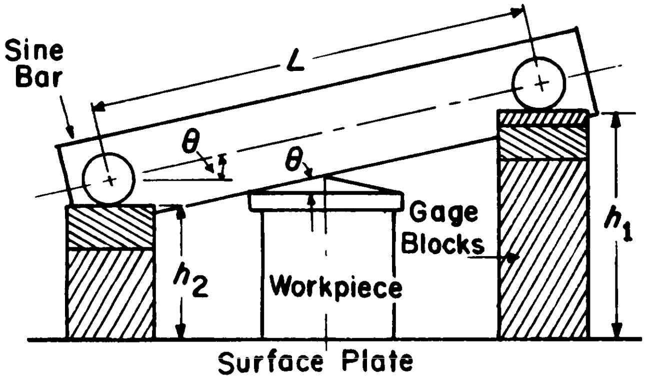

Figure 4-19. Sine Bar Setup on Gage Blocks for Measuring an Angle on a Workpiece

In this case

$$\text{Sin}\,\theta = \frac{h_1 - h_2}{L} \qquad (4\text{-}1)$$

where L *is* a known distance, either 127 or 254 mm (5 or 10 in.), depending on the size bar used. The heights h_1 and h_2 are built up to correct amounts with precision-gage blocks, and their difference in elevation over L gives the sine of angle 0 being checked.

When work is setup to be machined at a given angle, the operation is reversed. The bar is then set at the proper angle, which in turn acts as a gage to position the work correctly.

4. *Dividing heads.* Index or dividing heads were originally developed for checking angles about a common center. The head is made up of a worm and worm gear set having a ratio of 40:1. Hence one turn of the crank will turn the spindle one-fortieth of a revolution or 0.16 rad (9 deg). With the dividing head an angular measurement may be determined to an accuracy of 29 X 10^{-6} rad (6 seconds of arc).

5. *Three-wire system. The* three-wire system for checking screw threads can be used to obtain the pitch diameter. This diameter is difficult to measure directly, but by using three wires, as illustrated in Fig. 4-20, a micrometer reading M across the wires may be made, and the pitch diameter E calculated from the equation

$$E = M - \left(3G - \frac{0.86603}{n}\right) \qquad (4\text{-}2)$$

where

E = pitch diameter, in.
M = measurement over the wire, in.
G = diameter of the wires, in.
n = number of threads per inch.

The best size wire to use for this measurement is given by G = *0.57735/n.* Eq. 4-2 is satisfactory only for 1.05-rad (60-deg) threads, which have a lead angle of 0.09 rad (5 deg) or less. For other threads the equation must be modified. Threads also may be checked using a thread ring or thread plug gage.

4-1.3.2.2 Surface Measurements

Surface checking instruments are for obtaining some measure of the accuracy of a surface or the condition of a finish. Much of this work is done on a flat, accurately machined casting known as a surface plate. It is the base upon which parts are placed and checked with the aid of other measuring tools. These plates are very carefully made and must be accurate to within 0.03 mm (0.001 in.) from the mean plane to any place on the surface. Small plates, known as toolmakers' flats, are lapped to a much greater degree of accuracy. Their field of application is limited to small parts, and in most cases, they are used with precision-gage blocks.

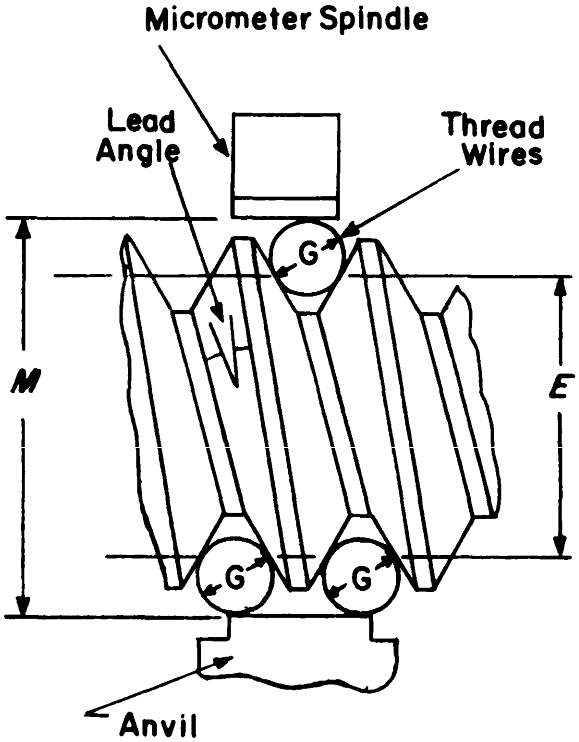

Figure 4-20. Measuring Pitch Diameter by the Three-Wire System

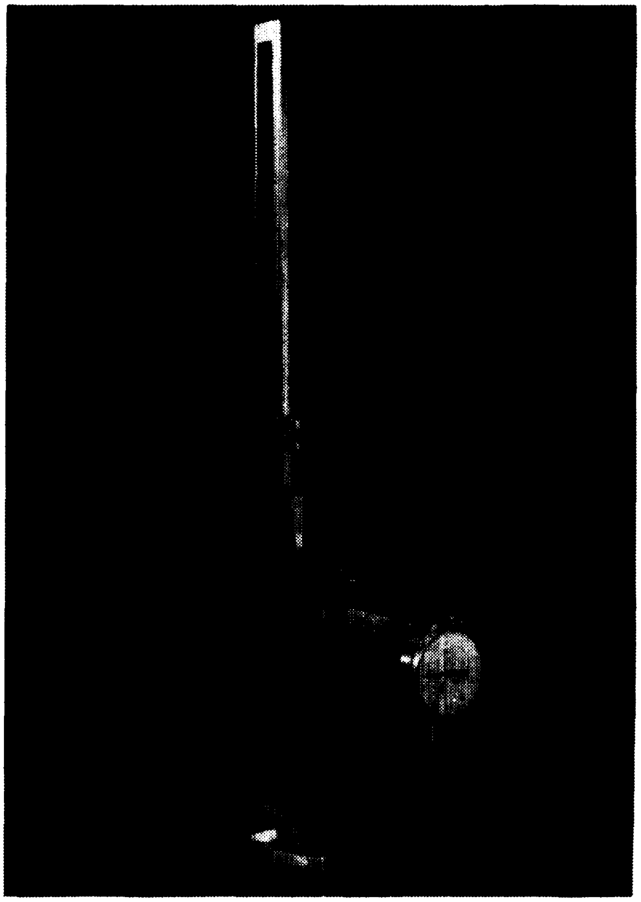

Figure 4-21. Surface Gage

The surface gage, shown in Fig. 4-21, checks the accuracy of parallelism of surfaces and transfer measurements in layout work. When in use, the gage is set in approximate position and locked. The spindle can be finely adjusted by turning the knurled nut that controls the rocking bracket. When used with the scriber, the surface gage is a line-measuring or -locating instrument. If the scriber is replaced by a dial indicator, it then becomes a precision instrument for checking surfaces.

4-1.3.2.3 NC Measuring Machines

These machines, sometimes referred to as digital measuring machines, have provided a degree of automation to the inspection process. They have a surface plate bed up to 910 mm X 1520 mm (3 ft X 5 ft). The machines contain a contact probe driven on three axes and precisely tracked by an inductosyn scale. The probe is either manually positioned on the part or driven by an NC drive over a precise measuring grid. It provides inspection dimensions of the part either through a digital readout or a computer printout. Its measurement accuracies are in the range of 0.08 mm (0.0003 in,), and it can be programmed to take these readings automatically at preselected locations with the same degree of accuracy.

4-2 SHEET METAL COMPONENTS

Sheet metal components are defined as those metal components fabricated from materials 4.76 mm (0.1875 in.) thick or less that employ the manufacturing processes of shearing, forming (i.e., rolling or bending), stamping, and drawing. Typical of the type of components included in this class are metal boxes, cups, brackets, springs, and cover plates. Common producibility problems for this class of parts are given in pars. 4-5.1, 4-5.4, and 4-5.6.

4-2.1 MAJOR MATERIAL CONSIDERATIONS

The variety and quality of materials available today give the designer broad latitude in selection and design. Both Government and private sector research will continue to expand this inventory. Designers should be aware of these changes and alert to the impact on producibility of sheet metal components.

4-2.1.1 Materials

The designer of sheet metal components is initially concerned with the properties of the available materials and their relationship to his design characteristics.

However, there are other considerations relating to producibility that should receive equal consideration. The more commonly used sheet metal materials of strip, sheet, and wire, along with some of the more typical applications, were discussed in par. 4-1, Tables 4-1 through 4-11. These tables also provide remarks on material adaptability to particular manufacturing processes that enhance the characteristics of producibility.

4-2.1.2 Material Properties and Producibility

Mechanical properties give some indication of the ability of a metal to be formed satisfactorily. If there is a relatively large difference between yield and ultimate strengths and elongation is high, the forming characteristics of a material are good.

These physical characteristics give only partial indication of the actual formability of a material. The rate of work hardening has a profound effect on the reduction that can be given to a material before annealing is required and is more important than the mechanical properties of annealed material. Work hardening rates of metals differ greatly, a factor that must be considered in selecting a material for forming operations. As the hardness of a metal increases, its ductility decreases. Some of the physical properties of materials in terms of their effect on producibility with which the designer is concerned were discussed in par. 4-1.1.2.

4-2.1.3 Cost Consideration

A primary consideration in the material selection process is the relative cost of the material. This factor is equally as important to good design practice as it is to good producibility. Actual material prices are very dynamic and should be specifically determined with the potential supplier on a case-by-case basis.

4-2.1.4 Material Availability y

Availability of sizes and shapes in specific geographical locations is determined by the local industry. Because there is such a vast array of size ranges in the various forms, the designer should check the supply listings of his local suppliers to verify these data.

In addition to the base metal and alloys already discussed, there is another line of materials common to sheet metal products of which the designer should be aware, namely, preplated or precoated materials. These materials come in many forms and generally have the same workability as the base materials from which they are made. Significant gains in time and money can be realized through use of these materials by avoiding the secondary operations of plating and coating.

The widespread commercial demand for preplated and precoated materials has greatly expanded the range of materials available to the designer. While some coatings merely improve appearance, most will also increase corrosion resistance or improve some other characteristic. For example, vinyl plastic-coated steels have wide decorative potential. However, vinyl film, which has high corrosion resistance, can be substituted for a more expensive corrosion-resistant material. Table 4-26 lists some of the more common preplated or precoated materials together with some typical applications. Tables 4-27 and 4-28 show some of the more common metal combinations and their typical uses, while Table 4-29 detai1s the common preprinted metals and their typical applications.

4-2.1.5 Material-Related Manufacturing Process

Not all materials can be used for all manufacturing processes. As discussed earlier in this chapter, the selection of a material has a direct bearing on the manufacturing process selected. Each material is directly associated with either a specific manufacturing process or a set of manufacturing processes. Consequently, since production processes are oriented to lot sizes, consideration of the ultimate production quantity must play an important role in material selection because of the resultant impact on producibility.

For example, if a cup is to be made of steel in small quantities, spinning is implied; in large quantities, it must be deep drawn. If the same cup is to have a hole in it and small quantities are desired, the drilling process is implied; medium quantities require that the cups be manually fed and punched; and large quantities necessitate automatic feed, punch, and ejection. Similarly, if the material to be used is stainless steel, heat treatment is implied unless the draw can be made in one operation. It is obvious from previous paragraphs that the physical characteristics, in addition to satisfying the basic design intent, also impact the manufacturing process or processes that may be used. Table 4-30 shows the sheet metal manufacturing processes normally associated with the more common manufacturing materials.

A word of caution to the design engineer interested in good producibility. Magnesium and beryllium are two materials that should be used judiciously. Magnesium creates a significant fire hazard in metalworking plants; accordingly, selected plants should have experience with magnesium and already have established correct safety procedures. Beryllium also creates a toxicity hazard in a metalworking plant and thus requires special handling. These two materials, unless thoroughly checked in advance with the potential manufacturer, can have detrimental effects on producibility.

4-2.2 MANUFACTURING PROCESS CONSIDERATIONS

Increasingly, the need of US industry is to improve productivity. Some significant contributions to this need have been made through technology that continues to grow in sophistication. Despite all the im-

TABLE 4-26. PREPLATED OR PRECOATED MATERIALS AND TYPICAL APPLICATIONS (Ref. 5)

Base Metal / Surface and Coating Method	Low-Carbon Steel	Cu Bearing Steel	Steel, ASTM A122*	Zinc	Aluminum	Brass	Copper	Cu, ASTM B101*	Applications
Aluminum, hot dipped	Sh St	Sh St							Oven door liners, aircraft firewalls, mufflers, space heater baffles
Aluminum, hot dipped			W						Guy wires, overhead ground wires
Brass, copperplated				Sh St					Molding, ornaments, trim, badges, buttons
Brass, copperplated	Sh St								Tubing, frames, luggage, hardware, costume jewelry
Bronze	St								Ornamental trim, shell cases
Chromium, plated				Sh St	Sh St	Sh St	Sh St		Toys, reflectors, trim, automobile accessories
Chromium, plated	Sh St								Heater and toaster shells
Lead, plated	Sh St								Telephone cable sheathing, containers
Lead, plated or hot dipped								Sh St	Roofing, flashing
Lead, hot dipped	Sh St								Ammunition boxes, ducts
Terne, hot dipped	St St								Gasoline tanks, door frames, paint and oil containers
Nickel, plated	Sh St								Toys, trays, knives, nameplates
Tin, plated	Sh St								Food product cans, kitchenware, parts to be soldered
Zinc, plated	Sh St F								Lighting fixtures, spools, reels, oil cans, refrigerator parts
Zinc, hot dipped*									Automobile mufflers, refrigerator and air conditioner parts
Zinc, hot dipped**									Water pipe, electrical conduits
Zinc, hot dipped	W								Fencing

Key: Sh = sheet, St = strip, W = wire, F = flat wire.

*Available as plate, bar, sheet, strip and shapes on low carbon steel (including ASTM A123).

**Available as tubing, pipe, and conduit on carbon or low alloy steel.

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TABLE 4-27. TYPICAL FORMS AND APPLICATIONS OF CLAD METALS (ALUMINUM, COPPER, AND COPPER ALLOYS) (Ref. 5)

Base Metal Surface	Low-Carbon Steel	Carbon Steel	High-Carbon Steel	Low-Alloy Steel	Low-Alloy Steel With Boron	Stainless Steel	F-15 Alloy	Austenitic Stainless	Copper	Beryllium Copper	Aluminum A92024	Aluminum A92014	Aluminum A95056	Aluminum A93003 and 93004	Aluminum A97075	Applications
Aluminum	St															Anode plates for receiving tubes
Aluminum with nickel on other side	St															Anode plates for receiving tubes, except where temperature is too high for aluminum
Aluminum A91100											Sh					Aircraft frames, cooking utensils
Aluminum A96053												Sh				Aircraft fillings
Aluminum A96053													W			Screen wire
Aluminum A97072														Sh		Cooking utensils, gas tanks, bus trim
Aluminum A97072															Sh	Aircraft structural parts
Brass	St															Gaskets, frames, cosmetic cases
Brass over copper	W															Lamp stands, indoor TV antennas
Copper		W R														Lead wire for electronic tubes, power lines
Copper										St						Current-carrying springs
Copper	St W															Gaskets, radiator tanks, electric contacts
Copper			St													Spiral-type springs, clips
Copper					W											Plated jewelry, grid supports for electron tubes
Copper		P W		P W												Chemical process equipment. lead wires, soft seals
Copper						St										Heat exchanger fins
Copper							St									Semiconductors, power tubes
Cupro-nickel								W								Wire rope
Cupro-nickel	St															Chemical process equipment
Phosphor bronze									St							Current-carrying springs and blades

Key: St = strip, Sh = sheet, W = wire, R = ribbon, P = plate.

TABLE 4-28. TYPICAL FORMS AND APPLICATIONS OF CLAD METALS (Ref. 5)

Surface \ Base Metal	Low-Carbon Steel	Low-Alloy Steel	Stainless Steel	Copper	Beryllium Copper	Brass	Aluminum	Aluminum A91100, A95052	Superalloys	Bronze	Nickel	Applications
Hardenable steel				St								Current-carrying springs, connectors, terminals
Stainless steel							C					Cookware, heat exchangers, appliances, trim
Stainless S44500, 52* alloy, F-15* alloy				W								Glass sealing wire for heaters
Stainless S30400, S31000 austenitic				St								Heat exchangers, power tube parts
Stainless S43000				St								Pots, pans, heating wells
Stainless	P Sh	P										Process equipment
Stainless, ferritic	St											Automobile bumpers, grills, trim, cooking utensils
Lead	T			T								Heat exchanger coils for chemical processing equipment
Inconel/monel	P	P										Process equipment
Nickel	W R											Typewriter key levers, grid support rods, tube lead-in wire
Nickel				W R								Electrical circuits for high-temperature environment
A nickel				W R								Electrical circuits in corrosive atmosphere
A or L nickel	P	P										Process equipment
L nickel	St					St						Process equipment
330 nickel*	St											Anode plates for electronic tubes
Hastelloy, Rene									H			Honeycomb, aerospace users
Platinum				T W		T W				T W	T W	Heat exchangers for chemical processes
Silver				W R							W R	High-temperature coils, radar cable braiding, lead wire
Silver						T	T					Waveguides for electronic transmission lines
Silver			St			St		St				Electrical contacts, slip rings
Gold, 14K or more		St		St		St				St	St	Bursting disks, other chemical process equipment, lead wire

Key: St = strip, Sh = sheet, P = plate, T = tube, W = wire,
R = ribbon, H = honeycomb, C = strip, sheet, plate.

*UNS numbers not assigned to all materials.

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TABLE 4-29. PREPAINTED METALS AND TYPICAL APPLICATIONS (Ref. 5)

Base Metal / Prepainted Metal Coating	Aluminum	Steel, Cold-Rolled	Tin Mill Black Plate Steel	Electrolytic Tin Steel	Electrogalvanized Steel	Hot Dipped Galvanized Steel	Aluminum Steel	Preplated Steel	Typical Applications
Alkyd-amino	2	2	2	3	2	2	2	3	Venetian blinds, toolsheds, drums, pails, toys, automobile parts
Vinyl-alkyd	2	2	2	3	2	2	2	3	Roof decking, license plates, baseboard heating covers
Silicone-alkyd	1	2	2	3	1	1	1	3	Telephone booths, building panels, mobile homes, siding
Acrylic	1	1	2	3	1	1	1	3	Wall panels, siding, radio and TV cabinets, hot water jackets
Epoxy (solution)	2	2	2	1	2	2	2	1	Air conditioners, vending machines, nondecorative interior uses
Epoxy (ester)	1	2	2	1	2	2	2	1	Uses requiring high resistance to high temperature, humidity, and chemicals
Polyester	1	1	1	1	1	1	1	1	Building panels, TV cabinets, appliance finishes
Vinyl (solution)	1	1	1	1	1	1	1	1	Siding, small appliances, wall tile, curtain rods, deep draw parts
Vinyl (organasol)	1	1	1	2	1	1	1	1	Siding, roof shingles, automobile parts, deep draw parts
Vinyl (plastisol)	1	1	1	2	1	1	1	2	Siding, luggage, business machines, furniture
Polyvinyl fluoride	1	2	2	2	2	1	1	2	Siding, roof shingles, chemical resistant parts
Polyvinylidene fluoride	1	2	2	2	2	1	1	2	Siding, roof shingles

Key: 1 = normal combination, 2 = combination used sometimes, 3 = combination not used.

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TABLE 4-30. SHEET METAL MANUFACTURING PROCESSES AND MATERIALS

Materials	Manufacturing Processes					
	Swaging	Bending	Drawing	Stamping and Forming	Spinning	Welding, Brazing, Bonding
Low carbon steels	x	x	x	x	x	x
High carbon steels	x			x	x	x
High alloy steels	x	x	x	x		x
Tungsten carbide						x
Stainless steel	x	x	x	x	x	x
Iron						x
Copper	x	x	x	x	x	x
Bronzes	x	x	x	x		x
Brasses	x	x	x	x	x	x
Nickel-base alloys	x	x		x	x	x
Noble metals	x	x	x	x		x
Zinc and its alloys	x	x	x	x	x	x
Lead		x	x		x	x
Tin alloys		x	x			x
Aluminum and its alloys	x	x	x	x	x	x
Magnesium and its alloys	x	x	x	x	x	x
Titanium alloys	x	x		x		x

provements in technology, the essence of improved productivity and good producibility is still found in product design. Unless the designer is fully cognizant of the manufacturing processes, both traditional and nontraditional, these benefits cannot be gained.

4-2.2.1 Traditional Secondary Manufacturing Processes

Table 4-31 provides an overview of the characteristics of the secondary processes most commonly used for sheet metal component manufacturing. All sheet metal processes can be classed as either cutting or forming. Cutting operations are those in which the metal is completely sheared by stressing it beyond its ultimate strength; forming operations are those in which the metal is stressed beyond the yield point and permanently deformed.

4-2.2.1.1 Stamping

Stamping consists of passing a cold sheet or strip of metal through a pair of dies to cut it to a predetermined size and shape. A stamped part is shallow formed and involves little or no change in the thickness of the metal. Parts that are deep formed are considered to be drawn parts.

Stamping is basically a mass production process, and quantity is the key to the effective usage of it. Generally, if a product can be designed as a stamping, it can be produced in large quantities at a lower cost than by any other process. However, to consider stamping as practical only in mass production applications is erroneous. Some short-run stampings with low cost tooling can produce as few as 100 parts in competition with other processes. The minimum quantity for economical production by stamping is determined by the design of the part. In fact, there are several low cost tooling processes designed specifically for short-run stamping.

4-2.2.1.2 Punching

Punching is the cutting of shapes from sheet stock, either to produce finished parts or to perform the first operation before a forming operation. If size is important, the die is made to size, and clearance is taken off the punch. If the blank is very large in relation to the metal thickness, curvature of the sheet may cause measurable inaccuracy in the blank even though the tools are accurate. Shearing and notching are punching operations; however, they differ from symmetrical punching in that they set up unbalanced lateral forces, which make it difficult to control dimensions. In the

TABLE 4-31. SECONDARY PROCESSES FOR SHEET METAL COMPONENT MANUFACTURING

	Typical Lot Sizes	Tooling cost	Finishing cost	Labor cost	Tolerance ±	
					mm	(in.)
Forming Processes						
Roll forming	7315 m (24,000 ft) min	High	Low	Medium	0.3	(0.01)
Impact extruding	100-10,000	Medium	Low	Low	0.13	(0.005)
Drawing	1000 (rein)	High	Low	Medium	0.10	(0.004)
Spinning	10-1000	Low	Low	High	0.08	(0.003)
Reduction Processes						
Stamping	1000 (rein)	High	Low	Medium	0.13	(0.005)
Punching	1000 (rein)	Medium	Low	Low	0.13	(0.005)
Nibbling	10-1000	Low	Medium	High	0.13	(0.005)

Note: All lot sizes are in quantities of items except roll forming, which is minimum linear length,

symmetrical punching operation, lateral forces are in balance and allow closer dimensional control than in shearing and notching. If holes are required in sheet metal parts, they are usually formed by punching, extruding, or piercing as shown in Fig. 4-22.

When a hole is punched, the bottom portion of the stock is torn; therefore, a punched hole is not clearly sheared. This results in the bottom end of a punched hole being larger in diameter than the size of the punch—this tearing varies with stock material, punch design, and punch wear. Fig. 4-23 shows this effect and uses 10% of the stock thickness as assumed tearing, This has a significant effect on hole tolerances as shown in Table 4-32.

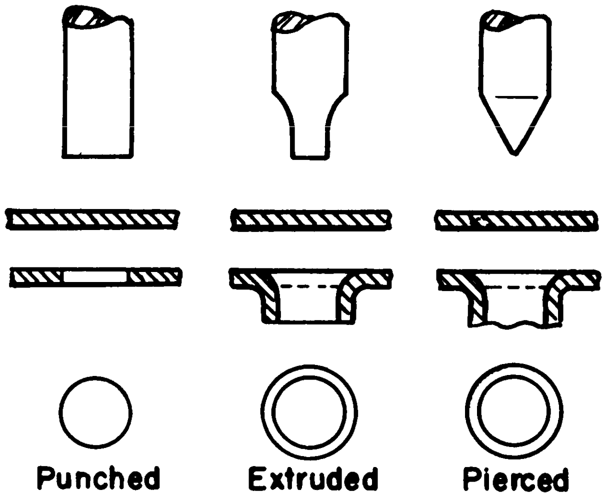

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Figure 4-22. Punched, Extruded, and Pierced Holes (Ref. 5)

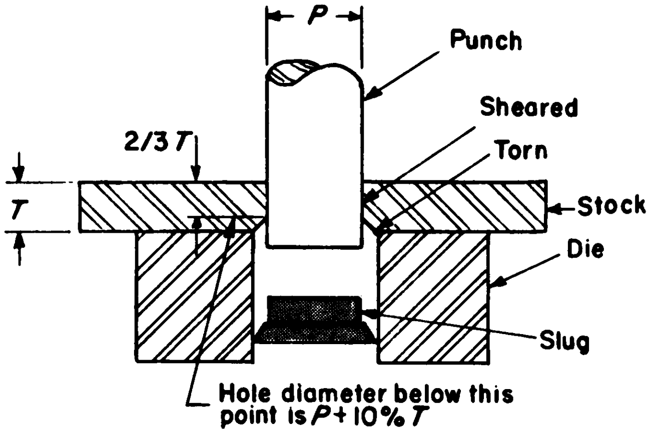

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Figure 4-23. Punched Hole Process (Ref. 5)

4-2.2.1.3 Forming

Forming includes all operations that produce a desired shape in sheet metal by stressing the metal beyond its yield point to produce a permanent dimensional change. This includes bending, drawing, and spinning.

Physical properties give some indication of the ability of a metal to form satisfactorily. If there is a relatively large difference between yield and ultimate strengths and elongation is high, the forming characteristics of a material are good. These physical characteristics give only a partial indication of the actual formability of a material, Rate-of-work hardening has a profound effect on the reduction that can be given to a material before annealing is required and is more important than the mechanical properties of annealed material. Work hardening rates of metals differ greatly,

TABLE 4-32. SUGGESTED MINIMUM TOLERANCES IN PUNCHED HOLES IN ALUMINUM, BRASS, AND LOW CARBON STEELS (Ref. 5)

Metal Thickness		Suggested Minimum Tolerances ± Nominal Diameter of Hole									
		mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)
mm	(in.)	<25	(1)	25 to 76	(1 to 3)	76 to 254	(3 to 10)	254 to 508	(10 to 20)	>508	(20)
<0.38	<(0.015)	0.038	(0.0015)	0.08	(0.003)	0.10	(0.004)	0.15	(0.006)	0.20	(0.008)
0.38 to 0.79	(0.015 to 0.031)	0.08	(0.003)	0.10	(0.004)	0.18	(0.007)	0.20	(0.008)	0.3	(0.01)
0.79 to 1.57	(0.031 to 0.062)	0.10	(0.004)	0.13	(0.005)	0.18	(0.007)	0.3	(0.01)	0.38	(0.015)
1.57 to 3.18	(0.062 to O. 125)	0.3	(0.01)	0.30	(0.012)	0.38	(0.015)	0.5	(0.02)	0.64	(0.025)
3.18	(0.125)	0.5	(0.02)	0.64	(0.025)	0.8	(0.03)	0.89	(0.035)	1.0	(0.04)

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and this is a factor that must be considered in selecting a material for forming operations. As the hardness of a metal increases, its ductility decreases; therefore, the rate-of-work hardening governs the total reduction possible before internal stresses become great enough to require stress relieving.

Difficulties frequently occur when attempting to make reduction beyond the capacity of the metal being formed. For example, if a material has a nominal elongation of 25%, commercial lots of that material may vary from 23 to 30%. If the tooling is established on the basis of 25% elongation, high scrap losses may result when a lot on the very low side of the range is received. There is nothing wrong with the material if it meets the minimum ductility requirement; on the contrary, the tooling is wrong because it was designed too close to the working limits of the material.

Difficulties may arise if commercial tolerances of the material are not taken into account in the designing stage. Thickness variation in sheet metals can cause parts made on the same tooling to be different in shape because of springback or because the pressure applied is either insufficient or excessive for forming the predetermined angles.

4-2.2.1.4 Spinning

Spinning is a method of forming sheet metal into conical, hemispherical, or cylindrical shapes by combined rotation and force. The forming is done by the application of pressure by a roller or spinning tool on the metal piece while it is being rotated by a revolving wooden or metal form, called the chuck, in a spinning lathe. Conventional spinning and displacement spinning are the two categories of this method of metal forming. Fig. 4-24 shows a compassion of these two processes.

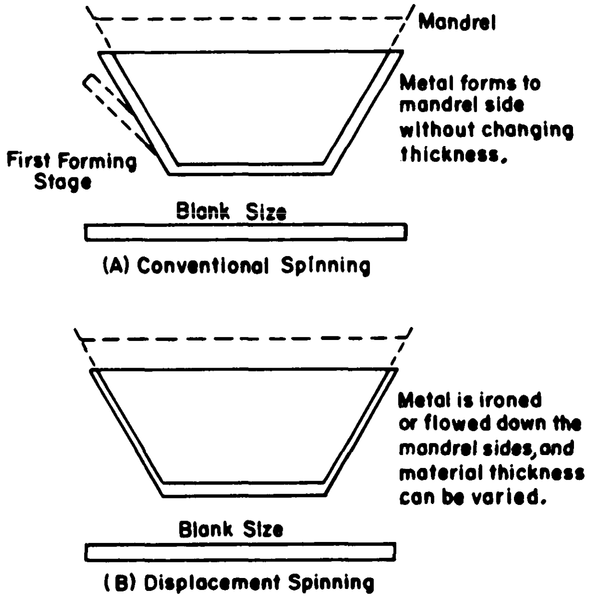

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Figure 4-24. Comparison of Conventional and Displacement Spinning (Ref. 5)

4-2.2.1.4.1 Conventional Spinning

Conventional spinning involves forming of the metal back along the chuck. The area of the blank must be approximately equal to the shell area; the shell thickness remains constant. Three different types of conventional spinning are described:

1. *Chuck spinning* refers to the spinning of open shapes with no reentrant contours. The spun shapes can be produced in tiers and by one or more regular

spinning operations. This is the most common and oldest method of spinning.

2. *Sectional chuck spinning* is used mainly on drawn shells to produce shapes having reentrant contours in which the neck or opening is smaller than the body. These chucks must be well matched at the section joints to prevent marks from showing on the finished shell.

3. *Internal roll spinning*, an improved method of spinning reentrant shapes, bulges, and necks, is capable of high production speeds since the piece can be quickly removed from the roll without taking the tool apart.

4-2.2.1.4.2 Displacement Spinning

Displacement spinning involves an ironing of the metal back along the chuck. In this process, a smaller, thicker blank is used so that the difference between the blank and the shell areas is equalized by thinning out a portion of the thick blank during spinning. Two different types of displacement spinning are described:

1. *Hydrospinning.* In the hydrospin process, a metal, disc-type blank is rotated at high speed while two opposing rollers force the material onto the rotating mandrel. The hydrospin machine is semiautomatic and hydraulically controlled, which gives it both power and flexibility. Hydrospinning can produce strong parts with maximum resistance to fatigue failure. When the metal is hydrospun, it undergoes a shear deformation that greatly elongates the grain structure. This deformation results in work hardening of the metal with a resultant increase in tensile strength.

2. *Flowturning.* Flowturn* is a trade name that has been applied to a Lodge and Shipley development. It is basically a cold-rolling process in which the metal is displaced parallel to the centerline of a part in a spiral manner. This differs from the application of pressure in a cold-rolling mill only in that displacement in a mill is in a longitudinal direction and the displacement by Flowturning is in a spiral manner. This is accomplished by flowing the metal over a mandrel with a roller that is actuated by mechanical or hydraulic forces.

There is one basic difference between the Flowturning method of cold-rolling and spinning. In spinning, a blank considerably larger than the finished piece is used. By exerting pressure, the blank is folded in a circular manner by using a hard tool against a round mold; this requires considerable skill on the part of the operator. In the Flowturning method the metal to form the part is obtained from the thickness of the blank instead of from the diameter of the blank. The blank diameter is the same as that of the finished part, but its thickness is greater. The additional metal provided by this greater thickness is flowed into the extended shape. The machine controls all operations, and all parts are produced to uniform accuracy. Some typical spinning tolerances are shown in Table 4-33.

4-2.2.1.5 Deep Drawing

Deep drawing is the plastic deformation of sheet metal usually performed on a press. In this process a blank of metal is stretched over a punch being forced into a mating or die cavity under very high pressure. There are three processes, i.e., marforming, conventional forming, and hydroforming.

1. *Marform.* In marforming the punch forces the blank into a series of rubber pads. The rubber forces the metal against the walls of the punch. The marform process shown in Fig. 4-25 uses a rubber pad to envelop the part and also a blank holder or pressure pad around the punch. A blank is laid on the punch and blank holder. The blank is drawn from between the rubber pad and blank holder as it is wrapped around the punch while the press pressures are mostly from 37 to 55 MPa (5500 to 8000 psi), but sometimes as high as 80 MPa (12,000 psi). Typical parts produced are flanged cups, spherical domes, conical and rectangular shells, and asymmetrical shapes with an embossed or recessed area. Marforming is slower but is more suitable for deep drawing and gives better definition to shallow forms than does rubber pad forming. Operation rates range from 60 to 240 cycles/h.

2. *Conventional:* In this process there are matching metal punch and die tools. The operations in this category produce thin-wall, hollow, or vessel-shaped parts from sheet metal. Examples are seamless pots, pans, tubs, cans, and covers; automobile panels, fenders, tops, and hoods; cartridge and projectile cases; and parabolic reflectors. The sheet metal is stretched in at

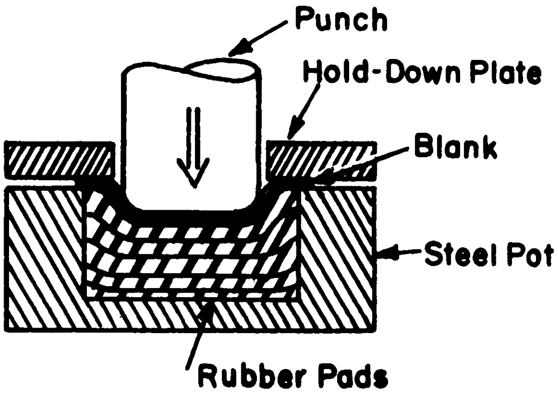

Figure 4-25. Marforming

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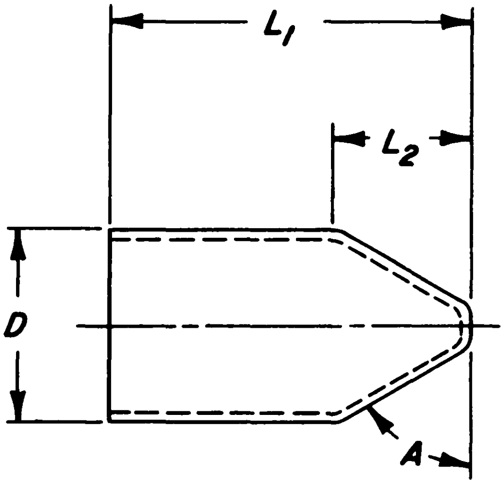
* The use of this trade name does not constitute an endorsement of this process.

TABLE 4-33. TYPICAL SPINNING TOLERANCES (Ref. 5)

Nominal Part Diameter		Minimum Tolerances ±					
		L_1		L_2		A	
mm	(in.)	mm	(in.)	mm	(in.)	rad	(deg)
<38	<(1.5)	0.3	(0.01)	0.38	(0.015)	0.03	(2)
38 to 127	(1.5 to 5)	0.38	(0.015)	0.8	(0.03)	0.10	(6)
127 to 508	(5 to 20)	0.8	(0.03)	0.8	(0.03)	0.10	(6)
508 to 914	(20 to 36)	1.5	(0.06)	1.14	(0.045)	0.17	(10)
914 to 1828	(36 to 72)	3.0	(0.12)	1.5	(0.06)	0.17	(10)



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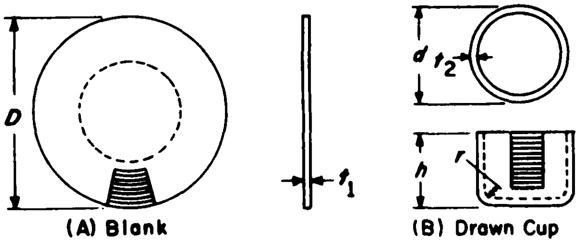
least one direction but also is often compressed in other directions in these operations. The work is mostly done cold, but sometimes it is done hot.

A great variety of shapes are drawn from sheet metal. The action basic to all is found in the drawing of a round cup. The cup depicted in Fig. 4-26 is formed by drawing it from the blank shown beside it. Shaded segments of the blank and cup indicate what is done to the metal. A trapezoid in the blank is stretched in one direction by tension and compressed in another direction into a rectangle. Metal must be stressed above the elastic limit to form the walls of the cup but not to form the bottom.



(A) Blank (B) Drawn Cup

Figure 4-26. An Example of a Cup Drawn from a Round Blank

The drawing of a cup is shown in Fig. 4-27. The blank is placed on the top of a die block. The punch pushes the bottom of the cup into the hole in the block and draws the remaining metal over the edge of the hole to form the sides. The edges of the punch and die must be rounded to avoid cutting or tearing the metal. The clearance between the punch and die block is a little larger than the stock thickness. As has been explained, compressive stresses are set up around the flange as it is drawn into smaller and smaller circles. If the flange is thin (less than 2% of the cup diameter), it can be expected to buckle like any thin piece of metal compressed in its weakest direction. To avoid wrinkling, pressure is applied to the flange by a pressure pad or blank holder. In practice, pressure is obtained from springs, rubber pads, compressed air cylinders, or an auxiliary ram on a double-action press. The force

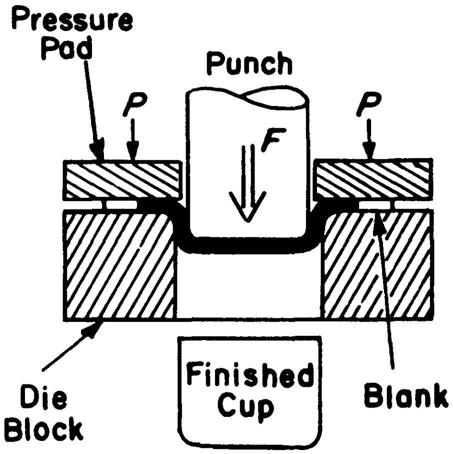


Figure 4-27. Drawing a Cup

required is normally less than 40% of the drawing force. Usually the blank is lubricated to help it slide under the pressure pad and over the edge of the die.

3. *Hydroform:* Hydroforming, shown in Fig. 4-28, employs a punch and a flexible die in the form of a rubber diaphragm backed by oil pressure. The blank is laid on a blank holder over the punch. First the dome is lowered until the diaphragm covers the blank, and initial oil pressure is applied. Then the punch is raised, and the oil pressure augmented to draw and form the metal to the desired shape. Hydroforming produces the same kind of parts as marforming with slightly sharper detail, particularly in external radii.

Hydroform presses and equipment are available in 203- to 812-mm (8 to 32 in.) sizes, which designate the diameter of the blank that can be drawn. Draw depths range from 127 to 304 mm (5 to 12 in.), and operating rates from 90 to 200 cycles/h. The small presses are fastest. A complete outfit may cost as much as $250,000.

As a rule, the marform and hydroform processes are not nearly as fast and cannot compete in production rate with conventional forming for large quantities of pieces. Marform and hydroform have an advantage for quantities up to several hundred or thousand pieces, depending on the part, because their tool costs are low (only a punch is required), and lead times are short. Only one member is needed, and if conditions are right, the member generally can be made from easily machined material, such as a plastic or soft metal, because the service is not harsh. Tooling costs are from 30 to 80% of those for hard steel dies, so savings are several hundred to thousands of dollars for each job. The mild forming action keeps maintenance costs low and does not mar the work material, not even preprinted sheets. Stock as thick as 6.35 mm (0.250 in.) to 9.52 mm (0.375 in.) is commonly worked, and even much thicker material has been formed from aluminum alloys. Tolerances of ± 0.05 mm (0.002 in.) are possible, and ± 0.13 mm (0.005 in.) are practical. These are comparable to performances with the best quality rigid dies. Fig. 4-29 explains some of the deep drawing process constraints regardless of the forming process.

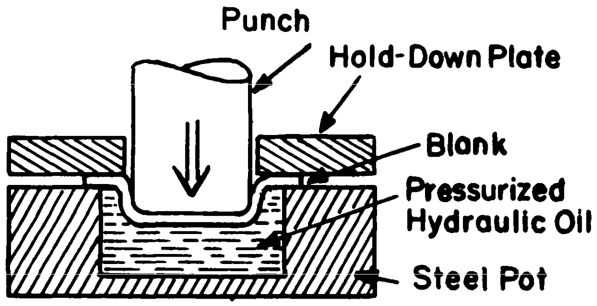
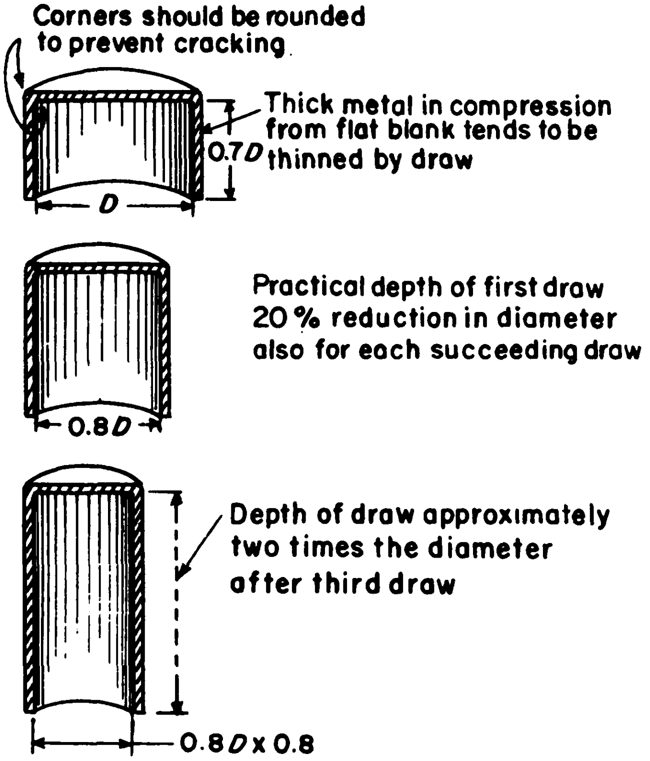


Figure 4-28. Hydroforming



Note: Shell should be annealed after third operation to remove work hardening. Hardening can be delayed by working fast enough to prevent cooling between successive draws.

Figure 4-29. Drawing Depth and Diameter for All Deep Drawing Processes

4-2.2.2 Nontraditional Secondary Manufacturing Processes

4-2.2.2.1 Numerical Control Machines (NCM)

Not a new technology, NCM have thus far made relatively small inroads into the traditional manufacturing processes. This technology is just what its name implies—control. It is a method of controlling machines at very high speeds and accuracies. Its largest penetration into the work of sheet metal component manufacturing has been on sheet metal punch presses. Current industrial estimates indicate that NC punch presses represent only about 4% of the total national NCM inventory, yet their application probably results in greater productivity improvements than does any other metal-cutting NCM. Improvement ratios of 10:1 and higher are not unusual, and this improvement is reflected in both the piece part cost and the throughput of the machine.

The tool builders have been making additional improvements in their machines and peripheral systems. A review of currently available equipment reveals some of these improvements. Table speeds up to 0.85 m/s (2000 in./min) punching speed (on 25-mm (l-in.) centers) up to 280 strokes/rein, hole sizes up to 200 mm (8-in.) diameter, press tonnages up to 90,700 kg (100 tons) are just a few of the more obvious ones. A few of the more startling improvements include milling and tapping attachments, contouring (not nibbling), special software features (canned cycles) to reduce the part programming work load, and control capabilities that permit the generation of management reports.

NC punch presses may be new, but in many respects they have led the trends specifically in the area of tool standardization, The initial turret toolholders quickly made the first users aware of how rapidly the turret could index to the next tool. It also made them very aware of the cost of changing tools in the turret. As early as 1966 and 1967 some shops with NC punch presses were beginning to standardize hole sizes. One manufacturer of electronic chassis who had purchased an eight-station turret press was quick to seize on the advantage. This manufacturer standardized six different hole sizes. These six punches (1.588, 3.18,6.4, 13,25, 51 mm (0.0625, 0.125, 0.25, 0.5, 1, 2 in.)) were permanently loaded in the first six turret positions. Any special sizes other than these must be justified. Two blank turrets were left for these specials when they are absolutely required. For almost 10 yr now that plant has been operating successfully with that standard. The resultant savings are obvious.

4-3 NET SHAPE OR MACHINED METAL COMPONENTS (NS/MMC)

For purposes of this handbook, net shape or machined metal components (NS/MMC) are those metal parts ranging from very simple m very complex configurations containing multiple flat and curved surfaces often in irregular shapes. Typical shapes of components included in this classification are solid and hollow concentric, cap or cone concentric, solid and hollow nonconcentrics, cap or cone nonconcentrics, flats and flanged parts, spirals and miscellaneous complex shapes. There are no size constraints for this class of parts; they are generally considered to fall within the envelope of commercial bar stock sizes and shapes. This class of parts generally would be produced by the forming, reduction, and finishing processes. Typical of the components in this category are fuze bodies, nozzles, gears, shafts, and other similar precision parts. Common producibility problems in this class of parts are given in pars. 4-5.2, 4-5.3, 4-5.5, 4-5.8, and 4-5.10.

4-3.1 MAJOR MATERIAL CONSIDERATIONS

NS/MMC probably offer the greatest range of material for consideration. They, therefore, offer the greatest mix of material characteristics and inherently provide the largest base for alternative selections. As a consequence, when selecting material to satisfy design criteria, the designer should consider a base or optimum material and a group of alternatives for producibility considerations. Early in the material selection process the design engineer should give some general consideration to the best suited manufacturing process and acceptable materials. This should result in a list of manufacturing process-related materials and a list of design characteristic materials. Subsequent trade-offs between these two lists would then provide a relatively firm basis for proceeding with the material selection process.

4-3.1.1 Materials

There is a wide range of metallic materials available for consideration in NS/MMC and hence a wide range of alternatives to optimize the satisfaction of design characteristics and producibility factors. The full range of material options is shown in Tables 4-1 through 4-9. These tables also show. some typical applications for each of the materials and some pertinent remarks relative to manufacturing constraints. The design engineer should select material that best satisfies both the design requirements and the producibility factors.

4-3.1.2 Material Properties and Producibility

In selecting a material to satisfy the design requirements, the characteristics or properties are of prime consideration. These are all available in a number of good reference books and, consequently, are not repeated here. During this initial step, severe constraints can be placed on the producibility of the item unless the designer is cognizant of how these properties impact the manufacturing processes. Some of the more pertinent material physical properties and how they affect producibility were discussed in par. 4-1.1.2.

4-3.1.3 Cost Considerations

In the basic material selection process one of the primary considerations is material cost, which will vary with the shape, form, and geographical location of the supplier in reference to the user.

Although the relative cost varies with changes in shape, size, quantity, market prices, etc., it is a good base for comparing costs when selecting materials for a new design or when changing from one material to another. The data in Table 4-12 are helpful in selecting the best materials for a specific part. For exotic materials not evaluated in Table 4-12, the designer should consult with metallurgists and suppliers to ascertain the proper uses, mechanical properties, and other required data on the material.

In addition to the base cost of materials, there are other cost factors to consider that can have an even greater impact on cost; specifically, materials affect manufacturing costs. This fact is illustrated in Fig. 4-1, which shows the relative costs for machining aluminum, carbon steels, alloy steels, and corrosion-resistant steels. Even for a given material there can be a substantial cost difference based on the alloy used. As an example, Table 4-34 shows manufacturing variations among some commonly used aluminum alloys.

4-3.1.4 Material Availability

Availability of resources is one of the first and, consequently, most important elements of good producibility. Certainly, the design engineer could not be expected to foresee every possible circumstance that would preclude the availability of a material. However, there are a number of precautions to be taken to avoid major pitfalls in this area.

Critical or strategic materials were discussed in Chapter 3. In this era of growing criticality of our natural resources, this factor must be considered in the material selection process. Additionally, world conditions at the time of the selection process can have significant impact on material availability.

Other important factors determining material availability are the stock shape and form commercially available. These factors are largely determined by the

TABLE 4-34. ALUMINUM ALLOY MATERIAL SELECTION CHART

Alloys and Temper	Resistance to Corrosion		Work-ability (cold)	Machin-ability	Braz-ability	Weldability			Typical Application
	General	Stress Corrosion Cracking				Gas	Arc Resistance	Spot and Seam	
A92024	—	—	—	D	D	D	D	D	Screw machine products and aircraft structure.
T4	D	C	C	B	D	C	B	B	
T6	D	B	C	B	D	D	C	B	
A95052	A	A	A	D	C	A	A	B	Sheet metal work and hydraulic tubes.
H32	A	A	B	D	C	A	A	A	
H34	A	A	B	C	C	A	A	A	
H36	A	A	C	C	C	A	A	A	
H38	A	A	C	C	C	A	A	A	
A96061	B	A	A	D	A	A	A	B	Heavy-duty structural requirements, good corrosion resistance.
T4	B	B	B	C	A	A	A	A	
T6	B	A	C	C	A	A	A	A	
A07075	—	—	—	D	D	D	C	B	Aircraft and other structures.
T6	C	C	D	B	D	D	D	C	

Ratings A through D are relative in decreasing order of merit. For weldability and brazability, ratings A through D are relative but are defined as follows:

A—Generally weldable by al1 commercial procedures and methods.
B—Weldable with special techniques or for specific applications which justify preliminary trials and testing to develop welding procedure and performance.
C—Limited weldability because of crack sensitivity or loss in resistance to corrosion and loss of mechanical properties.
D—No commonly used welding methods have been developed.

commercial market. In Table 4-12 some commercially available metal alloys and the forms in which they can be purchased are given.

Since the inventories of the suppliers will vary under differing circumstances and geographic locations, specific information should be obtained directly from potential suppliers.

4-3.1.5 Material-Related Manufacturing Processes

As discussed earlier in this chapter, there are definite producibility constraints placed on the manufacturing process selection by the material selection, To assist the designer, Table 4-35 shows some of the more common metal alloys and the related manufacturing processes that are recommended for use with them. This table is designed to provide only a general overview of material-related manufacturing processes. Obviously, the different alloys of each of the base materials have different physical characteristics and inherently different manufacturing constraints. These details are shown in Table 4-13.

4-3.1.5.1 Lot Sizes and Producibility

Production quantity requirements of NS/MMC will have significant bearing on material selection. The material selection considerations for a component to be produced in quantities of 1.500 yr are significantly different from the considerations for the same component m be produced in quantities of 1,000,000 yr. Historitally, this has been addressed after the requirement goes to production, and invariably a hasty decision on the acceptability of material alternatives has resulted. This obviously can lead to poor producibility. Ideally, the consideration of the impact of quantity requirements on material selection should be viewed early in the design process. Table 4-36 includes the production lot sizes of some of the processes common to NS MMC.

4-3.2 MANUFACTURING PROCESS CONSIDERATIONS

The selection of the manufacturing process has to rank high as a major producibility factor. In addition to selecting the right process, the factors of process availability, lead time, production time, and sufficiency of resources must also be considered. Selection of the most cost-effective manufacturing process that has insufficient capacity to meet the required delivery data does not result in good produibility.

In the subparagraphs that follow, the manufacturing process options, to include their charactcristics and

TABLE 4-35. MANUFACTURING PROCESSES AND MATERIALS FOR NS/MMC

Materials	Manufacturing Process						
	Castings	Forgings	Cold Heading	Extrusions	Powder Met*	Screw Machining	Welding, Brazing, Bonding
Low carbon steels	X	X	X	x	x	x	x
High carbon steels	X	X			x	x	x
High alloy steels	X	X		x	x		x
Tungsten carbide					x		x
Stainless steel	X	X	X		x		x
Iron	X				x		x
Copper	X			x	x		x
Bronzes	X	X	X	X	x		x
Brasses	X	X	X	X	x	x	x
Nickel base alloys	X	X	X	x	x		x
Noble metals	X				x	X	x
Zinc and its alloys	X			X	x		x
Lead	X			X	x		x
Tin alloys	X			x	x		x
Aluminum and its alloys	X	X	X	x	x	x	x
Magnesium and its alloys	X	X		x	x	x	x
Titanium alloys	X	X		X	x		x

*Powder Met = powder metallurgy

TABLE 4-36. MANUFACTURING PROCESS CAPABILITIES

Process	Surface Finishes		Lot Sizes	Tolerances ±		Relative Cost		Availability	
	µm	(µin.)		mm	(in.)	Tooling	Production		Lead Time, Weeks
Sand casting	6.35	(250)	25– 1000	0.76	(0.030)	Low	High	Fair	6
Investment casting	2.16	(85)	25–10,000	0.13	(0.005)	Medium	Medium	Fair	12
Permanent mold	2.16	(85)	1000–10,000	0,38	(0.015)	Medium	Low	Fair	12
Die casting	2.16	(85)	10,000+	0.13	(0.005)	High	Low	Fair	12
Drop forge	6.35	(250)	10,000+	0.13	(0.005)	High	Medium	Fair	1
Rotary forge	2.54	(loo)	2000+	0.13	(0.005)	High	Low	Poor	16
Press forge	6.35	(250)	500– 100,000	0.89	(0.035)	High	Medium	Fair	12
Machine forge	6.35	(250)	2000- 100,000	0.76	(0.030)	High	Medium	Fair	8
Powder metallurgy	3.18	(125)	1 000+	0.25	(0.010)	High	Medium	Fair	10
Extrusion, direct	1.6	(63)	1 000+	0.13	(0.005)	Medium	Low	Good	10
Extrusion, impact	1.6	(63)	1 000+	0.13	(0.005)	Low	Medium	Good	4
Extrusion, hooker	1.6	(63)	1 000+	0.13	(0.005)	Medium	Medium	Good	4
Coextrusion	1.6	(63)	1 000+	0.13	(0.005)	High	Low	Fair	12
Machining	1.6	(63)	1–100,000	0.13 to 0.38	(0.005 to 0.015)	Medium	Medium	Very good	3
Machining, NC	1.6	(63)	1–10,000	0.013 to 0.08	(0.0005 to 0.003)	Medium	Low	Good	3

capabilities, are discussed. These are addressed as traditional and nontraditional processes. Also provided are data relative to the availability and lead times for each. However, these latter two factors will vary under differing circumstances and geographic locations. Specific information should be obtained from potential suppliers at the time of need.

4-3.2.1 Traditional Secondary Manufacturing Processes

In par. 4-1.2 the primary and secondary manufacturing processes were discussed. This discussion will expand on those processes that are specifically applicable to the class of metal components under consideration here—net shape or machined components. The processes considered traditional are those conventional manufacturing processes that are well established and have been accepted as practice throughout the general metalworking industry. Those processes generally considered to be in this group and a summary of their capabilities are listed in Table 4-36 and are described in the paragraphs that follow.

4-3.2.1.1 Casting

Casting is performed by pouring molten metal into a cavity of desired shape, allowing the molten metal to solidify, and separating it from the cavity. There are several types of castings available, and Table 4-37 compares various casting processes.

A word of caution to the design engineer considering castings: environmental pollution controls and the Occupational Safety and Health Administration (OSHA) have had a significant impact on foundries. As a result, there has been a notable reduction in our national foundry resources. Therefore, availability of such facilities in the future should be watched carefully. Before committing a design to a casting process, the availability of foundry resources should be reviewed carefully with potential sources.

4-3.2.1.1.1 Sand Casting

Sand casting, one of the more prevalent casting methods, produces parts of moderate complexity in moderate quantities. In this process a master pattern, which contains the appropriate drafts and shrinkage allowances, is made of the finished part, usually from an easy to form material. An impression of the pattern is made in specially mixed sand. This impression is filled with the appropriate molten metal (aluminum, copper, magnesium alloys, beryllium copper, malleable iron, cast steel, or cast iron), which is allowed to harden. The normal production tolerance is+ 0.76 mm (0.030 in.) except for iron and steel, which will normally require approximately 0.13 mm (0.005 in.) more.

TABLE 4-37. GENERAL COMPARISON OF CASTING PROCESSES (Ref. 5)

Property or Characteristic	Sand	Permanent Mold	Die	Plaster or Investment
Strength	A	A	B	A
Structural density	B	A	c	A
Reproducibility	C	B	A	B
Pressure tightness	B	A	c	A
Cost per piece*	C	B	A	D
Production rate*	C	B	A	D
Flexibility as to alloys	A	B	c	A
Tolerances	D	c	A	B
Design flexibility	A	B	c	A
Size limitation	A	B	B	c
Surface finish	c	B	A	A
Time to obtain tooling	A	B	B	B
Pattern or mold cost	A	B	c	B
Thin sections	c	B	A	A
Freedom from porosity	B	B	D	A
Structural uniformity between pieces	B	B	D	A

Ratings A, B, C, and D indicate relative advantages; A is best.

* Although this rating covers the majority of castings, sand or permanent mold may take preeminence in the case of multiple patterns or mold cavities.

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Closer tolerances can be maintained, but only at additional cost. Fig. 4-30 shows the percentage of cost increase that can be expected from different tolerance levels. Holes and pockets may be produced in sand castings either by incorporating them in the pattern equipment or by inserting separately made sand cores. Cast surface finishes are 6.35 µm (250 µin.) for nonferrous metals and 12.7 µm (500 µin.) for ferrous metals.

4-3.2.1.1.2 Permanent Mold Casting

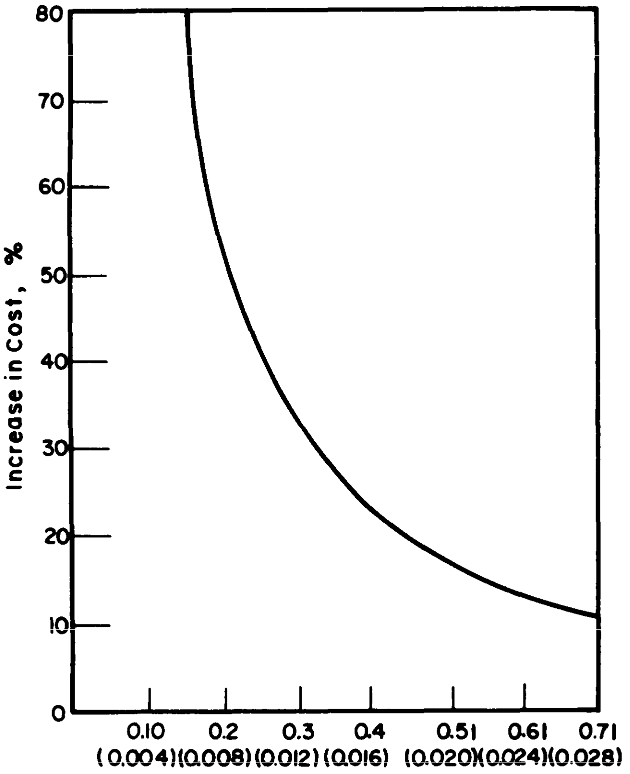
This process consists of pouring, without pressure (relying on gravity), molten metal into a permanent mold made of metal (iron, steel, or bronze). Draft angles are necessary. Although enhanced quality plays a significant role in selecting the permanent mold process, the economy of the process itself is usually the primary basis of selection. The cost of the mold and the accessory equipment is higher than that of the patterns used in sand casting. Where the number of castings required is sufficient to justify the initial tooling cost, permanent mold castings are usually more economical than sand castings because of the higher production rates and the generally lower level of skilled labor required. Further economy is often found in the opportunity to design to a smaller casting weight. Frequently, major savings are possible because of the decrease in machining costs permitted by closer dimensional tolerances.

In general, permanent mold castings must be of simple design. Some complexity is possible, however, by using sand cores with steel molds.

The most common casting materials are aluminum, brass, bronze, and magnesium. Permanent mold castings are usually very dense and have better surface finishes than sand castings.

Solid die tolerances for aluminum and magnesium alloys are ± 0.38 mm (0.015 in.) up to the first 25 mm (1 in.), and ± 0.05 mm (0.002 in.) for each additional increment of 25 mm (1 in.). Copper-based alloys have solid die tolerances of ± 0.38 mm (0.015 in.) up to the first 25 mm (1 in.) and ± 0.13 mm (0.005 in.) for each additional increment of 25 mm (1 in.).

The tolerances represent normal production capability at the most economical level. Closer tolerances should be specified only when absolutely necessary, i.e., to produce greater accuracy or finish. More liberal tolerance values can be specified, where practical, to



Tolerance ±per mm (in.) up to 152.4 mm (6 in.)

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Figure 4-30. Sand Casting Tolerances and Cost Comparison (Ref. 5)

further reduce production cost. Fig. 4-31 graphically demonstrates the cost of various tolerances for permanent mold casting.

4-3.2.1.1.3 Investment Casting

Investment casting begins with the making of a wax, plastic, or even a frozen mercury pattern from a die; the pattern is then surrounded (invested) with a wet refractory material, which is referred to as the investment material. The pattern is melted or burned out after the investment material has dried and set. Molten metal is poured into the cavity of the investment material, and when the metal has solidified, the investment material is broken off, which leaves the finished investment casting. Investment casting is an established foundry method that competes with machining. Generally, investment castings are more expensive than other castings, but as an end product they can be more economical since little, if any, machining will be required. Recent improvements in technology have both lowered costs and markedly improved product quality, making investment castings practical and available for many applications formerly beyond their scope.

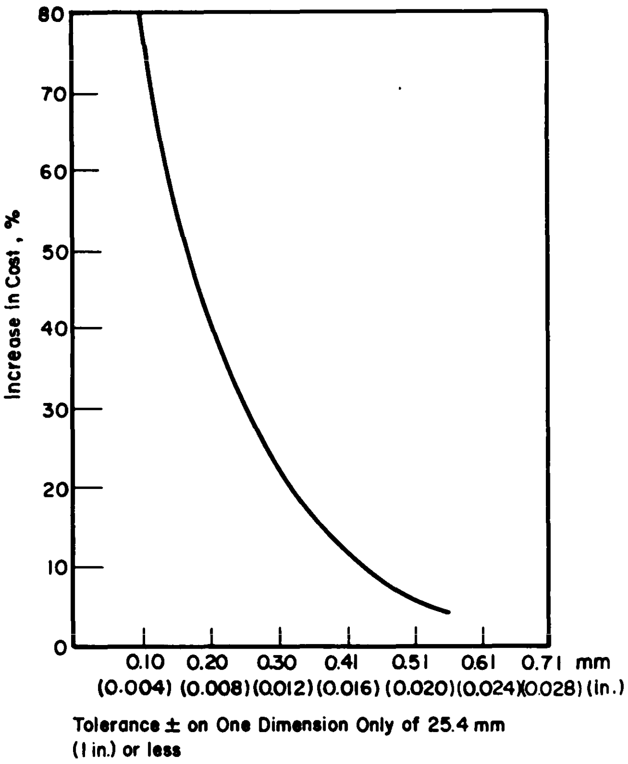

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Figure 4-31. Cost of Tolerance-Permanent Mold Casting (Ref. 5)

When the acceptance of complex shapes, the tooling costs, the economical tolerances, and the wide choice of metals that can be cast are taken into consideration, investment castings sometimes can be the most economical method for fabricating a part. Experienced users of investment castings take maximum advantage of the process by specifying “practical” dimensional tolerances (economical as well as functional).

-Used properly, investment castings offer new freedom of design and new areas of economy. The time to decide whether a part is suitable for investment casting, or any other casting method, is when the part is still on the drawing board. Although it is easy to modify the design of a machine part for investment casting, it is even easier to design the part to be investment cast from the start. Generally speaking, the designer can follow the same basic design rules for an investment casting that he would follow for any other casting method.

Deciding to use an investment casting is easy when a part is so complex or the alloy so difficult to machine that any other process is not economically feasible. An investment casting should be considered as an alternative for small lot sizes of parts planned for stamping, forging, die casting, or any other low-cost, mass production method.

It is more economical to investment cast a part when the machining operations can be reduced or eliminated or when internal contours or configurations are impossible to machine. This generally holds true—unless the quantity is small and the design is very likely to change—even if the part is made from various pieces and assembled by soldering, brazing, or welding. Table 4-38 is provided to assist the designer in selecting materials for the investment casting process; it also provides some suggested applications and design constraints.

4-3.2.1.1.4 Die Casting

Forcing metal, in a highly viscous state, under air or hydraulic pressure, into a closed metal die is called die casting. Die castings offer closer dimensional tolerances than any production casting process. As in any other casting design. tolerances should be held to a minimum only on dimensions that so require.

Simple forms that are easily cut into the die blocks help to minimize die cost, but it is entirely possible to make complex forms when they are necessary. Parts that have external undercuts or projections on side walls often require slides that materially increase the die costs.

Along with significant savings in the amount of metal actually used, die casting offers other advantages, such as more uniform wall sections, all of which offset the extra cost or effect a net economy in the overall cost of the part. This is especially true when large quantities are involved since a small savings per die casting may fully justify a much more expensive die. However, as in any casting design, the designer must analyze his design as to quantity and cost of machining and whether other methods can be used to fabricate the part. If the quantity is low and the die cost is high, it is perhaps better and more economical to use other fabrication methods. Table 4-39 provides some size constraints for the die casting process.

4-3.2.1.2 Forging

This is the age-old art of the blacksmith. Technically, it is the plastic deformation of material, usually hot, into desired shapes with compressive force. However, because of cost and OSHA requirements, both casting and forging are to some extent being replaced by weldments. The sources of supply are dwindling; during the 1980's this may be critical. This is especially true of larger-sectioned components. Forging consists of drop forging, rotary forging, press forging, and machine forging.

Different metals respond differently to forging. The amount of deformation a metal can be subjected to without exhibiting adverse effects must be considered in the selection of forging methods, the selection of forging equipment, and the die design.

Costs are affected by the kind of material selected and by the type of forging to be used with that material. The materials that follow are ranked in order of increasing forging difficulty:

1. Aluminum alloys
2. Magnesium alloys
3. Copper alloys
4. Carbon and alloy steels
5. Martensitic steels
6. Maraging steels
7. Austenitic stainless steel
8. Nickel alloys
9. Semiaustrnitic PH stainless steels
10. Titanium alloys
11. Iron-based superalloy's
12. Cobalt-based superalloys
13. Columbium a]loys
14. Tantalum alloys
15. Molybdenum alloys
16. Nickel-based super-alloys
17. Tungsten alloys
18. Beryllium.

4-3.2.1.2.1 Drop or Hammer Forging

Drop, or hammer, forgings are formed by impact pressure from either gravity drop hammers or direct-powered drop hammers. The parts are formed from pressure between impression dies, one of which is on the hammer face and the other on the anvil. The pressure is applied intermittently, and the plastic metal is gradually formed into shape. This is the most common of the forging processes. It is a high production process adaptable to all materials except high-strength magnesium alloys. The equipment cost is low, but the required die maintenance is high. Parts cannot usually be produced by this method to close tolerances.

4-3.2.1.2.2 Rotary Forging

This is a relatitely new process for producing accurate, reliable, forged parts at a good production rate. Unfortunately, the machines (which look likes hollow spindle lathe) that perform this operation are not readily available at this time. The material to be formed is preheated and fed into the machine through the headstock where a series of opposing radial forging hammers impact the stock. The depth of stroke, cyclic rate of stroke, and force of stroke are preprogrammed by' a computer control system. The parts produced have good surface finish, about 1.6 µm (63 µin.), and a good tolerance control, ± 0.05 mm (0.002 in.). The parts can be solid forgings or hollow forgings, which are predrilled and forged over a mandrel on the rotary forge. These parts generally come off the machine in a finished condition; therefore, a secondary finishing operation is not necessary.

TABLE 4-38. SELECTION CHART FOR INVESTMENT CASTING ALLOYS

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				Light Metals		
A-03560 T6	145 (21,000) 248 (36,000)	E65 F75	Recommended	Most useful light alloy; combines best foundry properties with best overall mechanical properties.	For instrument and light structural parts.	Maximum fluidity permits 0.76-mm (0.030-in.) walls, 0.50-mm (0.02-in.) holes in light sections, fine serrations, most intricate cored parts.
ASTM 43F	159 (23,000)	F70	Good	Slightly better corrosion resistance than other light alloys.	Used for unstressed instrument parts requiring maximum corrosion resistance.	
ASTM C113 H.T. and aged	145 (21,000) 248 (36,000)	E60 F80	Good	Lightest structural casting alloy; relatively poor corrosion resistance compared to aluminum alloys.	Applied to aircraft instrument and similar parts requiring maximum strength to weight ratio. It is not pressure tight nor suited for shock resistance.	Minimum walls are 0.8 mm (0.03 in.) for small areas and holes are 0.5 mm (0.02 in.) dia min. Not good for serration or stressed parts.
Aluminum 40E	228 (33,000)	F80	Fair	Self-hardening alloy, eliminates heat treatment, but most stable when stress annealed; not as corrosion resistant as A03560 or 43.	For instrument and structural parts subject to moderate and limited impact. It has greatest dimensional stability.	Walls under 1.3 mm (0.05 in.) not pressure tight; not good for stressed serrations or similar fine details.
				Copper Base Alloys		
Silicon-brass	331 (48,000)	F80	Recommended	Best general copper-based casting alloy; high corrosion resistance, good impact resistance, high fluidity; best chemical stability.	Used in the majority of industrial equipment components brackets, cases, gears, etc. Best for complex, thin-sectioned, and long castings.	Minimum wall for extended areas is 0.8 mm (0.03 in.) minimum holes are 0.50 mm (0.02 in.) section 0.8 mm (0.03 in.) thick. Good for fine raised letters, serrations, threads, etc.
C23000 Red brass (85-5-5-)	248 (36,000)	F70	Good	Best hydraulic castings alloy; good sleeve bearing properties. Possesses the best machinability.	For pressure tight castings; also for intricate stressed parts incorporating very fine holes.	Threads and details can be easily machined. Minimum wall for pressures is 1.3 mm (0.5 in). Smallest holes are 0.8 mm (0.03 in.); thinnest edges are 0.3 mm (0.01 in.).

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast annealed condition; the lower value is the maximum that can be obtained by heat treatment.

(cont'd on next page)

TABLE 4-38. (cont'd)

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				Copper Base Alloys (cont'd)		
C50200 Phosphor-bronze	324 (47,000)	F80	Good	Best electrical properties with 80% relative conductivity. It is good bearing alloy with superior corrosion resistance.	Second choice for moderately stressed general structural parts.	Not recommended for fine details, thin walls or fine holes.
C17200 Beryllium-copper	531 (77,000) 1213 (176,000)	F100	Good	The only heat treatable copper base alloy, which can be brought to good spring temper. One difficulty is to control the uniformity.	Used for small, intricately designed springs; gears not subject to impact. Good abrasion resistance when hardened; poor impact strength.	Minimum wall thickness is 0.8 mm (0.03 in.) over limited areas, 1.3 mm (0.05 in.) is better; minimum hole is 0.5 mm (0.02 in.) and minimum edges are 0.5 mm (0.02 in.).
C67500 Manganese-bronze	531 (77,000)	F95	Fair	Has maximum strength with good impact resistance; maximum corrosion resistance to salt water; good strength at temperatures up to 535°C (1000°F).	Not recommended when silicon-brass can be used. This metal has poor fluidity and not good for fine detail.	The minimum pressure-tight wall is 1.5 mm (0.06 in.) but this metal is not recommended for high pressures. Smallest holes are 0.8 mm (0.03 in.).
C61400 Aluminum-bronze	345 (50,000) 565 (82,000)	F80 B90	Fair	Alloy is best for abrasion resistance. Better than other copper base alloys for high temperature use up to 675°C (1250°F). Very good resistance to many chemicals, acids, etc.	Used only for gears or parts requiring good abrasion resistance and high impact strength; not recommended for intricate, fine detail, due to high drossing tendency.	On well tapered simple sections the minimum edge is 0.38 mm (0.015 in.), minimum holes are (0.03 in.); while pressure-tight wall thickness is 1.3 mm (0.05 in.).
Nickel-silver	241 (35,000)	F90	Fair	Chiefly used for ornamental purposes, musical instruments, etc. Possesses good corrosion resistance to atmosphere.	Not recommended for stressed parts or for extended wall areas requiring high surface cleanliness.	Minimum edges are 0.3 mm (0.01 in.) on tapered sections; smallest holes possible are 0.8 mm (0.03 in.).
6A1-4V Titanium	896 (130,000)	—	Fair	Good strength to weight ratio in 200 to 425°C (390 to 800°F) temperature range.	Aircraft engine castings.	

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast and annealed condition; the lower value is the maximum that can be obtained by heat treatment.

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TABLE 4-38. (cont'd)

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				Ferrous Tool Steels		
SAE Type A2		C63	Good	Air-hardening steel with moderate corrosion resistance; it has better wear and impact resistance than stainless up to 225°C (440°F).	Used where corrosion resistance is requisite. A substitute for G10950 tool steel up to 225°C (440°F) for impact resistance.	Minimum useful edge radius is 0.38 mm (0.015 in.)—not good for thin walls or fine projecting details.
SAE Type 01		C65	Good	Oil-hardening steel with maximum dimensional stability when heat treated to full hardness.	Used for cast tools involving contours which cannot be finished and must be held to close tolerance when hardened.	Not as castable as SAE 52100; minimum useful edge radius is 0.5 mm (0.02 in.) and is not recommended for thin walls.
S44004 or 440F Stainless		C62	Good	In the heat-treated condition, it is less corrosion resistant than type S42000. It is inherently brittle. It can be machined when annealed.	Used for tools requiring corrosion resistance; it is an alternate for G10950 carbon steel and a substitute for S41000 or S41600 stainless for parts not requiring ductility but needing hardness for wear resistance.	It is as fluid as SAE 52100 but the minimum useful radius is 0.64 mm (0.025 in.) because of its brittleness. Poor impact resistance at all hardness levels above 45 R.C.
SAE 52100		C30 to 67	Fair	Good low alloy ferrous alloy; has finest inherent grain size (when vanadium modified) is least susceptible to deep surface decarburization. Readily case carburized or nitrided to highest hardness.	Moderate structural carburized C65 or nitrided to C67, has minimum spalling tendency.	Recommended for fine detail; minimum edges are 0.31 mm (0.012 in.) and minimum walls are 1.14 mm (0.045) in.). Not suited for tools subject to impact.
				Stainless Steels		
Stainless types S30200 S30300 S30400	517 (75,000)	B80	Recommended	Essentially identical in investment cast form. L-type S30200 should be specified for most applications. Corrosion resistance good to 815°C (1500°F) continuous service.	Used for structural castings requiring high impact resistance; often the cheapest substitute for SAE G10200 or 3120 because of superior foundry properties.	Recommended for most intricate designs with a minimum edge radius of 0.30 mm (0.012 in.) and minimum walls of 1.14 mm (0.045 in.). Fine projecting details, some serrations and thread designs may be cast.

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast and annealed condition; the lower value is the maximum that can be obtained by heat treatment.

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TABLE 4-38. (cont'd)

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				Stainless Steels (cont'd)		
Stainless types S30900 S31000 312, 330	517 (75,000) 434 (63,000) 621 (90,000) 483 (70,000)	B80 — B92 B90	Recommended	Alloys have better corrosion resistance at high temperatures as their alloy content increases. All suited for continuous service in air at 1090°C (2000°F) and in oxidizing, sulphurous gases at 1040°C (1900°F). Type 330 not good for reducing atmospheres at 980°C (1800°F); however, the others are.	Type S30900 is widely used for intricate aircraft turbine stator parts; type S31000 is somewhat stronger above 815°C (1500°F). 312 is particularly resistant to oxidizing hot acids, and 330 is resistant to carburizing gases and chemicals.	All alloys are as fluid as type SAE 30200 and reproduce the finest details.
Stainless type S31600	593 (86,000)	B82	Recommended	Particularly resistant to intergranular attack when used in the range of 430 to 760°C (800 to 1400°F) (because of a 2.5% Mo).	Recommended for high temperature steam turbine blades and for castings contacting hot sulphurous exhaust gases up to 1040°C (1900°F).	Equally castable as type SAE 30200.
Stainless types S32100 S34700	552 (80,000)	B80	Good	The use of Ti and Cb as suppressants of intergranular attack in critical range 430 to 760°C (800 to 1400°F) is questionable.	Used for general structural parts not requiring high strength. Corrosion resistance at elevated temperatures is similar to SAE 30200.	Best to use type S30400 in place of these modified types unless a definite advantage exists.
Armco 17-4PH	621 (90,000) 1172 (170,000)	B90 C45	Good	This only chrome-copper precipitation hardening stainless alloy. Possesses most properties of austenitic stainless, except that it is magnetic.	Used for structural castings requiring good corrosion resistance and high strength.	Preferred as a substitute for SAE 41000 or SAE 41600 stainless as well as SAE 42000, G10200, and SAE 3120. Good fluidity gives good detail reproduction; minimum edges of 1.3 mm (0.05 in.) and minimum wall thickness of 1.3 mm (0.05 in.)
Stainless type SAE 42000	689 (100,000) 1241 (180,000)	B80 C50	Fair	Moderately corrosion resistant; inherently brittle at subzero temperatures.	For hardenable low-stressed structural parts.	Use in place of SAE 41000 or SAE 41600. Minimum edges are 0.5 mm (0.02 in.). Not good for projecting details.

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast and annealed conditons; the lower value is the maximum that can be obtained by the heat treatment.

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TABLE 4-38. (cont'd)

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				Low Carbon and Low Alloy Ferrous Alloys		
G41300	517 (75,000) 1207 (175,000)	B90	Good	Has good carburizing properties and moderate grain size.	Used for moderately stressed parts. Maximum uniformity of properties of all low alloy steels when suitably heat-treated.	It is a recommended substitute for G10200 or SAE 3120. Minimum wall of 1.3 mm (0.05 in.), minimum holes are 1.3 mm (0.05 in.), and minimum edge radius on tapered sections is 0.30 mm (0.012 in.).
G41400	758 (110,000) 1379 (200,000)	C24 C55	Good	Higher strength than G41300 but lower impact resistance. Available in wide range of heat-treated conditions; can be case carburized readily; however, it is susceptible to surface decarburization.	Recommended substitute for all other 0.4% carbon steels such as G10400, SAE 3140, SAE 4640, SAE 6140, G86400.	Still machinable when hardened to 440 BHN due to molybdenum. It has the same castability as G41300. Best machinability when heat treated to 200 to 280 BHN.
SAE 3120	517 (75,000) 724 (105,000)	B75 B90	Fair	Easily case carburized with moderate physical properties. It is a substitute for G10200.	Used for simple structural parts not subject to high stress or impact.	Not good for fine detail, the minimum edges are 0.64 mm (0.025 in.) and minimum wall thickness is 1.5 mm (0.06 in.).
Nitralloy	655 (95,000)	B95	Fair	Readily case hardened by nitriding. It has maximum wear resistance with good impact strength and corrosion resistance. Fine grain size.	Used for journals, gears sprockets, and similar applications requiring maximum wear resistance.	Not as castable as G41400. The minimum edge radius is 0.5 mm (0.02 in.); the smallest hole is 1.3 mm (0.05 in.) and minimum wall is 1.3 mm (0.05 in.).

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast and annealed condition; the lower value is the maximum that can be obtained by heat treatment.

TABLE 4-38. (cont'd)

Alloy	Tensile** Strength MPa (psi) avg	Rockwell Hardness	Castability Rating	Special Properties	Applications	Design Recommendations
				High Temperature Alloys		
Vitallium	400 (58,000)	A65	Recommended	The cobalt base alloys are as castable as the austenitic stainless steels. These alloys can sustain appreciable static and dynamic stresses above 650 to 815°C (1200 to 1500°F). Cobalt alloys have been used up to 1090°C (2000°F). In the resistance to erosion or corrosion, these alloys compare with the higher temperature grades of stainless.	Widely used in extreme service parts for oil, mining and chemical industries; also in turbine blade applications.	Specific difference between the cobalt alloys must be obtained from the foundry. The useful minimum castable details are edges 0.38 mm (0.015 in.); holes 1.3 mm (0.05 in.); walls 1.3 mm (0.05) in.). Cast threads to class fit are only threads possible, as these alloys are unmachinable.
HS21; R3004	407 (59,000)	A65				
HS23;R30023	352 (51,000)	A61				
HS27;R30027	421 (61,000)	A60				
HS31;R30031	538 (78,000)	C26				
Inconel	310 (45,000)	B87	Recommended	Possesses superior electromagnetic properties, comparable to pure nickel in cast form.	Used for electronic equipment parts as an alternative for pure nickel.	Not suited to very fine detail; minimum useful edge radius is 0.41 mm (0.016 in.).
Hastelloy						
A	359 (52,000)	B90	Recommended	Outstanding chemical resistance to hot HCl, H_2SO_4, wet Cl_2 and most organics; good mechanical properties at temperatures above 815°C (1500°F); exceptional abrasion and erosion resistance. Has exceptional as-cast hardness.	Recommended for applications in oil producing equipment, and mining drill and excavating machinery parts where wear and chemical erosion resistance is important.	Can be cast to fine detail, but low ductility limits its use for intricate parts subject to impact.
B	400 (58,000)	B95				
Monel	565 (82,000)	B75	Good	Has good corrosion resistance, good electrical and magnetic properties.	Primarily developed for food process equipment; it has wide use in chemical industries.	Not as castable as austenitic stainless; fairly intricate details are producible; thin sections are not readily cast; Monel S has low impact resistance.
Monel H	724 (105,000)	B95				
Monel S	896 (130,000)	C37				

In each group the first alloy listed is generally the best from a casting standpoint and is recommended wherever possible.

*UNS numbers have not been assigned to all materials.

**When two values are given, the upper value represents the as-cast and annealed condition; the lower value is the maximum that can be obtained by heat treatment.

TABLE 4-39. APPROXIMATE DIMENSIONAL AND WEIGHT LIMITS FOR DIE CASTING IN DIFFERENT ALLOYS (Ref. 5)

Type of Alloy (Base Metal)	Zinc		Aluminum		Magnesium		Copper	
	kg	(lb)	kg	(lb)	kg	(lb)	kg	(lb)
Maximum weight of casting	15	(35)	9	(20)	4	(lo)	2	(5)
	mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)
Minimum wall thickness of large castings over 0.9 kg (2 lb)	1.27	(0.050)	2.03	(0.080)	2.03	(0.080)	2.29	(0.090)
Minimum wall thickness of small castings up to 0.9 kg (2 lb)	0.64	(0.025)	1.27	(0.050)	1.27	(0.050)	1.27	(0.050)
Minimum variation per 25.4 mm (1 in.) of diameter	0.038	(0.0015)	0.038	(0.0015)	0.038	(0.0015)	0.051	(0.002)
Cored holes, minimum diameter mm (in.)	2.39	(0.094)	3.18	(0.125)	3.18	(0.125)	6.35	(0.250)
Minimum draft on cores mm/mm (in./in.) of length or diameter	0.13	(0.005)	0.25	(0.010)	0.25	(0.010)	0.51	(0.020)
Minimum draft on side walls mm/mm (in./in.) of depth	0.18	(0.007)	0.38	(0.015)	0.25	(0.010)	0.51	(0.020)
Cast threads, maximum number per 25.4 mm (1 in.) external	24		24		16		10	

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4-3.2.1.2.3 Press Forging

Press forging is similar to drop forging; the main distinction is that press forging employs squeezing pressure rather than impact pressure. The process usually is performed on mechanical or hydraulic presses with impression dies, which contain mechanical ejectors to knock the work out of the die after the stroke is completed. (This process is also called closed die forging.) Press forgings produce a part by a single blow rather than by repeated blows as in drop forging. Although this process is adaptable to all materials, it is most commonly used in producing aluminum or magnesium parts. The parts produced by press forging can have close tolerances as well as thin webs and low or no-draft angles, as in no-draft forgings.

4-3.2.1.2.4 Machine Forging

Machine, or upset, forging is limited to producing symmetrical parts—but of any variety of size and material. Upsetting increases the cross-sectional area of the part by squeezing the metal between the dies and striking it with a heading tool. Machine forging is done on a horizontal, double-acting press known as an upsetter. This produces the part with no flash, and thus eliminates machining. Machine forging is particularly adaptable to mass production of identical parts. It can handle all materials and is probably the best operation for high production rates.

4-3.2.1.2.5 Forgings vs Machining From Bar Stock

In the design of a product to be produced in limited quantities, the designer must consider relative costs—as indicated in Table 4-40—to determine whether he should design the part to be machined from bar stock or to be made from a forging. The most important differences when deciding between bar stock and forging are in tooling costs and direct labor costs per piece.

The designer must determine whether the total production of forged pieces can assure that savings. in increment cost per piece will justify the extra tooling investment, The possibility of frequent design changes must also be considered in making that determination.

Representative calculations in Table 4-40 and Fig. 4-32 for this example show that it will be more economical to design a given part as a forging rather than machining it from bar stock if the total production is 1500 parts or more. Unit costs for the given part shown in Table 4-41 were computed for production from 400 to 4000 units.

TABLE 4-40. RELATIVE COSTS—MACHINING VS FORGING (Ref. 5)

Item	Part from Bar Stock	Part by Forging
Investment in Tooling		
Forging die		$2175.00
Drill jig	$300.00	270.00
Milling fixture	480.00	120.00
Direct material cost per piece	1.38	1.35
Setup Cost per Lot		
Forging die setup		48.00
Machine setup	22.50	12.00
Direct labor cost per piece	1.92	0.525

TABLE 4-41. CALCULATIONS OF UNIT COST OF ALTERNATIVE DESIGNS (Ref. 5)

	Part Machined From Bar Stock			Forging		
	Total Production			Total Production		
	400	2000	4000	400	2000	4000
Tooling cost	$780	$780	$ 780	$2565	$2565	$ 2565
setup cost	45	225	450	120	600	1200
Direct material cost	552	2760	5520	540	2700	5400
Direct labor cost	768	3840	7680	210	1050	2100
Total cost	$2145	$7605	$14,430	$3435	$6915	$11,265
Comparative unit cost	$5.36	$3.80	$ 3.61	$8.59	$3.46	$ 2.82

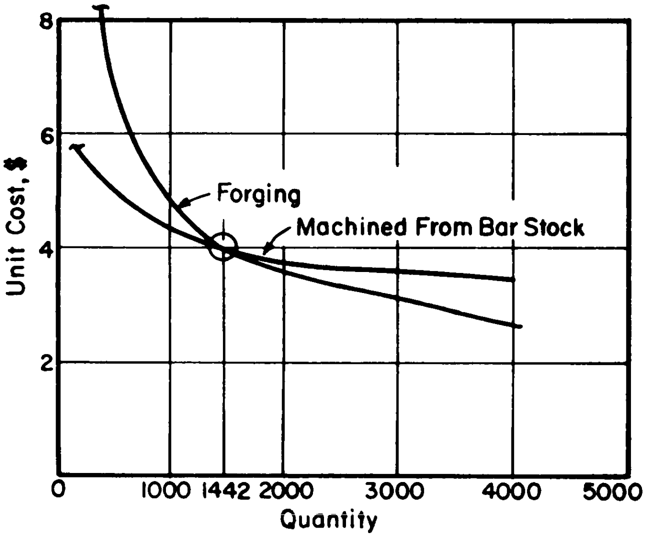

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Figure 4-32. Comparative Unit Cost of Alternative Designs of a Manufactured Product in Relation to Total Production (Ref. 5)

The curves shown in Fig. 4-32 are based on the assumption that total production is a multiple of the lot size of 200. By using this assumption, setup costs may be treated as variable costs per unit of 45/400 = $0.1125, and 120/400 = $0.30, respectively. The break-even point calculations follow:

where x is the number of parts required to break even.

4-3.2.1.3 Powder Metallurgy

Powder metal parts are made by compacting metal powders in a precision die. Subsequently, the compacted part is ejected and then sintered in a controlled atmosphere to develop its mechanical and physical properties. A comparison of powder metallurgy with other processes is shown in Table 4-42.

Virtually every metallurgical composition used by man is available in one or more powder formulations, including iron, carbon steel, stainless steel, nickel steel, copper steel, nickel silver, copper, brass, aluminum, bronze, and even the refractory and reactive metals. Each is available in a number of different compositions or special blends that give the designer a wide choice of properties and enable him to select the optimum material for his particular application.

The mechanical property of tensile strength is commonly used in the evaluation of powder metallurgy materials although other properties may also be of prime importance; this depends upon intended applications. Powder metallurgy parts, such as bronze bearings, can be produced with high porosity while structural parts can have high density, minimum porosity, and tensile strengths ranging from 1034.2 to 1241.1 MPa (150,000 to 180,000 psi)—even approaching 1379 MPa (200,000 psi) in special circumstances. In many cases, properties of powder metallurgy parts either equal those of wrought materials or exceed them; however, ductility and resistance to impact are often much lower.

Through selective compacting, parts can be produced with multiple densities. This feature, available only with powder metallurgy, enables the design engineer to specify, for example, a hard, dense, wear-resisting surface and a porous, oil-impregnated running surface.

Information relative to shapes and sizes follows:

1. Shapes. Powdered metal parts can be compressed only in the direction of punch movement. Parts with threads, holes, or undercuts at angles to the direction of pressure, reentrant angles, and reverse tapers are either impossible to press or restrict the ejection of the part from the die. These design limitations can frequently be overcome by secondary machining. Inserts should not be molded into powdered metal parts. Table 4-43 summarizes economical tolerances for powdered metal parts.
2. Sizes. The available press stroke and the compression ratio of the material determine the practical sizes that can be produced by the powder metallurgy process. Parts weighing as much as 23 kg (50 lb) and having a compacting area of 25,800 mm^2 (40 $in.^2$) can be produced with modern presses.

4-3.2.1.4 Extruding

Extruding is a plastic forming process usually done hot, but in some instances cold. It differs basically from forging in that the extruded shape has either a constant cross section or the same type of cross section with a tapered effect along its length. Because of its severe metalworking characteristics, extrusion provides fiber-oriented and fine-grained wrought products.

An extrusion is a product whose configuration is formed by first confining a billet of the material to be formed, sometimes with heat applied. A ram is then used to force the material through a die opening in much the same manner that toothpaste is squeezed from a tube. The emerging extrusion, traveling in the same direction as the ram, takes on a cross-sectional shape identical to that of the die opening.

Aluminum and aluminum alloys, copper and copper alloys, low-carbon and medium-carbon steels, and stainless steels are the metals most commonly cold

TABLE 4-42. GENERAL COMPARISON OF METALLURGICAL PROCESSES (Ref. 5)

Method as Compared to Powder Metallurgy	Production Rates	Strength of Part	Tooling costs	Tolerances	Piece Price
Die cast small parts	Lower	Lower	Higher	Looser	Generally lower
Die cast large parts	Lower	Lower	Higher	Looser	Lower
Investment casting	Lower	Equal	Lower	Looser	Higher
Precision sand casting	Lower	Equal	Lower	Looser	Higher
Screw machine small parts—no second operation	Same	Equal or higher	Lower	Same	Same
Screw machine parts with second operation	Lower	Equal or higher	Lower	Same	Higher
Screw machine large parts	Lower	Equal or higher	Lower	Same	Higher

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TABLE 4-43. ECONOMICAL TOLERANCES FOR POWDERED METAL PARTS (Ref. 5)

Diameter or Length vs Tolerance					
Diameter or Length		Length Tolerance ±		Diameter Tolerance ±	
mm	(in.)	mm	(in.)	mm	(in.)
< 25	(< 1)	0.13	(0.005)	0.05	(0.002)
>25 to 38	(> 1 to 1.5)	0.19	(0.0075)	0.05	(0.002)
>38 to 51	(> 1.5 to 2)	0.38	(0.015)	0.08	(0.003)
>51 to 64	(> 2 to 2.5)	0.38	(0.015)	0.10	(0.004)
>64 to 76	(> 2.5 to 3)	0.38	(0.015)	0.13	(0.005)
Flange Diameter vs Tolerance					
Diameter ±				Tolerance ±	
< 25	(< 1)			0.10	(0.004)
>25 to 38	(> 1 to 1.5)			0.15	(0.006)
>38 to 51	(> 1.5 to 2)			0.20	(0.008)
>51 to 64	(> 2 to 2.5)			0.25	(0.01)
>64 to 76	(> 2.5 to 3)			0.36	(0.014)
76 to 102	(3 to 4)			0,41	(0.016)
Flange Thickness vs Tolerance					
Thickness				Tolerance ±	
< 6.4	(< 0.25)			0.10	(0.004)
>6.4 to 9.52	(> 0.25 to 0.375)			0.15	(0,006)
>9.52 to 12.7	(> 0.375 to 0.5)			0.20	(0.008)
Concentricity Tolerance					
Diameter				Total Indicator Reading	
< 25	(< 1)			0.08	(0.003)
>25 to 38	(> 1 to 1.5)			0,10	(0.004)
>38 to 51	(> 1.5 to 2)			0.127	(0.005)
>51 to 64	(> 2 to 2.5)			0.152	(0.006)
>63.5 to 76	(> 2.5 to 3)			0.178	(0.007)

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extruded. These materials are listed in the order of decreasing extrudability.

Most of the austenitic stainless steels, martensitic stainless steels, ferritic stainless steels, and carbon steels are cold or hot extruded. American Iron and Steel Institute (AISI) alloy steels, tool steels, nickel-base alloys, high-temperature and specialty alloys, and titanium and titanium alloys are hot extruded.

Extrusion equipment is one of two categories of machiner—impact or press. Within either of these categories, extrusions can be made by the direct method as previously described or by the inverse method, whereby the extrusion travels backward along the outside or inside of the pressure ram. A limitation of the inverse method is that the available length of the ram precludes the extrusion of very long pieces (see Fig. 4-33).

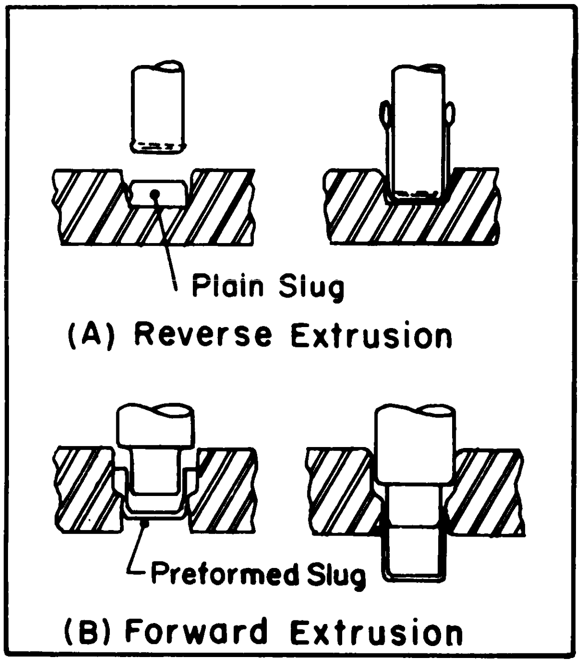

Figure 4-33. Impact Extrusion

4-3.2.1.4.1 Direct Extrusion

A direct extrusion is made in the previously described manner. The maximum circumscribing circle for aluminum, magnesium, copper, and copper alloys is approximately 305 mm (12 in.), but some of the new presses have increased the maximum circle to 685 mm (27 in.). The maximum circumscribing circle for alloy steel and stainless steel is 136.5 mm (5.375 in.), and for carbon and titanium, 165.1 mm (6.5 in.).

Extruded shapes can be straightened in lengths up to 18.29 m (60 ft). Maximum product weight per 0.305 m (1 ft) of extruded shape is 9.07 kg (20 lb) for aluminum and 6.8 kg (15 lb) for steel. The minimum cross section is not less than 65 mm^2 (0.10 in.^{2}) for aluminum and not less than 323 mm^2 (0.50 in.^{2}) for steel. Tables 4-44 and 4-45 provide tolerance information for extrusion processes.

4-3.2.1.4.2 Coextrusion

A coextrusion results when two different alloys are extruded together to form a composite part as in Fig. 4-34.

Alclad tubing is an example of coextrusion. In this instance, a clad layer of one aluminum alloy can be placed inside, outside, or on both sides of a core alloy of another composition.

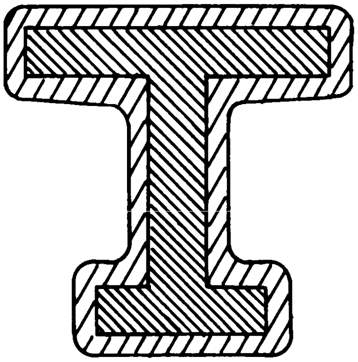

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Figure 4-34. Coextrusion (Ref. 5)

4-3.2.1.4.3 Cold Extrusion

There are two methods of cold extrusion: impact extrusion and the Hooker process. Aluminum, tin, copper alloys, and steel are worked by these two extrusion methods. The low strength, ductile alloys are easier to extrude by the Hooker processor by impact extrusion. When higher mechanical properties are required in the final product, heat treatable grades are used. However, extrusions from these grades are more susceptible to defects, such as laps or cracks, than those extruded from the lower strength alloys. A description of the processes follows:

1. *Impact extrusion.* There are three variants of the impact extrusion process:
   a. Forward, or direct, wherein the metal flows in the same direction as the applied force
   b. Backward, or indirect, wherein the metal flow is opposite to the force, or back over the punch
   c. Opposed, wherein the metal is forced to flow simultaneously with, and opposite to, the direction of applied force.

TABLE 4-44. GENERAL SHAPE TOLERANCES OF EXTRUSIONS (Ref. 5)

Type of Tolerance	Dimensions to Which Tolerance Applies	Tolerance ±
Straightness	Circumscribing circle diameter up through 38.07 mm (1.499 in.)	1.27 mm (0.05 in. per ft for minimum thickness up through 2.39 mm (0.094 in.)); 0.318 mm (0.0125in.) per ft for minimum thickness 2,41 mm (0.095 in.) and up
	38.1 mm (1.5 in.) and up	0.318 mm (0.0125 in.) per ft
Twist	Circumscribing circle diameter up through 38.07 mm (1.499 in.)	0.0174 rad per 304.8 mm (1 deg per ft)
	38.1 to 75.94 mm (1.50 to 2.99 in.)	0.0087 rad per 304.8 mm; 0.0872 rad total (0.5 deg per ft); (5 deg total)
	76.2 mm (3.0 in.) and up	0,0044 rad per 304.8 mm; 0.0524 rad total (0.25 deg per ft); (3 deg total)
Contour	Deviation from specified	0.13 mm per 25.4 mm (0.005 in. per in. of chord width (0.13 mm (0.005 in.) minimum)
Corner and fillet radii	Sharp corners	0.396 mm (0.0156 in.)
	Radius up through 5.004 mm (0.197 in.)	0.792 mm (0.0312 in.)
	Specified radius 4.775 mm (0.188 in.) and up	10%
Angles	Minimum leg thickness; under 4.775 mm (0.188 in.)	0.0349 rad (2 deg)
	4.775 mm to 190.5 mm (0.188 to 0.750 in.)	0.262 rad (1.5 deg)
	19.05 mm (0.75 in.) to solid	0.0174 rad (1 deg)
Flatness		0.101 mm (0.004 in.) per 25.4 mm (1 in.) of width 0.10 mm (0.004 in.) minimum
Surface roughness	Section thickness: up through 1.60 mm (0.063 in.)	Maximum depth of defect: 0.038 mm (0.0015 in.)
	1.63 to 3.18 mm (0.064 to 0.125 in.)	0.051 mm (0.002 in.)
	3.20 to 4.78 mm (0.126 to 0.188 in.)	0.064 mm (0.0025 in.)
	4.80 to 6.35 mm (0.189 to 0.250 in.)	0.076 mm (0.003 in.)
	6.38 mm (0.251 in.) and up	0.102 mm (0.004 in.)

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TABLE 4-45. TOLERANCES FOR IMPACT EXTRUSIONS (Ref. 5)

Diameter		Tolerances ±					
		Outside Diameter		Inside Diameter		Bottom Thickness	
mm	(in.)	mm	(in.)	mm	(in.)	mm	(in.)
<19.0	(<0.75)	0.03	(0.001)	0.05	(0.002)	0.18	(0.007)
>19.0 to 38.1	(> 0.75 to 1.5)	0.08	(0.003)	0.10	(0.004)	0.25	(0.01)
>38.1 to 44.4	(> 1.5 to 1.75)	0.13	(0.005)	0.15	(0.006)	0.30	(0.012)
>44.4 to 50.8	(> 1.75 to 2)	0.15	(0.006)	0.18	(0.007)	0.30	(0.012)
>50.8 to 63.5	(> 2 to 2.5)	0.18	(0.007)	0.20	(0.008)	0.30	(0.012)
>63.5 to 88.9	(> 2.5 to 3.5)	0.23	(0.009)	0.25	(0.01)	0.38	(0.015)
>88.9 to 101.6	(> 3.5 to 4)	0.25	(0.01)	0.28	(0.011)	0.38	(0.015)
>101.6 to 114.3	(> 4 to 4.5)	0.28	(0.011)	0.30	(0.012)	0.38	(0.015)
>114.3 to 127.0	(> 4.5 to 5)	0.36	(0.014)	0.38	(0.015)	0.38	(0.015)
>127.0 to 152.4	(> 5 to 6)	0.51	(0.02)	0.51	(0.02)	0.38	(0.015)

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It is possible to form a part with any combination of inside and outside shapes plus splines, bottoms with bosses, etc. Fig. 4-35 shows some of the common extruded sections.

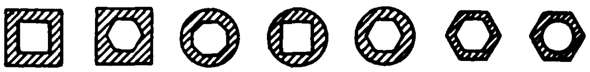

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Figure 4-35. Common Extruded Sections (Ref. 5)

2. *Hooker process*. A cupped blank used in this process is shown in Fig. 4-36. The blank is placed in the die, the punch enters, and pressure causes the metal to flow between the nose of the punch and the land of the die. Both large and small tubings and cups can be extruded to a considerable length and extreme thinness if required.

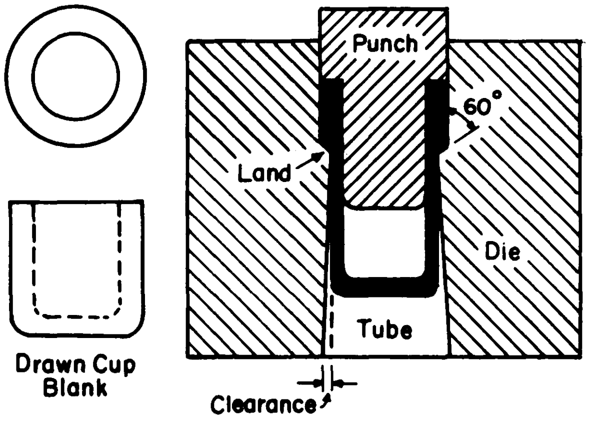

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Figure 4-36. Hooker Process for Extrusion (Ref. 5)

4-3.2.1.5 Machining

Machining is the process of controlled removal of material from oversized stock to achieve a desired configuration size. Fig. 4-37 illustrates various machining operations.

4-3.2.1.5.1 Turning

Turning is a machining process for generating an external surface of revolution by the action of a cutting tool in a rotating workpiece, usually in a lathe. When this same action is applied to an internal surface of revolution, the process is termed boring. In a few instances turning and boring are performed simultaneously, but mostly they are done consecutively in the same setup.

Several other machining operations are often performed in conjunction with turning. These include facing, longitudinal drilling, reaming, tapping, threading, chamfering, and knurling.

Availability of equipment that can hold and rotate the workpiece is the major restriction on the size of the workpiece that can be turned. Turning is done on parts ranging in size from those used in watches up to steel propeller shafts more than 24 m (80 ft) long. Alumi-

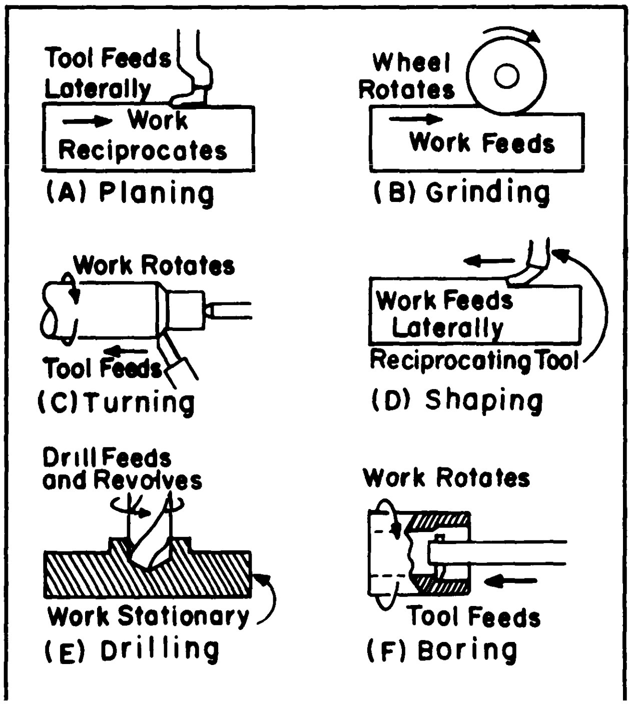

Figure 4-37. Basic Machine Tool Motions for Removing Material

num parts (about one-third the density of steel or brass) over 3 m (10 ft) in diameter have been successfully turned. In practice, the weight of the work metal per unit of volume may restrict the size workpiece that is practical to turn because problems in holding and handling increase *as* weight and size increase. Some large parts are turned in vertical boring mills. Table 4-46 provides information on the type of lathe to use in turning operations of various lot sizes.

4-3.2.1.5.2 Milling

Milling is a machining process in which metal is removed from a stationary piece by a rotating cutter with multiple teeth. Tolerances of ± 0.05 mm (0.002 in.) are not unusual for this process. Because both workpiece and cutter can be moved in more than one direction at the same time, surfaces with almost any orientation can be machined.

Milling is most efficient when the work is no harder than Rockwell C25. However, steel at Rockwell C35 is commonly milled, and steel as hard as Rockwell C56 has been successfully milled.

Spindle orientation is one means of classifying milling machines. Machines that drive cutters with horizontal spindles are the most common although vertical spindles are widely used also. Some special purpose machines have horizontal, vertical, and angular spindles that operate consecutively, simultaneously, or both.

Milling is not an efficient production process. Other methods (casting, forging, powder metallurgy) should be examined thoroughly if quantities exceed 300 to 500 pieces. Break-even analysis charts mill provide a definite decision on a case-by-case basis.

4-3.2.1.5.3 Drilling

This is an operation performed by a rotary end cutting tool with one or more cutting lips and usually one or more flutes for the passage of chips and cutting fluid. Holes drilled by this process are limited by the available drill sizes. Table 4-47 provides the tolerances of the holes produced by some of these drills. These tolerances are often adequate without further machining operations, such as reaming or boring.

Here location also can add significantly to production cost. As shown in Fig. 4-38, the tolerance on hole locations can affect the process, which in turn has significant cost effects. Deep hole drilling is also a factor affecting cost. Fig. 4-39 shows how cost increases as the ratio of length to diameter goes beyond 3 to 1.

TABLE 4-46. TURNING TOLERANCES AND TYPICAL LOT SIZES

Type of Lathe	Lot Sizes	Tolerance ±	
		mm	(in.)
Engine lathe	1-10	0.005	(0.0002)
Turret lathe	10-100	0.127	(0.005)
Single-spindle auto	100-10,000	0.076	(0.003)
Six-spindle auto	10,000-100,000	0.127	(0.005)

TABLE 4-47. DRILL HOLE SIZES AND TOLERANCES (Ref. 5)

Drill	Size		Tolerance			
			Plus		Minus	
	mm	(in.)	mm	(in.)	mm	(in.)
80	0.343	(0.0135)	0.058	(0.0023)	0.013	(0.0005)
79	0.368	(0.0145)	0.061	(0.0024)	0.013	(0.0005)
1/64	0.396	(0.0156)	0.064	(0.0025)	0.013	(0.0005)
78	0.406	(0.016)	0.064	(0.0025)	0.013	(0.0005)
77	0.457	(0.018)	0.066	(0.0026)	0.013	(0.0005)
76	0.508	(0.020)	0.069	(0.0027)	0.013	(0.0005)
75	0.533	(0.021)	0.069	(0.0027)	0.013	(0.0005)
74	0.572	(0.0225)	0.071	(0.0028)	0.013	(0.0005)
73	0.610	(0.024)	0.071	(0.0028)	0.013	(0.0005)
72	0.635	(0.025)	0.074	(0.0029)	0.013	(0.0005)
71	0.660	(0.026)	0.074	(0.0029)	0.013	(0.0005)
70	0.711	(0.028)	0.076	(0.003)	0.013	(0.0005)
69	0.742	(0.0292)	0.076	(0.003)	0.013	(0.0005)
68	0.787	(0.031)	0.079	(0.0031)	0.013	(0.0005)
1/32	0,794	(0.0312)	0.079	(0.0031)	0.013	(0.0005)
67	0.813	(0.032)	0.079	(0.0031)	0.013	(0.0005)
66	0.838	(0.033)	0.081	(0.0032)	0.013	(0.0005)
65	0.889	(0.035)	0.081	(0.0032)	0.013	(0.0005)
64	0.914	(0.036)	0.084	(0.0033)	0.013	(0.0005)
63	0.940	(0.037)	0.084	(0.0033)	0.013	(0.0005)
62	0.965	(0.038)	0.084	(0.0033)	0.013	(0.0005)
61	0.991	(0.039)	0.084	(0.0033)	0.013	(0.0005)
60	1.016	(0.040)	0.086	(0.0034)	0.013	(0.0005)
59	1.041	(0.041)	0.086	(0.0034)	0.025	(0.001)
58	1.067	(0.042)	0.086	(0.0034)	0.025	(0.001)
57	1.092	(0.043)	0.089	(0.0035)	0.025	(0.001)
56	1.181	(0.0465)	0.089	(0.0035)	0.025	(0.001)
3/64	1.191	(0.0469)	0.091	(0.0036)	0.025	(0.001)
55	1.321	(0.052)	0.094	(0.0037)	0.025	(0.001)
54	1.397	(0.055)	0.097	(0.0038)	0.025	(0.001)
53	1.511	(0.0595)	0.099	(0.0039)	0.025	(0.001)
1/16	1.588	(0.0625)	0.099	(0.0039)	0.025	(0.001)
52	1.613	(0.0635)	0.099	(0.0039)	0.025	(0.001)
51	1.702	(0.067)	0.102	(0.004)	0.025	(0.001)
50	1.778	(0.070)	0.104	(0.0041)	0.025	(0.001)
49	1.854	(0.073)	0.104	(0.0041)	0.025	(0.001)
48	1.930	(0.076)	0.107	(0.0042)	0.025	(0.001)
5/64	1.984	(0.0781)	0.107	(0.0042)	0.025	(0.001)
47	1.994	(0.0785)	0.107	(0.0042)	0.025	(0.001)
46	2.057	(0.081)	0.109	(0.0043)	0.025	(0.001)

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TABLE 4-47. (cont'd)

Drill	Size		Tolerance			
			Plus		Minus	
	mm	(in.)	mm	(in.)	mm	(in.)
45	2.083	(0.082)	0.109	(0.0043)	0.025	(0.001)
44	2.184	(0.086)	0.112	(0.0044)	0.025	(0.001)
43	2.261	(0.089)	0.112	(0.0044)	0.025	(0.001)
42	2.375	(0.0935)	0.114	(0.0045)	0.025	(0.001
3/32	2.381	(0.0938)	0.114	(0.0045)	0.025	(0.001
41	2.438	(0.096)	0.114	(0.0045)	0.025	(0.001
40	2.488	(0.098)	0.117	(0.0046)	0.025	(0.001
39	2.527	(0.0995)	0.117	(0.0046)	0.025	(0.001
38	2.578	(0.1015)	0.117	(0.0046)	0.025	(0.001
37	2.642	(0.104)	0.119	(0.0047)	0.025	(0.001)
36	2.705	(0.1065)	0.119	(0.0047)	0,025	(0.001)
7/64	2.779	(0.1094)	0.119	(0.0047)	0.025	(0.001)
35	2.794	(0.110)	0.119	(0.0047)	0.025	(0.001)
34	2.819	(0.111)	0.122	(0.0048)	0.025	(0.001)
33	2.870	(0.113)	0.122	(0.0048)	0.025	(0.001)
32	2.946	(0.116)	0.122	(0.0048)	0.025	(0.001)
31	3.048	(0.120)	0.124	(0.0049)	0.025	(0.001)
1/8	3.175	(0.125)	0.127	(0.005)	0.025	(0.001)
30	3.264	(0.1285)	0.127	(0.005)	0.025	(0.001)
29	3.454	(0.136)	0.130	(0.0051)	0.025	(0.001)
28	3.569	(0.1405)	0.132	(0.0052)	0.025	(0.001)
9/64	3.572	(0.1406)	0.132	(0.0052)	0.025	(0.001)
27	3.658	(0.144)	0.132	(0.0052)	0.025	(0.001)
26	3.734	(0.147)	0.132	(0.0052)	0.025	(0.001)
25	3.797	(0.1495)	0.135	(0.0053)	0.025	(0.001)
24	3.861	(0.152)	0.135	(0.0053)	0.025	(0.001)
23	3.912	(0.154)	0.135	(0.0053)	0.025	(0.001)
5/32	3.969	(0.1562)	0.135	(0.0053)	0.025	(0.001)
22	3.988	(0.157)	0.135	(0.0053)	0.025	(0.001)
21	4.039	(0.159)	0.137	(0.0054)	0.025	(0.001)
20	4.089	(0.161)	0.137	(0.0054)	0.025	(0.001)
19	4.216	(0.166)	0.140	(0.0055)	0.025	(0.001)
18	4.305	(0.1695)	0.140	(0.0055)	0.025	(0.001)
11/64	4,366	(0.1719)	0.140	(0.0055)	0.025	(0.001)
17	4.394	(0.173)	0.140	(0.0055)	0.025	(0.001)
16	4.496	(0.177)	0.142	(0.0056)	0.025	(0.001)
15	4.572	(0.180)	0.142	(0.0056)	0.025	(0.001)
14	4.623	(0.182)	0.142	(0.0056)	0.025	(0.001)
13	4.699	(0.185)	0.145	(0.0057)	0.025	(0.001)
3/16	4.762	(0.1875)	0.145	(0.0057)	0.025	(0.001)

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TABLE 4-47. (cont'd)

Drill	Size		Tolerance			
			Plus		Minus	
	mm	(in.)	mm	(in.)	mm	(in.)
12	4.801	(0.189)	0.145	(0.0057)	0.025	(0.001)
11	4.851	(0.191)	0.145	(0.0057)	0.025	(0.001)
10	4.915	(o.1935)	0.145	(0.0057)	0.025	(0.001)
9	4.978	(0.196)	0.147	(0.0058)	0.025	(0.001)
8	5.055	(0.199)	0.147	(0.0058)	0.025	(0.001)
7	5.105	(0.201)	0.147	(0.0058)	0.025	(0.001)
13/64	5.159	(0.2031)	0.147	(0.0058)	0.025	(0.001)
6	5.182	(0.204)	0.147	(0.0058)	0.025	(0.001)
5	5.220	(0.2055)	0.150	(0.0059)	0.025	(0.001)
4	5.309	(0.209)	0.150	(0.0059)	0.025	(0.001)
3	5.410	(0.213)	0.150	(0.0059)	0.025	(0.001)
7/32	5.556	(0.2188)	0.152	(0.006)	0.025	(0.001)
2	5.613	(0.221)	0.152	(0.006)	0.025	(0.001)
1	5.791	(0.228)	0.155	(0.0061)	0.025	(0.001)
A	5.944	(0.234)	0.155	(0.0061)	0.025	(0.001)
15/64	5.953	(0.2344)	0.155	(0.0061)	0.025	(0.001)
B	6.045	(0.238)	0.155	(0.0061)	0.025	(0.001)
c	6.147	(0.242)	0.157	(0.0062)	0.025	(0.001)
D	6.248	(0.246)	0.157	(0.0062)	0.025	(0.001)
1/4	6.350	(0.250)	0.160	(0.0063)	0.025	(0.001)
F	6.528	(0.257)	0.160	(0.0063)	0.025	(0.001)
G	6.629	(0.261)	0.160	(0.0063)	0.025	(0.001)
17/64	6.747	(0.2656)	0.163	(0.0064)	0.025	(0.001)
H	6.756	(0.266)	0.163	(0.0064)	0.025	(0.001)
I	6.909	(0.272)	0.163	(0.0064)	0.025	(0,001)
J	7.036	(0,277)	0.165	(00065)	0.051	(0.002)
K	7.137	(0.281)	0.165	(0.0065)	0.051	(0.002)
9/32	7.144	(0.2812)	0.165	(0.0065)	0.051	(0.002)
L	7.366	(0.290)	0.168	(0.0066)	0.051	(0.002)
M	7.493	(0.295)	0.168	(0.0066)	0.051	(0.002)
19/64	7.541	(0.2969)	0.168	(0.0066)	0.051	(0.002)
N	7.671	(0.302)	0.170	(0.0067)	0.051	(0.002)
5/16	7.938	(0.3125)	0.170	(0.0067)	0.051	(0.002)
o	8.026	(0.316)	0.173	(0.0068)	0.051	(0.002)
P	8.204	(0.323)	0.173	(0.0068)	0.051	(0.002)
21/64	8.334	(0.3281)	0.173	(0.0068)	0.051	(0.002)
Q	8.433	(0.332)	0.175	(0.0069)	0.051	(0.002)
R	8.611	(0.339)	0.175	(0.0069)	0.051	(0.002)
11/32	8.731	(0.3438)	0.178	(0.007)	0.051	(0.002)
s	8.839	(0.348)	0.178	(0.007)	0.051	(0.002)

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TABLE 4-47. (cont'd)

Drill	Size		Tolerance			
			Plus		Minus	
	mm	(in.)	mm	(in.)	mm	(in.)
T	9.093	(0.358)	0.180	(0.0071)	0.051	(0.002)
23/64	9.128	(0.3594)	0.180	(0.0071)	0.051	(0.002)
u	9.347	(0.368)	0.183	(0.0072)	0.051	(0.002)
3/8	9.525	(0.375)	0.183	(0.0072)	0.051	(0.002)
v	9.576	(0.377)	0.183	(0.0072)	0.051	(0.002)
w	9.804	(0.386)	0.183	(0.0072)	0.051	(0.002)
25/64	9.922	(0.3906)	0.185	(0.0073)	0.051	(0.002)
x	10.084	(0.397)	0.185	(0.0073)	0.051	(0.002)
Y	10.262	(0.404)	0.185	(0.0073)	0.051	(0.002)
13/32	10.319	(0.4062)	0.188	(0.0074)	0.051	(0.002)
z	10.490	(0.413)	0.188	(0.0074)	0.051	(0.002)
27/64	10.716	(0.4219)	0,190	(0.0075)	0.051	(0.002)
7/16	11.112	(0.4375)	0.190	(0.0075)	0.051	(0.002)
29/64	11.509	(0.4531)	0.193	(0.0076)	0.051	(0.002)
15/32	11.906	(0.4688)	0.196	(0.0077)	0.051	(0.002)
31/64	12.303	(0.4844)	0.198	(0.0078)	0.051	(0.002)
1/2	12.700	(0.500)	0.201	(0.0079)	0.051	(0.002)
33/64	13.097	(0.5156)	0.203	(0.008)	0.051	(0.002)
17/32	13.494	(0.5312)	0.206	(0.0081)	0.051	(0.002)
35/64	13.891	(0.5469)	0.206	(0.0081)	0.051	(0.002)
9/16	14.288	(0.5625)	0.208	(0.0082)	0.051	(0.002)
37/64	14.684	(0.5781)	0.211	(0.0083)	0.051	(0.002)
19/32	15.081	(0.59375)	0.213	(0.0084)	0.051	(0.002)
43/64	15.478	(0.6094)	0.213	(0.0084)	0.051	(0.002)
5/8	15.875	(0.625)	0.216	(0.0085)	0.051	(0.002)
41/64	16.272	(0.6406)	0.218	(0.0086)	0.051	(0.002)
21/32	16.669	(0.65625)	0.218	(0.0086)	0.051	(0.002)
43/64	17.066	(0.6719)	0.221	(0.0087)	0.051	(0.002)
11/16	17.462	(0.6875)	0.224	(0.0088)	0.051	(0.002)
45/64	17.859	(0.7031)	0.224	(0.0088)	0.051	(0.002)
23/32	18.256	(0.7188)	0.226	(0.0089)	0.051	(0.002)
47/64	18.653	(0.7344)	0.229	(0.009)	0.051	(0.002)
3/4	19.050	(0.750)	0.229	(0.009)	0.051	(0.002)
49/64	19.447	(0.7656)	0.231	(0.0091)	0.076	(0.003)
25/32	19.844	(0.7812)	0.234	(0.0092)	0.076	(0.003)
51/64	20.241	(0.7969)	0,234	(0.0092)	0.076	(0.003)
13/16	20.638	(0.8125)	0.236	(0.0093)	0.076	(0.003)
53/64	21.034	(0.8281)	0.236	(0.0093)	0.076	(0.003)
27/32	21.431	(0.8438)	0.239	(0.0094)	0.076	(0.003)
55/64	21.828	(0.8594)	0.241	(0.0095)	0.076	(0.003)

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TABLE 4-47. (cont'd)

Drill	Size		Tolerance			
			Plus		Minus	
	mm	(in.)	mm	(in.)	mm	(in.)
7/8	22.228	(0.8751)	0.241	(0.0095)	0.076	(0.003)
57/64	22.622	(0.8906)	0.244	(0.0096)	0.076	(0.003)
29/32	23.019	(0.9062)	0.244	(0.0096)	0.076	(0.003)
59/64	23.416	(0.9219)	0.246	(0.0097)	0.076	(0.003)
15/16	23.813	(0.9375)	0.246	(0.0097)	0.076	(0.003)
61/64	24.209	(0.9531)	0.249	(0.0098)	0.076	(0.003)
31 /32	24.606	(0.9688)	0.249	(0.0098)	0.076	(0.003)
1	25.400	(1.000)	0.254	(0.010)	0.076	(0.003)

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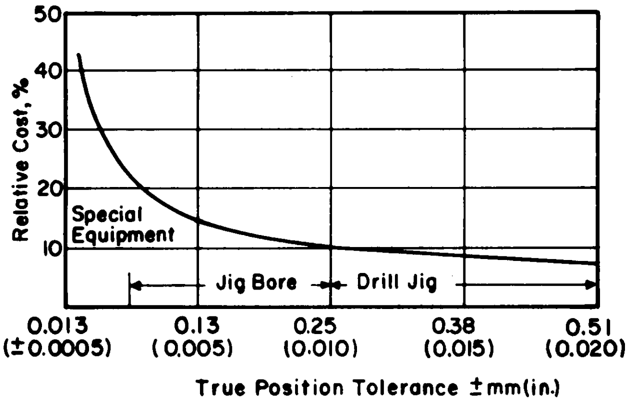

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Figure 4-38. Cost vs True Position Tolerance (Ref. 5)

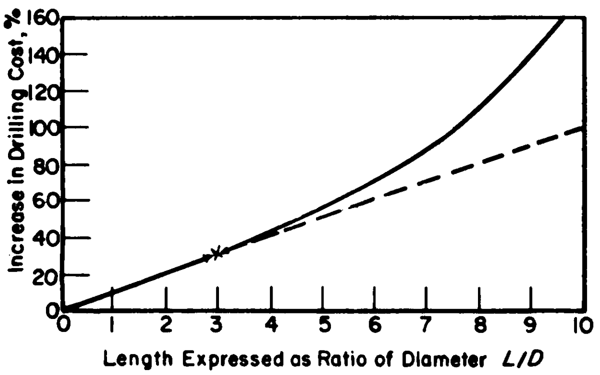

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Figure 4-39. Cost Comparison of Drilled Holes as Affected by Depth (Ref. 5)

There are two classifications for tapped holes: the open or through hole and the closed or blind hole. When blind holes cannot be avoided in design, the depth of perfect thread should not exceed two times the thread diameter. The depth of the drilled hole should be the depth of the perfect thread plus the K (clearance) factor. A bottom tap-chamfer (1 to 1.5 threads) is used only where the depth prohibits use of a plug tap-chamfer (3 to 5 threads). Adequate clearance, which can be determined from Tables 4-48 and 4-49, is required between the ends of the thread and the drilled hole to produce the maximum number of perfect threads. Drill depth must be specified to permit tapping in the following order of preference: plug tapping, bottom tapping.

4-3.2.1.5.4 Reaming

Reaming is a machining operation in which a rotary tool takes a light cut, which improves the accuracy and reduces the roughness of a hole surface as shown in Fig, 4-40. Most holes reamed are from 3.18 to 31.75 mm (0.125 to 1.250 in.) in diameter. Reamers for holes as small as 0.13 mm (0.005 in.) in diameter are available, while the largest reamers are about 150 mm (6 in.) in diameter. The length of the holes that can be reamed depends on the reamer and the accuracy required. Tolerances for reamed holes follow:

1. Holes under 12.7 mm (0.5 in.), ± 0.025 mm (0.001 in.)
2. Holes between 12.7 mm (0.5 in.) and 25.4 mm (1 in.), ± 0.038 mm (0.0015 in.)
3. Holes over 25.4 mm (1 in.), ±0.051 mm (0.002 in.).

Holes may be out of round by as much as size tolerance. Finishes of 0.81 µm (32 µin.) or less can be expected.

TABLE 4-48. DRILL DEPTH FOR BLIND TAPPED HOLES—COARSE THREAD (Ref. 5)

UNC Thread Designation	K dimension			
	Plug Tap, First Choice		Bottom Tap, Second Choice	
	mm	(in.)	mm	(in.)
1-64	3.0	(0.12)	1.8	(0.07)
2-56	3.6	(0.14)	2.0	(0.08)
3-48	4.3	(0.17)	2.3	(0.09)
4-40	5.1	(0.20)	2.8	(0.11)
5-40	5.1	(0.20)	2.8	(0.11)
6-32	6.4	(0.25)	3.6	(0.14)
8-32	6.4	(0.25)	3.6	(0.14)
10-24	8.4	(0.33)	4.8	(0.19)
12-24	8.4	(0.33)	4.8	(0.19)
1/4-20	10.2	(0.40)	5.8	(0.23)
5/16-18	11.2	(0.44)	6.4	(0.25)
3/8-16	12.7	(0.50)	7.1	(0.28)
7/16-4	14.5	(0.57)	8.1	(0.32)
1/2-13	15.7	(0.62)	8.9	(0.35)
9/16-12	17.0	(0.67)	9.4	(0.37)
5/8-11	18.5	(0.73)	10.4	(0.41)
3/4-10	20.3	(0.80)	11.4	(0.45)
7/8-9	22.6	(0.89)	12.7	(0.50)
1-8	25.4	(1.00)	14.2	(0.56)

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TABLE 4-49. DRILL DEPTH FOR BLIND TAPPED HOLES—FINE THREAD (Ref. 5)

UNF Thread Designation	K dimension			
	Plug Tap, First Choice		Bottom Tap, Second Choice	
	mm	(in.)	mm	(in.)
0-80	2.5	(0.10)	1.5	(0.06)
1-72	2.8	(0.11)	1.5	(0.06)
2-64	3.0	(0.12)	1.8	(0.07)
3-56	3.6	(0.14)	2.0	(0.08)
4-48	4.3	(0.17)	2.3	(0.09)
5-44	4.6	(0.18)	2.5	(0.10)
6-40	5.1	(0.20)	2.8	(0.11)
8-36	5.6	(0.22)	3.3	(0.13)
10-32	6.4	(0.25)	3.6	(0,14)
12-28	7.1	(0.28)	4.1	(0.16)
1/4-28	7.1	(0.28)	4.1	(0.16)
5/ 16-24	8.4	(0.33)	4.8	(0.19)
3/8-24	8.4	(0.33)	4.8	(0.19)
7/16-20	10.2	(0.40)	5.8	(0.23)
1/2-20	10.2	(0.40)	5.8	(0.23)
9/16-18	11.2	(0.44)	6.4	(0.25)
5/8-18	11.2	(0.44)	6.4	(0.25)
3/4-16	12.7	(0.50)	7.1	(0.28)
7/8-14	14.5	(0.57)	8.1	(0.32)
1-12	17.0	(0.67)	9.4	(0.37)
1-1/8-12	17.0	(0.67)	9.4	(0.37)
1-1/4-12	17.0	(0.67)	9.4	(0.37)
1-3/8-12	17.0	(0.67)	9.4	(0.37)
1-1/2-12	17.0	(0.67)	9.4	(0.37)

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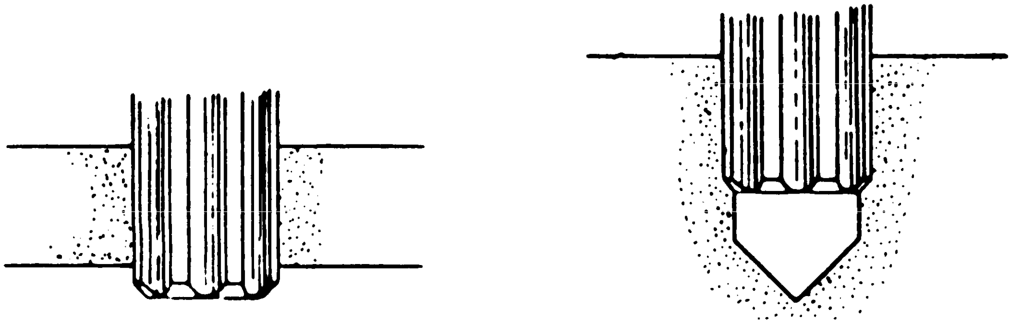


(A) Ream Through

(B) Control Depth Of Ream

Figure 4-40. Reaming

4-3.2.1.5.5 Broaching

Broaching is a machining process in which a cutting tool with multiple transverse cutting edges is pushed or pulled through a hole or over a surface to remove metal by axial cutting. Almost any surface can be broached if it is uniform in cross section in the direction of broach travel, which must be in a straight line. The process is very adaptable to high production rates; however, broaching must be considered when parts are being designed if the benefits of it are to be realized. The tolerances for the broach process follow:

1. Round and square holes: ±0.013 to ±0.025 mm (0.0005 to 0.001 in.)
2. Plain splined holes: ±0.025 to ± 0.051 mm (0.001 to 0.002 in.) on diameter and ±0.025 mm (0.001 in.) on spline width
3. Surfaces: (straddle broached), ±0.025 mm (0.001 in.); when design demands, ±0.003 mm (0.0001 in.) can be held on size and parallelism
4. Slots: ±0.005 mm (0.0002 in.) can be obtained; ± 0.025 to ±0.0508 mm (0.001 to 0.002 in.) is more economical
5. Surface finishes: within 0.818 μm (32 μin.) are typical.

4-3.2.1.5.6 Boring

Boring is the generation of internal diameters about a spindle centerline with a single-point cutting tool to enlarge or finish holes or circular contours. Straight-through holes are most common; however, blind holes, stepped holes, holes with undercuts, or contoured holes are more expensive to generate, but they can be bored. The minimum diameter for boring is about 6.35 mm (0.250 in.); the maximum diameter is limited by the size of the machine which holds and rotates the workpiece and by the deflection of the boring bar. Tolerances on large machines follow:

1. Bores: 610 mm (24 in.) in diameter, ±0.127 to ± 0.013 mm (0.005 to 0.0005 in.)
2. Tolerances: ±0.025 mm (0.001 in.) on holes up to 152.4 mm (6 in.), and greater limits on larger diameters are more producible.
3. Hole location: to ±0.013 mm (0.0005 in.).

Tolerances on special production machines follow:

1. Small holes: ±0.003 to ±0.005 mm (0.0001 to 0.0002 in.)
2. Large bores: up to 380 mm (15 in.), ± 0.025 mm (0.001 in.)
3. Threads: to a class 3 fit.

Tolerances on jig bores follow:

1. Threads: to a class 4 fit
2. Hole location: to 0.003 mm (0.0001 in.).

4-3.2.1.5.7 Hobbing

Hobbing, first used on cutting gears, maybe applied to the production of almost any form that regularly repeats itself on the periphery of a circular part. The hob is designed so that the cutting teeth lie in a helical path around the tool as sho~vn in Fig. 4-41. The bobbing machine, which looks like a small, horizontal milling machine, rotates the workpiece and the bob, controls the movement of the bob, and causes the cutting teeth to move in a positive progression through the workpiece, Each tooth removes a small shaving, and since cutting action is continuous and automatically controlled, the desired full form outline is produced. Tolerances for the bobbing process follow:

1. Large gears: 254mm (10 in.) OD, pitch diameter tolerance is ±0.025 mm (0.001 in.).
2. Gears: (30 to 268 pitch) pitch diameter tolerance is ± 0.008 to 0.013 mm (0.0003 to 0.0005 in.).
3. Profiles: accurate to ± 0.013 mm (0.0005 in.).

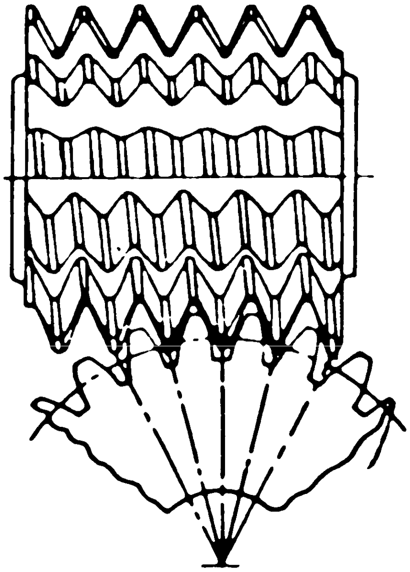


Figure 4-41. Single-Thread Hob Cutting Gear

4-3.2.1.5.8 Sawing

Bandsawing is the most widely used sawing method because it is versatile and capable of making relatively intricate contour cuts. A wide variety of saw blades, including diamond and abrasive blades, are available, which make it possible to cut such substances as steel, tungsten carbide, glass, and vitreous materials.

Friction bandsawing, sometimes referred to as high-velocity sawing, is a frictional melting or burning process. The high friction speed permits contour cutting of extremely hard materials. Generally, it is limited to 12.7 mm (0.5 in.) thicknesses; however, 50.8-mm (2-in.) armor has been cut on a production basis. The following tolerances apply to sawing processes:

1. Circular saws, cross cutting: accuracy of ± 0.13 to 0.25 mm (0.005 to 0.010 in.) per 25.4 mm(l in.)
2. Conventional bandsawing: ± 0.20 to 0.25 mm (0.008 to 0.010 in.) on layout line.

4-3.2.1.5.9 Trepanning

Trepanning operations are used to produce round discs, large, shallow through holes, circular grooves, or deep holes. One or more cutters revolving around a center produces a circular hole or a groove with a remaining solid center core as shown in Fig. 4-42. Discs up to 152 mm (6 in.) in diameter can be produced from plate up to 6.4 mm (0.25 in.) thick in a hand-fed drill press. In a similar fashion, large through holes can be readily trepanned in plate, or by controlling the depth of the cut, circular grooves can be produced. Deep holes, 51 mm (2in.) or more in diameter and 203 mm (8 in.) or more in depth, can be trepanned from solid stock.

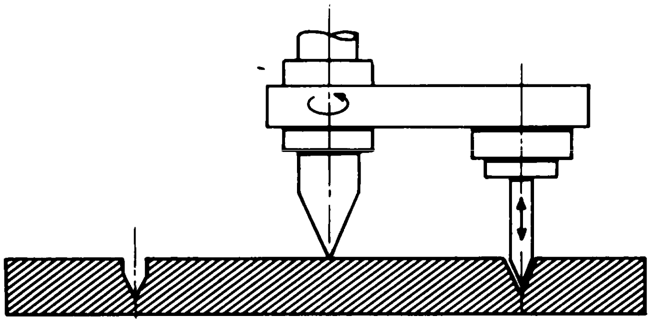


Figure 4-42. A Form of Trepanning

Trepanning uses self-piloting cutting action, requires a pressurized cutting fluid system, and offers the following advantages over spade or twist drilling:

1. Closer diameter and straightness tolerances
2. Deeper holes
3. Higher metal removal rate
4. More valuable solid core produced.

Production rates for trepanning operations, as such, are not high; however, machining time on deep holes might be as much as 50 to 75% lower than on those made by center drilling, twist drilling, or boring.

4-3.2.1.5.10 Grinding

A principal metal removal method is grinding. Grinding processes used in metal finishing, such as honing or lapping, are discussed in par. 4-1.2.2.4.1. This paragraph addresses those grinding processes primarily intended to remove metal, including cylindrical, centerless, surface, and abrasive belt grinding.

1. *Cylindrical grinding:*

Cylindrical grinding is a method of grinding the outside surfaces of cylindrical parts. Four movements are involved: the workpiece rotates on centers or a mandrel; the grinding wheel rotates; the grinding wheel moves in or out from the workpiece; and the workpiece traverses the wheel. (On some large machines, the wheel may traverse the workpiece.)

Tolerances appropriate to the cylindrical grinding process are

a. Cylindrical grinders: ± 0.003 to 0.013 mm (0.0001 to 0.0005 in.) on diameters, if practical for production

b. Surface finish dependent on work material, grinding wheel grit size, and other factors: 0.81 to 1.60 µm (32 to 63 µin.) typical for production.

2. *Centerless grinding:*

Centerless grinding is a method of grinding the inner or outer surfaces of cylindrical parts; it is similar to cylindrical grinding except that the workpiece is not mounted on centers. Instead, it is supported by a work rest blade and a regulating wheel.

The tolerances for centerless grinding are

a. Dimensions: held within the range 0.0010 to 0.13 mm (0.00004 to 0.005 in.)

b. Out of roundness: held to 0.0003 mm (0.00001 in.).

3. *Surface grinding:*

Surface grinding is accomplished by grinding wheels mounted on tables that move under the wheel in either horizontal or rotary passes.

Tolerances for surface grinding are

a. On surface grinders: flatness held to within 0.005 to 0.008 mm (0.0002 to 0.0003 in.) over 6.1 m (20 ft)

b. On rotary table machines: flatness held to 0.005 to 0.013 mm (0.0002 to 0.0005 in.), parallelism to 0.010 to 0.013 mm (0.0004 to 0.0005 in,), and length to ± 0.005 mm (0.0002 in.).

Surface finish generally is dependent on the material being ground; however, 0.10 µm (4 µin.) can be obtained in production on hardened steel.

4. *Abrasive belt grinders:*

This method uses driven, endless abrasive belts supported by suitable contact wheels, which provide opposing pressure to the workpiece to achieve stock removal.

The tolerances for abrasive belt grinding are

a. Flat surfaces: ± 0.05 mm (0.002 in.) flatness and parallelism

b. Centerless grinding operations: ± 0.013 mm (0.0005 in.) with fine grits, in production

c. Finishes of 0.20 µm (8 µin.) are typical.

4-3.2.1.5.11 Planing

Planing is the removal of metal from horizontal, vertical, or angular surfaces of the workpiece. This is accomplished by moving the workpiece in a linear direction against one or more fixed, single-point tools. Standard planers are available for making cuts up to 15.2 m (50 ft) long. Planing is not for high production volume; it is best adapted to large workplaces and low volume jobs.

The tolerances connected with planing operations are

1. Precision flat surfaces: to ± 0.13 mm (0.005 in.) with surface finish from 3.18 to 12.70 µm (125 to 500 µin.) obtainable
2. Cast iron: ± 0.03 to 0.05 mm (0.001 to 0.002 in.) with a 1.60-µm (63-µin.) finish possible.

Tolerances on dimensions depend on the size and complexity of the part; however, ± 0.03 to 0.13 mm (0.001 to 0.005 in.) can be held on small and medium dimensions.

4-3.2.1.5.12 Shaping

Shaping is a metal removal process whereby a single-point tool reciprocates in a linear direction against a stationary workpiece to form horizontal, vertical, or angular plane surfaces. Standard shapers have a stroke of 910 mm (36 in.); therefore, the size of the work is limited. Generally, shaping is considered to be inefficient; however, the short time required for setup and its inexpensive tooling make the process practical for some jobs. In addition, deep internal slots and certain operations in blind holes, awkward for broaching or milling, can be achieved.

The tolerances obtained on shapers are comparable to those achieved by planing.

4-3.2.1.6 Summary

The importance of material availability to producibility was discussed earlier. The availability factor applies equally to the manufacturing process. There are some processes that require significantly longer production lead times than others. These factors should be considered early in the acquisition process if producibility problems are to be avoided. Generally, process availability should be determined directly with the potential supplier on a case-by-case basis. However, there are some general characteristics concerning lead times of the various processes that are cited in Table 4-36.

Obviously, the lack of availability of a process when needed or the inability of a process to meet a specific demand must be anticipated. If a change should occur due to process availability at a critical time in the production phase, it could have a chain reaction—going all the way back through the cycle to material selection and, thus, could create a significant producibility problem.

The preceding paragraphs have all discussed the various machining procedures for the removal of metal and the metal forming processes for the creation of near net shape metal parts. The designer always should strive to achieve the finished component in as few operations as possible, ideally in a single process of metal forming to a final, desired net shape and size. However, this is not always possible, and often it is necessary to use a secondary process of metal cutting to achieve the desired surface finish or dimensional accuracy, For information on these processes refer to par. 4-1.2.2.4.1.

4-3.2.2 Nontraditional secondary Manufacturing Processes

Nontraditional processes are those that have not as yet made a significant penetration in the metal working industry. These would also include some processes that are in an early stage of development but that show a good potential for success and acceptance in the industry; these are discussed in par. 4-1.2.2.2. One of these that bears further discussion here is NC and its subsets. DNC and CNC. These are, as the names imly, control systems, not manufacturing processes. However, their greatest use has been in the control of metal cutting processes, particularly those addresscd ill this handbook as NS/MMC. When these controls are added to the various metal reduction processes, the general capabilities of the processes are changed significantly.

4-3.2.2.1 Numerical Control Machining (NCM)

When NCM is used, the general tolerance <capabilities are enhanced significantly. The one outstandingly significant point that the designer should keep in mind about NCM is that it is not a high production process. Many people rightfully classify NCM as automation, but then they erroneously associate automation with mass production. It is not. NCM is merely the precise control of a process that was formerly manual. There are far faster and lower test methods for mass production than NCM.

NCM has achieved a fair degree of penetration into the industry. It is relatively available across the United States even though its actual use is less than 2% of the total United States machine tool inventor}.

4-3.2.2.2 NCM Processes

NCM embraces numerous metal cutting processes. Table 4-50 provides a list of the more common metal cutting processes, to which this control technology has been applied, and also the resultant ratios of productivity improvement, typical lot sizes, and tolerance capabilities.

4-4 HEAVY STRUCTURAL COMPONENTS

The producibility considerations for components in this class are unique. Because of their size, weight, and bulk, these parts require special handling techniques. Typical of parts in this class are large shafts, compo-

TABLE 4-50. METAL CUTTING PROCESSES USING NC

Process	Improve Ratio	Typical Lot Size	Standard Tolerance		Special Tolerance At Added Cost	
			mm	(in.)	mm	(in.)
Drilling	2.8 to 1	1-2000	± 0.05	(0.002)	± 0.025	(0.001)
Milling	3.2 to 1	5-3000	± 0.05	(0.002)	± 0.013	(0.0005)
Turning	2.9 to 1	1-10,000	± 0.08	(0.003)	± 0.025	(0.001)
Boring	3.7 to 1	1-25	± 0.03	(0.001)	± 0.008	(0.0003)

nents for military tanks, machine tool bases, large forgings for structural supports, and large castings for heavy equipment supports and frames. Probably more than any other class of parts, the heavy structural components demand greater producibility concern from the designer. The cost and time investment at any stage of production is sufficiently large to warrant very careful and thorough producibility planning. Common producibility problems in this class are given in pars. 4-5.7 and 4-5.9.

4-4.1 MAJOR MATERIAL CONSIDERATIONS

The variety of material options for this class of metal parts is probably smaller than for any other class. This makes the designer's job of trade-offs far more difficult. The designer's primary objective of maintaining the structural integrity of his design compounds the problem further. However, this should not deter the designer from carefully considering all aspects of producibility in addition to structural integrity. Implied manufacturing processes need to be examined carefully; particularly important is material handling during manufacturing. Consideration of the commercial availability of structural material is vital to good producibility; transportation methods also can influence producibility significantly. The importance of all these potential producibility impacts must receive equal consideration during the material selection phase of a project.

4-4.1.1 Materials

Table 4-12 shows the primary material options and their availability in various shapes and forms. In the design of heavy structural components, the obvious major concern is structural integrity. In large structural components an often overlooked factor in material selection is the standard manufacturing tolerance used in producing the raw material shape in the steel mill. Fig. 4-43 shows some of these basic shapes and their tolerances. The designer, in seeking structural strength with minimum weight, should not overlook other possible means to achieve the same results. Fig. 4-44 provides data on plate fabrication with stiffeners to achieve higher strength for the same weight. When plates of sheet metal are stiffened with channels, honeycombing, gussets, etc., the strength is increased. The amount of increase over the basic plate for each stiffener design is shown. The stiffness value of the basic plate is established as 1, and chart values indicate how many times stiffer they are for each design. All plates tested for these data were 508.0 mm (20 in.) square and 3.18 mm (0.125 in.) thick. Web thickness was 1.02 mm (0.040 in.), height was 38.10 mm (1.5 in.), and construction was welded. Note that these examples are given to indicate what is possible; a structural analysis is required to select a specific design. Tables 4-1 through 4-11 show some typical applications of the more common metals and give some pertinent remarks relative to producibility.

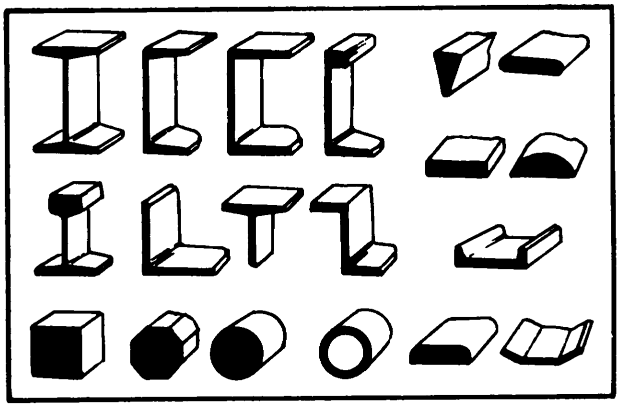
4-4.1.2 Material Selection Factors

When selecting the material for his design, the designer is initially concerned with satisfying the demands of structural integrity for design performance. In the case of heavy structural components, this is particularly true. The significant point with heavy structural parts is that the designer must carefully check the physical characteristics of each material to determine its applicability for the design intent or performance characteristics. These same physical characteristics, to a large extent, impact the production process and ultimately the producibility of the design. Discussion on each of these aspects is contained in par. 4-1.1.2.

In the material selection process, the designer should consider also the possible use of nonmetals, The relative strength-to-weight ratio of plastics is shown on Fig. 4-45. This figure also shows the comparative values for some metals. More details on this area are given in Chapter 5 on producibility considerations for plastic components.

4-4.1.3 Cost Considerations

Since the actual cost of materials is very dynamic, the ratio number from Fig. 4-45 provides a comparative



(A) Standard Hot Rolled Shapes

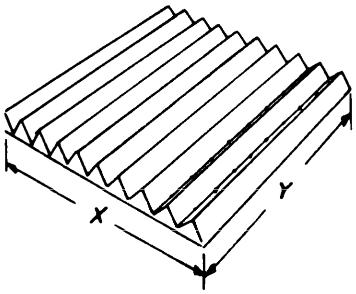
Specified Size		Tolerance			
		Plus		Minus	
mm	(in.)	mm	(in.)	mm	(in.)
25	(1.0)	0.23	(0.009)	0.23	(0.009)
38	(1.5)	0.36	(0.014)	0.36	(0.014)
51	(2.0)	0.41	(0.016)	0.41	(0.016)
64	(2.5)	0.79	(0.031)	0	
114	(4.5)	1.60	(0.063)	0	
216	(8.5)	4.78	(0.188)	0	
254	(10)	6.35	(0.250)	0	

(B) Tolerance Rounds and Squares

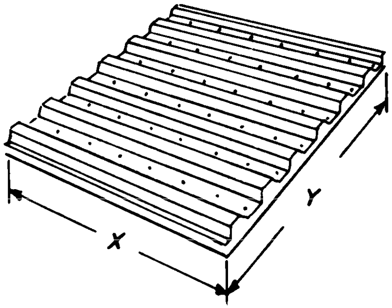
Specified Size		Tolerance			
		Plus		Minus	
mm	(in.)	mm	(in.)	mm	(in.)
13	(0.5)	0.18	(0.007)	0.18	(0.007)
25	(1.0)	0.25	(0.010)	0.25	(0.010)
38	(1.5)	0.53	(0.021)	0.33	(0.013)
51	(2.0)	0.79	(0.031)	0.41	(0.016)
64	(2.5)	1.19	(0.047)	0.41	(0.016)
89	(3.5)	1.60	(0.063)	0.41	(0.016)

(C) Tolerance Hexagons

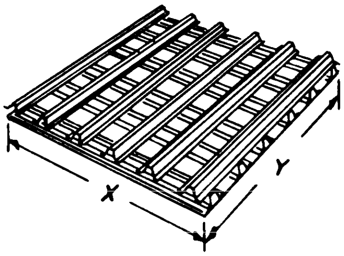
Figure 4-43. Basic Hot Rolled Steel Shapes and Tolerances



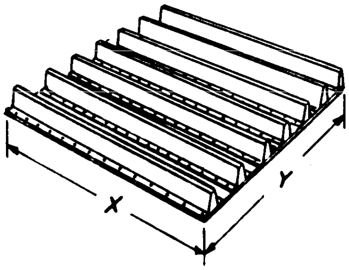
1. Angles



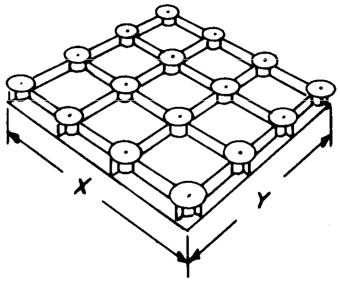
2. Corrugated Plate



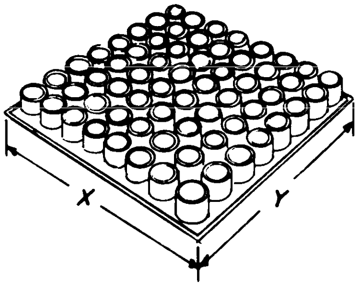
3. Two Layers of Single Channels Arranged Crosswise



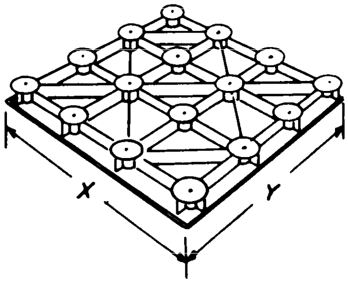
4. Single Layer of Channels



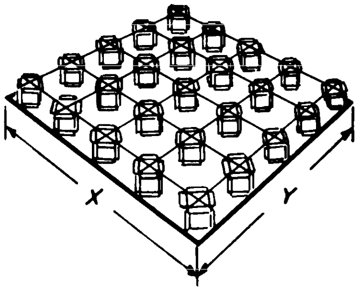
5. Round Gussets and Straight Ribs



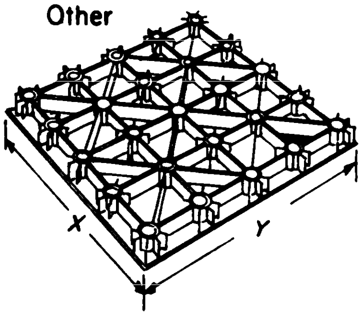
6. Tube Sections Welded to Each Other



7. Round Gussets Straight and Diagonal Ribs



8. Round Gussets Made from Channel Sections



9. Starlike Gussets and Radial Ribs (close together)

Load	Direction		Plate Number								
			1	2	3	4	5	6	7	8	9
Torsion			48.00*	40.00	28.00	11.30	3.50	27.00	33.00	24.00	1.30
Bending	x axis		112.00	58.00	18.00	47.00	10.00	10,30	12.50	22.50	16.30
(single)	y axis		1.10	1.30	30.00	1.20	10.00	10.30	12.50	7.80	16.30
Strength Weight	Single Torsion		30.70	26.00	17.00	8.10	2.10	10.00	18.00	1.50	7.30
	Single Bending	x	72.00	28.20	10.00	34.50	5.80	3,40	6.70	13.00	9.10
		y	0.75	0.80	18.00	0.85	5.80	3.40	6.70	4.60	

*Numbers represent the ratio of the parameter listed for this construction with the same weight of sheet metal plate,

Figure 4-44. Fabrication Plates to Achieve Structural Integrity

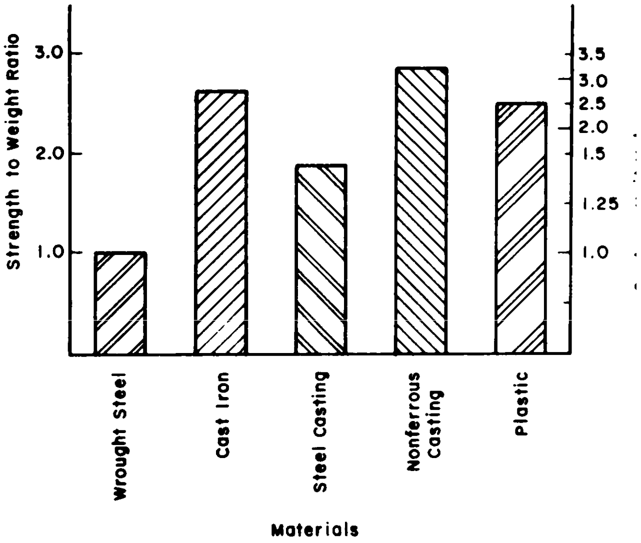


Figure 4-45. Strength-to-Weight Ratio Relative to Cost per Unit Volume for Several Materials

basis using steel as a reference base. Actual cost should be determined from potential suppliers.

4-4.1.4 Material Availability

The size and weight of the material in heavy structural components severely limit the metal suppliers who always stock large quantities of these materials. Consequently, even though the material shape, form, and size selected by the designer are mill standards, it does not necessarily follow that the material will be in stock when needed. As outlined in Table 4-12, a wide variety of materials can be obtained in shapes either prefabricated by the mill and stocked as mill standards or fabricated to the requirements of the customer. The shape configurations carried as standard stock vary among producers; therefore, catalogs must be consulted for details.

At first glance, the use of special shapes could appear to have disadvantages. However, subsequent savings in fabrication time and cost will often outweigh the higher procurement cost and longer lead time required for the acquisition of custom-made shapes.

Structural shapes are standard for the steel and aluminum industries. The aluminum industry fabricates a wide variety of architectural shapes. However, some producers have designated them standard and made them stock items. Standard steel structural shapes are designated as follows:

1. Wide flange sections: (depth of flange) X (width across) X (weight per foot)
2. Beams and channels: (depth of section) X (weight per foot)
3. Angles: (length of leg) X (length of leg) X [thickness (fraction of an inch)]; also (length of leg) X (weight per foot); the longer leg is commonly stated first.
4. Tees: (width of flange) X (overall stem depth) X (weight per foot).

4-4.1.5 Material-Related Manufacturing Processes

As discussed earlier in this chapter, the selection of the material is an iterative process. Each material has different physical characteristics, which dictate certain manufacturing process constraints. Consequenstly, each material selected by the designer has specific manufacturing process implications, and these implications should be thoroughly explored to assure compatibility with the intended design. Table 4-12 lists the material options for this class of components and shows the implied manufacturing processes for each of the materials. While examining and being aware of the manufacturing processes implied by the material selection are important, there are other equally important related facts to consider. Probably one of the more significant of these is the availability of the process-particularly geographic proximity. Transportation cost and time can often contribute to poor producibility if they have not been considered. Since a large majority of the heavy structural parts will be castings or forgings. they will serve as good examples of the geographic availability of structural components. The map in Fig. 4-46 shows the location and density of these industries in the United States. Solid lines indicate relatively heavy concentrations, and dotted lines outline moderate conctrations of the forging casting industry.

4-4.2 MANUFACTURING PROCESS CONSIDERATIONS

The number of manufacturing processes amenable to heavy structural parts is constrained due to the size

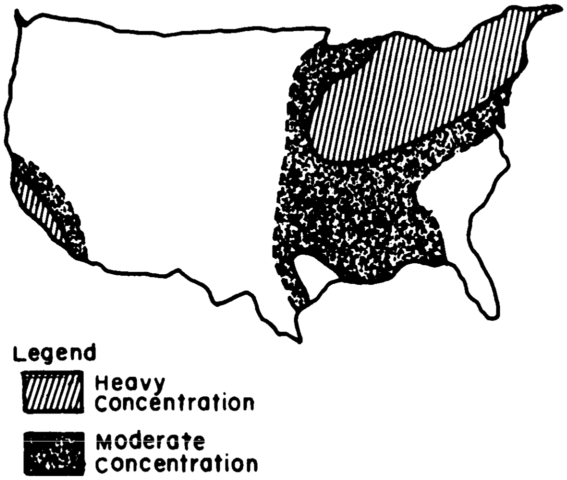


Figure 4-46. Geographic Location of Forging/ Casting Industry

limitations inherent in the processes. Another factor that is also limiting and might be overlooked is material handling, which can be critical on large, heavy components.

A third factor to consider is the availability of a particular process for a particular demand. Processes are equipment oriented, and consequently, heavy structural parts demand large, heavy machine tools and equipment. Since the equipment is unique, it requires significant capital investment, which demands a high machine utilization factor. As a consequence, the population density of this type equipment is comparatively low, and available equipment has high utilization rates. Invariably, this means long production lead times. If good producibility is to result, these factors must be considered from the outset.

Information on availability and lead times of various manufacturing processes is provided in Table 4-36; however, this information has, by necessity, been averaged. Specific requirements should be checked with potential suppliers since availability and lead times may vary significantly depending on geographical location and individual requirements.

4-4.2.1 Traditional Secondary Manufacturing Processes

The manufacturing processes that follow and their subsets are the basic processes for this class of parts. Few of these processes are amenable to mass production techniques. This follows since this class of parts is seldom fabricated in large quantities. However, this does not mean that automation is not applied, but rather that it can rarely be economical y justified.

4-4.2.1.1 Machining Processes

Generally, the applicable machining processes are the same as those discussed in par. 4-3 on net shapes. The primary difference is in the size of the machines performing the processes. The various processes are boring, drilling, milling, planing, slotting, reaming, trepanning, and turning. The paragraphs that follow describe some machining processes that are generally associated with heavy structural components.

4-4.2.1.1.1 Planing

Planing is the removal of metal from horizontal, vertical, or angular surfaces of the workpiece. This is accomplished by moving the workpiece in a linear direction against one or more fixed, single-point tools. Standard planers are available for making cuts up to 15.2 m (50 ft) long. Planing is not suitable for high production volume but is best adapted to large workplaces and low volume jobs. The tolerances connected with planing operations follow:

1. Precision flat surfaces: to ± 0.13 mm (0.005 in.) with surface finish from 3.18 to 12.70 ±m (125 to 500 µin.) obtainable
2. Cast iron:+ 0.03 to 0.05 mm (0.001 to 0.002 in.) with a 1.60-µm (63-µin.) surface finish possible.

4-4.2.1.1.2 Slotting

Slotting is a metal removal process by which a single-point tool reciprocates in a linear direction against a stationary workpiece to form horizontal, vertical, or angular slots. The tolerances obtained are comparable to those achieved by planing. The ram carrying the cutting tool cuts on vertical downstroke which can be as long as 1.829 m (72 in.).

4-4.2.1.1.3 Turning

A machining process for generating concentric, external and internal surfaces by the action of a cutting tool against a rotating workpiece on a lathe is referred to as turning. Of particular interest to this class of parts are two particular types of lathe: the gap bed lathe and the vertical lathe shown in Fig. 4-47. The gap bed lathe has a gap between the bed and the headstock of the lathe, which permits it to swing large diameters, up to 1.8 m (6 ft) or more. The vertical lathe is a lathe that has the turning part resting on a horizontal table and rotating about a vertical axis. The cutting tool is introduced from the side or the top. These machines will generally swing parts 1.5 to 1.8 m (5 to 6 ft) in diameter. Tolerances for both these machines are generally ± 0.13 mm (0.005 in.); however, closer tolerances, ± 0.05 mm (0.002) in.), can be held at additional cost.

4-4.2.1.2 Cutting Processes

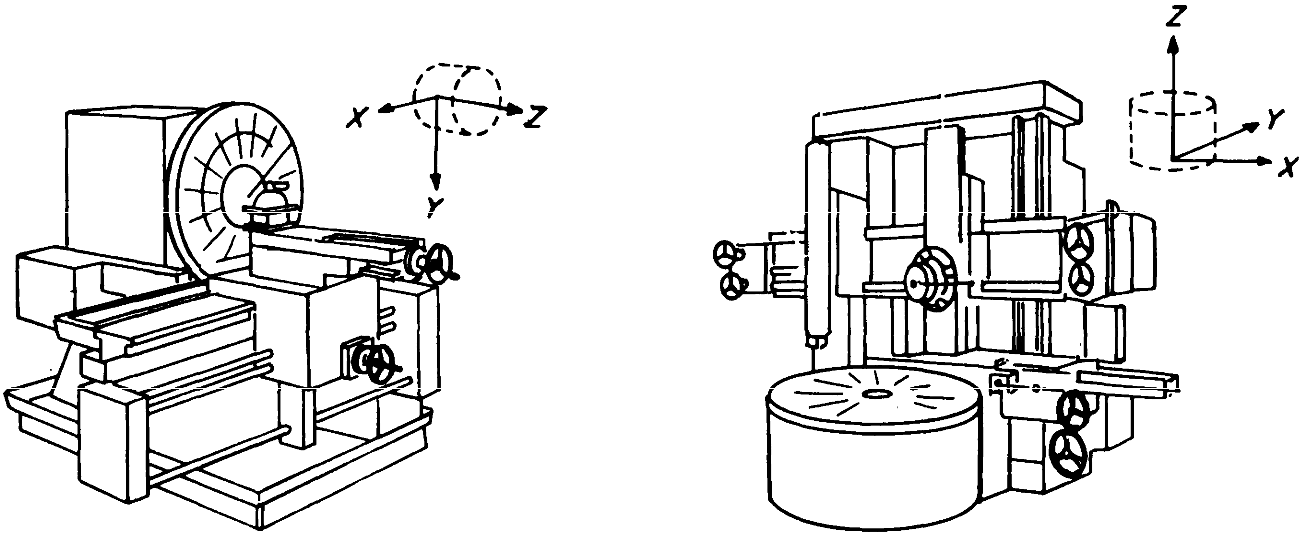
The discussion of cutting processes is restricted to sawing and flame cutting. Most cutoff or contour cutting is accomplished by the use of one of these two processes. The sawing processes are discussed in par. 4-3.2.1.5.8.

Flame cutting is a process used to cut ferrous metals by having a jet of pure oxygen directed at a point in the metal that has been heated to the fusion point. Mechanical flame cutting machines capable of cutting as many as 20 patterns simultaneously have been developed. Work as thick as 150 mm (6 in.) can be accommodated at cutting speeds from 254 to 508 mm/min (10 to 20 in./min).

The accuracy of the flame cutting operation depends on the thickness of the material, how easily it can be cut, the method of clamping it, the distortion, and the inherent accuracy of the machine. Tolerances for the flame cutting process are

1. Portable straight line machines: average ± 3.18 mm (0.125 in.)
2. Portable shape cutting machines: ± 1.588 mm (0.0625 in.) possible
3. Stationary machines: ± 1.588 mm (0.0625 in.).

The usual work distortion allowances, which vary with



(A) Gap Bed or Right Angle Lathe

(B) Vertical Turret Lathe

Figure 4-47. Gap Bed and Vertical Lathe

the particular cut being made, also must be considered. Depending on the size of the torch jet, kerf width varies from 0.7938 mm (0.03125 in.) to over 9.52 mm (0.375 in.).

4-4.2.2 Nontraditional Secondary Manufacturing Processes

The high cost of rejecting a heavy structural component makes reliability and accuracy of the manufacturing process extremely important. This fact has been the driving force in most nontraditional developments. The other driving force has been the necessity to improve production rates and thereby reduce the high labor cost normally associated with heavy structural parts. Some of the more recent nontraditional processes that have been reduced to practice include: NC machining and cutting, rotary forging, and NC frame bending.

4-4.2.2.1 Machining and Cutting Processes

These processes include NC machining, NC flame cutting, and plasma arc burning.

4-4.2.2.1.1 NC Machining (NCM)

The adaptation of NC to the traditional machining processes has done much to raise the reliability and accuracy factors; therefore, NC has been adapted to almost every machining process. Highly reliable tolerances of from 0.13 to 0.05 mm (0.005 to 0.002 in.) are standard in NCM today, and repeatability factors within 0.013 mm (0.0005 in.) are easily obtainable. The ability to drive and precisely control a cutting tool moving in three-, four-, or even five-axes simultaneously has provided a capability that never existed in normal traditional operations. Most, if not all, heavy equipment manufacturers have a good inventory of this type of equipment. In fact, they are, in many instances, leaders in the field of NCM applications.

4-4.2.2.1.2 NC Flame Cutting

The flame cutting process is an obvious application for NC. It requires only two or three axes of control to move a burning torch accurately and reliably over a large steel plate. Because of this added control, actual production burning rates have been doubled over their conventional counterparts. It is now possible to burn large 12.2 m X 6.1 m (40 ft X 20 ft) steel plates at 10.2 mm's (24 in. rein) with a finished dimensional tolerance of ± 0.76mm (0.030 in.) on all linear and curvilinear dimensions. The penetration of this equipment into the industrial inventory has been very slow. While most large shipyards have a good complement of NC flame cutters, only a few heavy equipment builders have even one machine.

4-4.2.2.1.3 Plasma Arc Burning

This is a new method of burning metal, which has also been adapted to NC. In fact, its cutting speed is so high that it requires a sophisticated form of control, such as NC, to obtain good results. Fig, 4-48 illustrates this process. Plasma arc burning cuts material by using a superheated stream of electrically ionized gas. Since the process does not rely on the heat of combustion between the gas and the workpiece material, it can be used on almost any conductive metal. One electrode

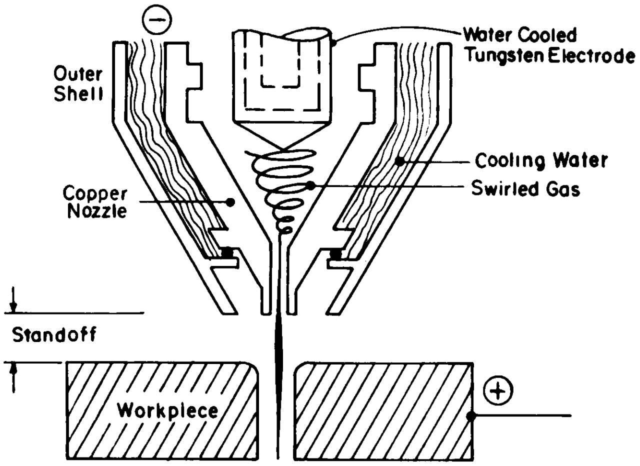


Figure 4-48. Plasma Arc Burning

size can be used to machine a wide range of materials and thicknesses by suitable adjustments to the power level, gas type, gas flow rate, traverse speed, and flame angle.

Profile cutting of metals, particularly stainless steel and aluminum, has been the most prominent commercial application; however, mild steel, alloy steel, titanium, bronze, and most metals can be cut cleanly and rapidly. Multiple torch cuts are possible on programmed or tracer-controlled cutting tables on plates up to 203 mm (8 in.) thick in mild steel. Smoothness of cut with freedom from contaminants is an advantage while well-attached dross on the underside of the cut can be a problem. Eye shielding and noise protection are necessary for the operator and those in nearby areas. The amount of heat conducted into the material varies depending on the material thickness and thermal conductivity; this heat affects cutting speeds. For example, an aluminum plate 25.4 mm (1 in.) can be cut at 13 mm/s (30 in./min) while 6.4 mm (0.25 in.) carbon steel can be cut at 68 mm s (160 in./min). Corner radius is a minimum of 3.969 mm (0.15625 in.) on thinner plates. Tolerances for slots and holes ordinarily range from ± 0.794 mm (0.03125 in.) on 6.4-mm (0.25 -in.) to 34.9-mm (1.375 -in.) thick plates and up to ± 3.2 mm (0.125 in.) on 150- to 200-mm (6- to 8-in.) thick plates. The heat-affected zone can range from 0.794 to 4.762 mm (0.03 125 to 0.1875 in.) wide; however, this depends on workpiece material and on the depth and speed of cut.

4-4.2.2.2 NC Frame Bending

This is a recent development in the shipbuilding industry for making controlled bends on structural steel beams up to 910 mm (36 in.) deep. It is a four-point, hydraulically powered bending device. It is computer controlled and measures the springback in each piece as it is being bent, compensates for that springback, and creates the final, desired bend.

This machine is in an advanced stage of development and should be in production in the very near future. However, its availability will never be very high because the current marketplace demands appear to be limited to shipbuilding and the equipment requires a high capital expenditure.

4-5 MAJOR PRODUCIBILITY PROBLEMS

To compile information on repeated producibility problems, man y sources were contacted. These included manufacturers, production engineers, design engineers, etc., from both Government and industry. The 10 producibility problems described in the paragraphs that follow typify the major causes of poor producibility. It should be the objective of those engaged in producibility to eliminate these types of problems.

In pursuing this objective, the designer occupies a unique and commanding position since he alone is responsible for the original design. He is intimately knowledgeable of the special requirements of the design— whether it be a piece part, an assembly, a subsystem, or the complete system—and it is he who plans for the orderly incorporation of his design into the overall system. He conducts his activities within a defined time frame and uses all available resources to consider fully all aspects of the design. He weighs and judges them and incorporates all the most desirable features. If, perhaps, he is not knowledgeable, did not plan, or is not provided with sufficient time and resources, errors will occur that inhibit good producibility.

In this chapter the nature of such deficiencies and how they relate to design, and thus to producibility, are broadly approached. Any deficiency in design, if detected, becomes the subject of effort to correct it, and the corrective action itself becomes essential. This may lead to a long-term improvement in producibility, or it may not influence producibility at all. But, without question, any design deficiency certainly reduces the prospects of attaining the fullest measure of producibility.

Selecting material with strength that is inadequate for the intended application, specifying the drilling of blind holes for a subsequent tapping operation when holes could have been drilled through, or choosing a material whose location in the galvanic series would preclude its use are but a few of the examples of errors that may be attributed to oversight or ignorance.

The majority of errors, however, includes simpler offenses, such as inconsistent double dimensioning or specification of a particular material that is incompatible with a specified process. Such errors invariably confuse the production department, waste man-hours and material, and cause distressing delays, and often a cumulative effect is created. Hold-ups of critical components— which occur while isolating and correcting these errors—can also cause delays in the delivery of a complete system, increases in cost, and degradation of producibility. The ten producibility problems previously referred to are presented together with their solutions.

4-5.1 HEAT-TREAT WARPAGE

4-5.1.1 Cause and Effect

The design specifies a 0.25-mm (0.010 -in.) tolerance on the curvature of a thin section of aluminum that had to be formed and heat-treated to a tempered condition. Heat treating caused severe warpage on the thin section, which caused rejection of the section.

4-5.1.2 Solution

Form the aluminum curved section, heat-treat by normal procedures up to, but not including, age-hardening. Form the section and then allow to age harden at room temperature.

4-5.2 SQUARE CORNERS ON MACHINED INTERIOR CONTOURS

4-5.2.1 Cause and Effect

The design requires a box-like cavity in a cast metal block to have internal square corners. However, this results in a high reject rate caused by cracking, which results from the stresses at the squared corners.

4-5.2.2 Solution

Subsequent review of the design intent revealed this feature was not necessary. The correct radius, which matched a standard milling cutter, was used, and the problem was resolved. If the square corners are in fact required, other processes such as EDM should be considered.

4-5.3 FLAT BOTTOM BLIND HOLES

4-5.3.1 Cause and Effect

The design required a metal container to have four flat bottom tapped holes. This caused slow production due to the time required to clear chips during threading and the need for final drilling to be accomplished with a flat bottom end mill.

4-5.3.2 Solution

Flat bottoms in holes are not generally necessary; consequently, the design can be changed to permit a standard drill taper hole bottom, and the problem is eliminated. If flat bottoms are mandatory, EDM should be considered.

4-5.4 SQUARE CORNERS ON DRAWN SHEET EXTERIOR

4-5.4.1 Cause and Effect

The exterior corners of a deep drawn sheet metal container had to be square (maximum permissible radius was 0.13 mm (0.005 in.). Standard deep drawing practices would not produce corners with a radius sharper than 0.76 mm (0.030 in.). Tooling changes only caused the corner to fracture, which caused rejection.

4-5.4.2 Solution

A special set of tooling was developed to draw the container and force (almost extrude) excess metal into the 0.76-mm (0.030 -in.) radius corners. A secondary coining operation had to be developed to forge the corners into a 0.13-mm (0.005 -in.) radius. Alternately the potential of reducing the design requirements should be considered to solve this problem.

4-5.5 DRILLED HOLE TOLERANCING

4-5.5.1 Cause and Effect

The design specified a 6.747-mm (17/64-in.) drilled hole with a tolerance of +0.25 mm (0.010 in.) and –0.05 mm (0.002 in.). The producer, to comply with the special tolerance specification, set up a special reaming operation to assure conmpliance, but this special requirement added extra cost and time.

4-5.5.2 Solution

Neither the designer nor the producer recognized that this was not a special tolerance. The standard 6.747-mm (17/64-in.) drill produces a drilled hole that has a tolerance of +0.16256 mm and –0.0254 mm (0.0064 in. anti 0.001 in.). When this was recognized, the special tolerance note was removed. Subsequent manufacturers used only a standard drill and no secondary operations; the item functioned perfectly.

4-5.6 FAILURE TO USE AVAILABLE MATERIAL

4-5.6.1 Cause and Effect

The design specified 0.51-mm (0.020-in.) thick aluminum be formed into a shallow, container and then gold color anodized; however, the cost for special racks and fixtures to hold the part during anodizing and the time for anodizing were prohibitive.

4-5.6.2 Solution

Subsequent investigation revealed the availability of 0.51-mm (0.020-in.) thick aluminum that was gold color anodized. The design was changed, and the parts were produced without the secondary anodizing operation.

4-5.7 UNREALISTIC TOLERANCES

4-5.7.1 Cause and Effect

A steel member had a long series of holes and slots in the edge, and the location of each was individually tolerance. The cumulative dimensions and tolerances created a conflict with the overall dimension, which resulted in numerous change orders and many scrapped parts.

4-5.7.2 Solution

Properly dimensioned and tolerance locations from a single common baseline solved the problem.

4-5.8 UNREALISTIC INSPECTION REQUIREMENTS

4-5.8.1 Cause and Effect

The design specifies a helium leak test of an aluminum tube that has end caps made from discs cut from an aluminum rod. The grain structure of the end caps running lengthwise through the cap permits leakage of helium and causes a 100% reject rate.

4-5.8.2 Solution

Since the design specified the raw material for the end caps as bar stock, it implied the process of cutting discs off a rod. The design should have specified sheet stock, which would have implied stamping the disc. In this form the material grain structure would run across the surface of the disc and, therefore, permit helium containment. The correction was made, and the tests were passed.

4-5.9 PRODUCT WEIGHT

4-5.9.1 Cause and Effect

A design specified that a large quantity of heavy 136.1 kg (300 lb) metal weldments be machined. The budget for accomplishing the job was overrun 100% due to the necessity of having two workmen to load and unload the heavy part.

4-5.9.2 Solution

The designer should always keep in mind the actual true size and weight of the parts he is designing because it is easy to be misled by scaled drawings. The job could have been run with two machines and two operators—each helping the other load and unload. This would have reduced greatly the overrun if it had been anticipated.

4-5.10 SURFACE STRESSES IN CASTINGS

4-5.10.1 Cause and Effect

The design specified long, thin castings as internal structural members of a container skin. To assure good contact for joining, a surface finish of 1.60 µm (63 µin.) was specified on the mating surface. After casting and heat-treating, milling operations were started to achieve the surface finish. Cutting the surface of a heat-treated casting releases surface stresses that have built up in the parts. This causes massive warpage and very high rejection rates.

4-5.10.2 Solution

Reexamine the 1.60µm (63 µin.) requirement. In this case it was not necessary and was eliminated along with the problem. Had it been necessary to hold the 1.60 µm (63 µin,), the designer could have changed the material and permitted machining of the entire part from a bar stock. An alternative would be to use a thin foil of softer compatible material between the "as cast" surface and the skin prior to joining.

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CHAPTER 5

PRODUCIBILITY CONSIDERATIONS FOR PLASTIC COMPONENTS

This chapter is structured to provide the design engineer with guidance on producibility that may be used in the design of plastic components. The discussion of materials considers the basic selection process, available material forms for processing, and cost considerations. Also included are a description of the major manufacturing processes and summaries of the characteristics of each. Joining and finishing operations are discussed along with test and evaluation methods. Relatively new advances in plastics technology are indicated, and the chapter concludes with examples of typical problems in producibility.

5-1 INTRODUCTION

The plastics to be considered in this chapter include both filled and unfilled thermoplastic (TP) and thermosetting (TS) resins. The strengths and elastic moduli of these materials vary over a broad range and are relatively low compared to the reinforced plastics and composites of Chapter 6. From a fabrication standpoint they can be molded, extruded, cast, and thermoformed by using conventional processes and equipment.

Thermoplastic resins soften and melt when heated and harden when cooled; this heating and cooling sequence can be repeated indefinitely. Thermosetting resins contain catalysts or curing agents. Heating initiates irreversible chemical reactions, which convert these resins to a permanently hardened or cured state.

Thermoplastics and thermoses display different processing characteristics and finished properties. The thermoplastics are more versatile in regard to processing and more processes are applicable to them, whereas thermoses are more rigid as a rule but are capable of withstanding higher service temperatures. Despite these differences, both types are competitive in many applications and have shown excellent producibility.

Fillers are added to resins to improve mechanical, chemical, or electrical properties, to reduce resin brittleness, or as extenders to lower material costs. Specific fillers are used for each purpose, and all thermoset resins, with the exception of a few casting compounds, contain fillers. Thermoplastics may or may not be modified. In some instances, plasticizers are added to thermoplastics to form more flexible materials or to lower melting temperatures for easier processing. The type and amount of filler or plasticizer are additional factors to be considered in determining the producibility of a material.

Approximately 22 generic resins are commercially available, most of which have several variations. The number of compounds formed by combining resins with fillers is therefore large and diverse, and numerous advantages are to be realized by use of these compounds, Important physical features include

1. Low density and high strength-to-weight ratio (STWR)
2. Resistance to shock loading
3. Resistance to atmospheric corrosion and chemical attack
4. Electrical insulation properties
5. Thermal insulation.

Perhaps the most significant advantage of plastics compared to metals is their formability. Existing processes permit the fabrication of a variety of complex shapes. For example, ribs, bosses, threads, throughholes, and inserts can be readily incorporated into a design. Consolidation of components into single-piece constructions is a frequent possibility. Such designs improve producibility by either eliminating or facilitating subsequent assembly operations.

Not all plastic designs are successful, and failures are often attributed to the material. In actuality, however, they are more likely due to misapplication of a material, inadequate evaluation of properties, or defects in the processing. A thorough analysis of material capabilities before final selection and a close coordination of the component design with the designated fabrication process are essential in preventing failures and in attaining satisfactory performance.

5-2 MAJOR MATERIAL CONSIDERATIONS

The extensive use of plastics in commercial and military applications is based on a number of factors. Some parts are simple structures with minor load-bearing requirements for which the choice of a plastic may depend on a low material cost and/or the ease of fabrication. For other parts the performance might depend on strength, rigidity, impact resistance, chemical resistance, or other properties. Many designs entail a combination of properties; therefore, trade-offs involving properties, fabrication processes, and cost are frequently required. As a result, the screening process and the selection of optimum materials are complicated procedures, and the peculiarities of the behavior of plastic materials must be considered. Emphasis is placed on such characteristics as strength and stiffness, creep, impact resistance, and chemical resistance. Availability and cost are additional material considerations; processing characteristics are discussed in par. 5-3.

5-2.1 STRENGTH AND STIFFNESS

All plastics are viscoelastic, i.e., their behavior under stress is intermediate to an elastic solid and a viscous fluid. Stress-strain relations and all mechanical properties are dependent upon temperature, the rate at which stress is applied, and the time under stress. Typical stress-strain curves for plastics are illustrated in Fig. 5-1. The Type 1 curve of Fig. 5-1 represents a brittle material approximating an elastic response to load, the Type 2 materials yield more abruptly, and Type 3 indicates the gradual yielding of a more viscous or ductile material. Material constants, such as ultimate strength and strain, yield strength and strain, the initial modulus, and the secant modulus, are shown on the curves.

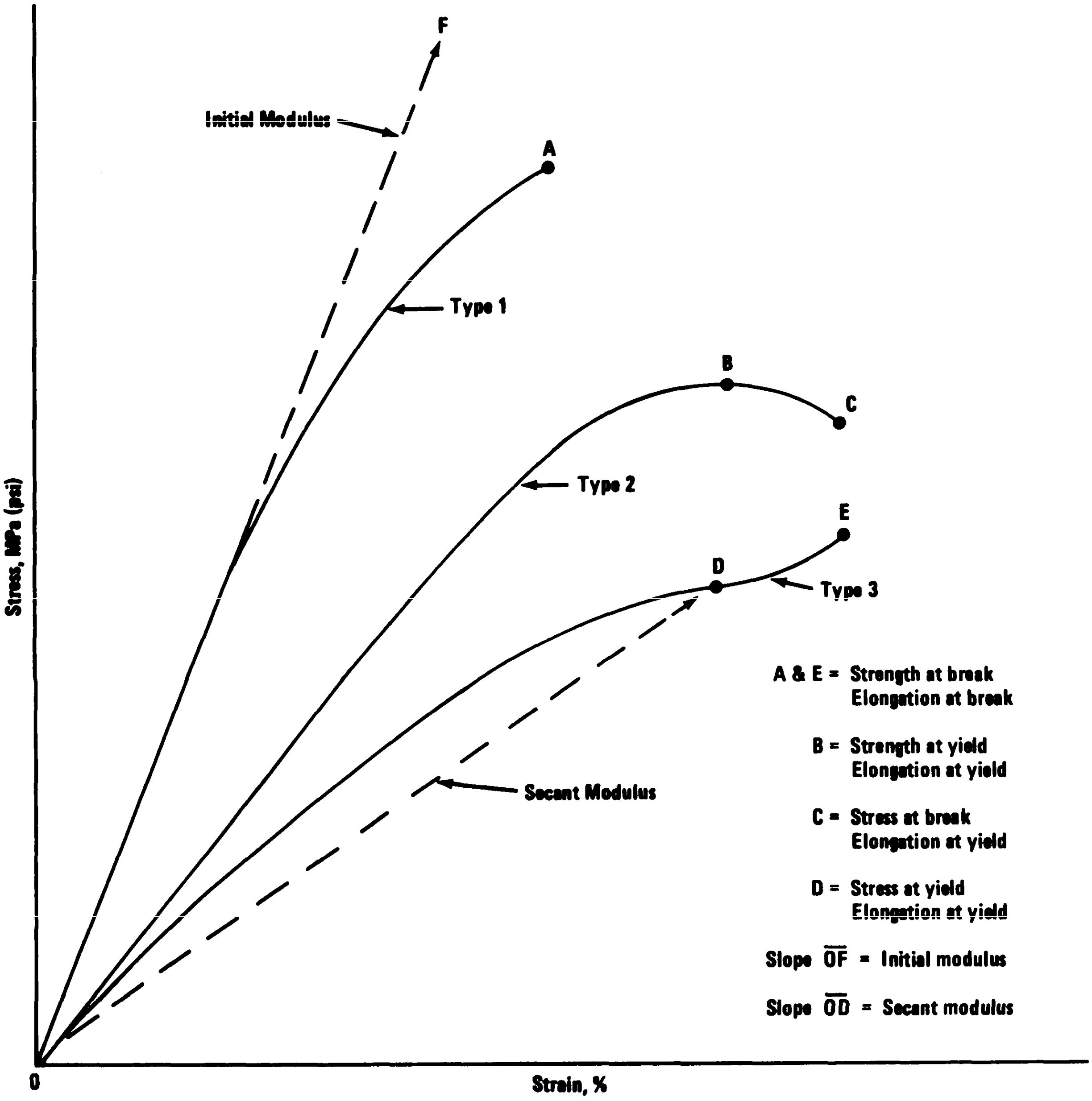

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Figure 5-1. Types of Plastic Stress-Strain Curves (Ref. 1)

The influence of temperature and strain rate on the shape of the curve is depicted schematically in Fig. 5-2. The stress-strain curves shown in Fig. 5-2 are for the same plastic material at various temperatures and strain rates. The curves from left to right indicate an increased test temperature at a constant strain rate; conversely, they also indicate decreased strain rates at a constant temperature. The trends noted are a decrease in linearity, a lower ultimate strength, and a greater ultimate strain as the temperature is increased or the strain rate decreased. These trends occur in tension, compression, flexure and shear. The material constants derived from the curves, however, have different values for each type of applied stress.

At ambient temperatures, the linear portion of the stress-strain curve is of short duration for many plastics. In some cases, it may not exist at all. As temperatures are increased above ambient, the deviation from linearity increases for all plastics. At low temperatures, on the other hand, practically all plastics exhibit brittle behavior. In essence, this means that all plastics vary from brittle to ductile behavior over a range of temperatures. Behavior also varies with material type and filler content. Thermoset resins and highly filled thermoplastics tend to follow the more brittle Type 1 pattern of Fig. 5-1. Similarly, as the rate at which stress is applied (strain-rate) is increased, plastics behave in a more brittle manner (Ref. 2).

5-2.2 CREEP BEHAVIOR

All plastics under a constant stress are subject to creep. Upon initial loading, the plastic deforms rapidly until reaching a strain level consistent with its stress-strain relationship. It then continues to deform at a slower rate for an indefinite period. At high enough stresses, the material will eventually rupture. Depending on the applied stress, the time frame for failure may be in hours or years. Creep can also be defined as a decrease in stress with time as the material is held at a constant strain.

Creep curves for an idealized ductile and nonductile plastic each at several stress levels are illustrated in Fig. 5-3. The creep rupture envelope shown in Fig. 5-3 marks the failure stresses to be anticipated at different time intervals. Temperature has a significant effect on creep behavior, i.e., increased temperatures result in greater strains for a specified stress at a specified time and shorter times to rupture.

Raw creep data (strain versus time at constant stress) are usually modified to yield more convenient design information. For example, a creep modulus of elasticity (also known as apparent modulus or viscoelastic modu-

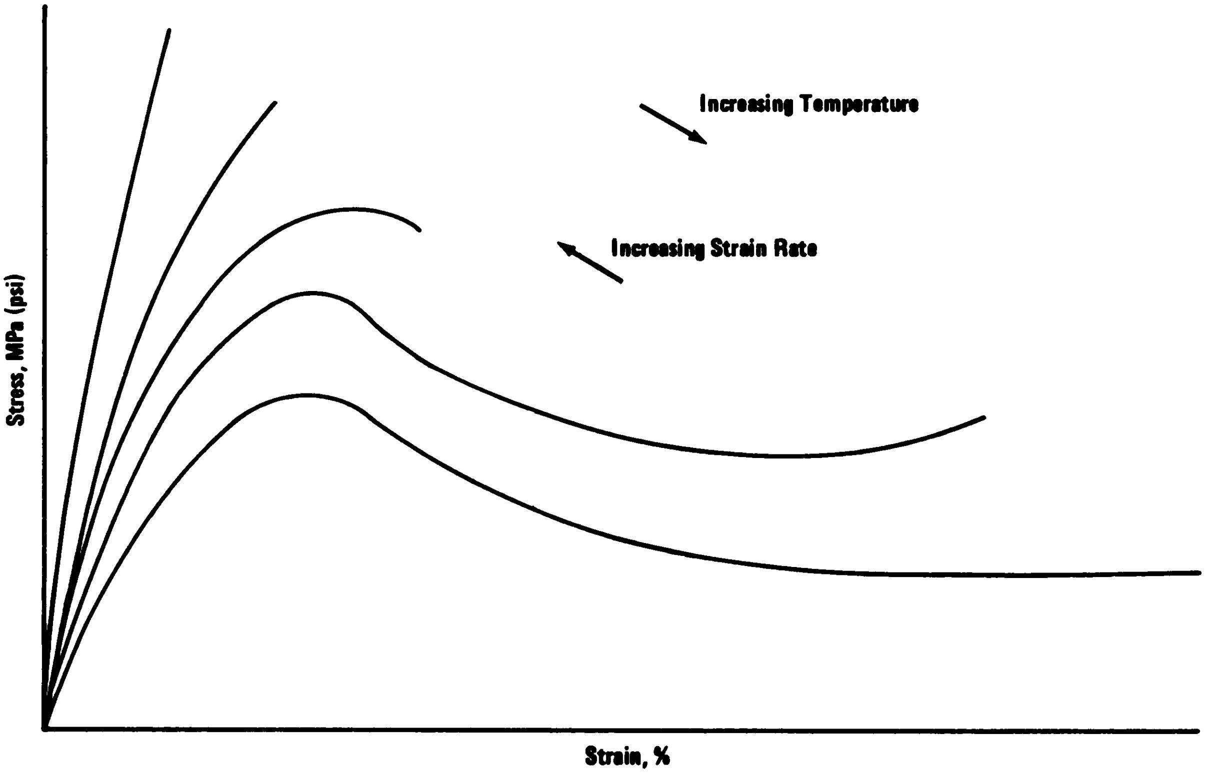

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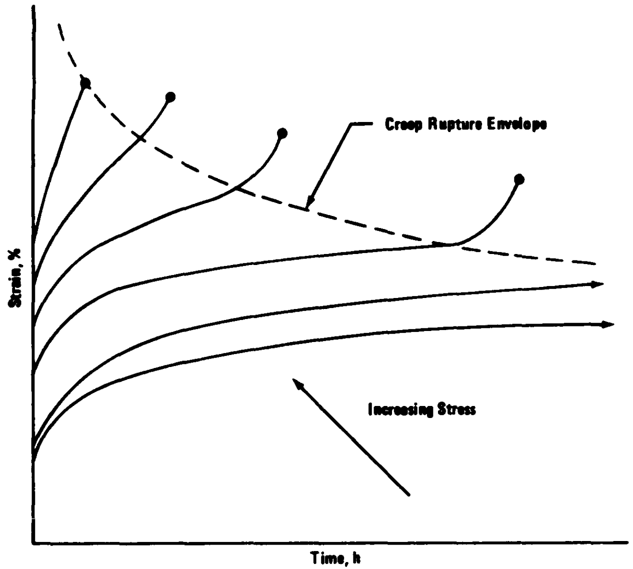
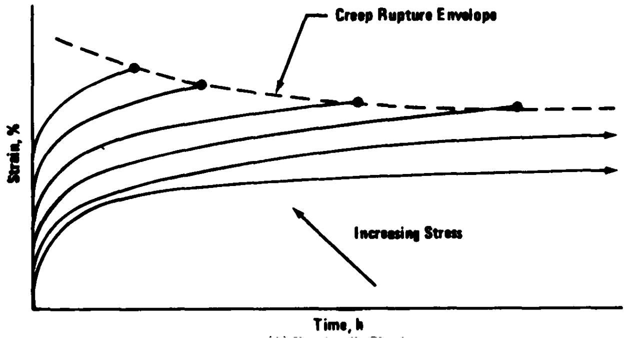
Figure 5-2. Effect of Temperature and Strain Rate on Stress-Strain Curve (Ref. 2)



(A) Ductile Plastic



(B) Nonductile Plastic

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Figure 5-3. Creep Behavior for Ductile and Nonductile Plastics (Ref. 2)

lus) is plotted against time under load. The creep modulus is frequently used in place of the more conventional modulus, which is obtained without reference to the effect of time. A second example is a plot of applied stress against time to rupture. Extrapolations of this function permit estimates to be made as to the expected life of a component at various stress levels. Such estimates are shown in Fig. 5-4 for a hypothetical plastic. A third example is the isochronous stress-strain curve, a plot of stress-strain at a given time under either sustained stress or strain (Ref. 3).

5-2.3 SELECTION OF MATERIAL CONSTANTS

A major problem in screening materials is the determination of strength and modulus values to use in conventional design equations. The limitations of data derived from stress-strain tests must always be considered in selecting constants. In some instances, stress-strain data may be adequate, but at other times creep tests yield more realistic values. As a general rule, stress-strain data are appropriate for simple momentary loading conditions, for material comparisons, and for determining ductile or brittle behavior. It is rarely correct to use ultimate strengths and the related strains as failure criteria. Yield stress or strain is better suited for these purposes, but they may have limitations also. For example, elongation at yield ranges from 3 to 20% for most plastics, and such high strains may not be tolerable in many applications. In these cases, arbitrary strains and the corresponding stresses are selected as maximum allowable values.

When the rigidity of materials is being considered, the use of a modulus based on initial linearity often leads to an overestimation of the actual stiffness. A secant modulus may be a better choice, particularly with ductile materials.

Elastic limits, taken from stress-strain curves, are not satisfactory criteria for either strength or rigidity. The elastic limit varies with temperature and time under load so that elastic recovery is best determined from creep tests. Typical creep and stress relaxation for a thermoplastic are shown in Fig. 5-5. As seen in the figure, considerable strain can remain after unloading. These residual strains vary from material to material and may be detrimental in some designs.

The selection of material constants to be used for design and screening purposes presumes the availability of critical stress-strain and creep data. Unfortunately, such is not always the case, and the designer must rely upon material suppliers to furnish information. Other excellent sources are the annual conference proceedings of the Society of Plastics Engineers and the proceedings of the Reinforced Plastics/Composites Institute of the Society of the Plastics Industry. Refs. 2, 3, 4, and *5* contain related data and provide detailed treatments of creep and viscoelasticity.

5-2.4 IMPACT RESISTANCE

Impact resistance—the ability to absorb shock—is an important consideration in material selection. Characterization of this property is difficult at best, and existing tests do not correlate well with actual performance. The design and analysis of components to resist impact are complicated processes and are considered beyond the state of the art in most cases (Ref. 3).

Stress-strain curves and unnotched impact tests provide the most reliable information. The area under a stress-strain curve represents the maximum amount of energy that a material can absorb. Ductile materials which yield gradually have a greater area under the curve and a greater capacity for absorbing energy. The sensitivity of stress-strain tests to temperature and test speed as previously noted detracts from the significance of this method.

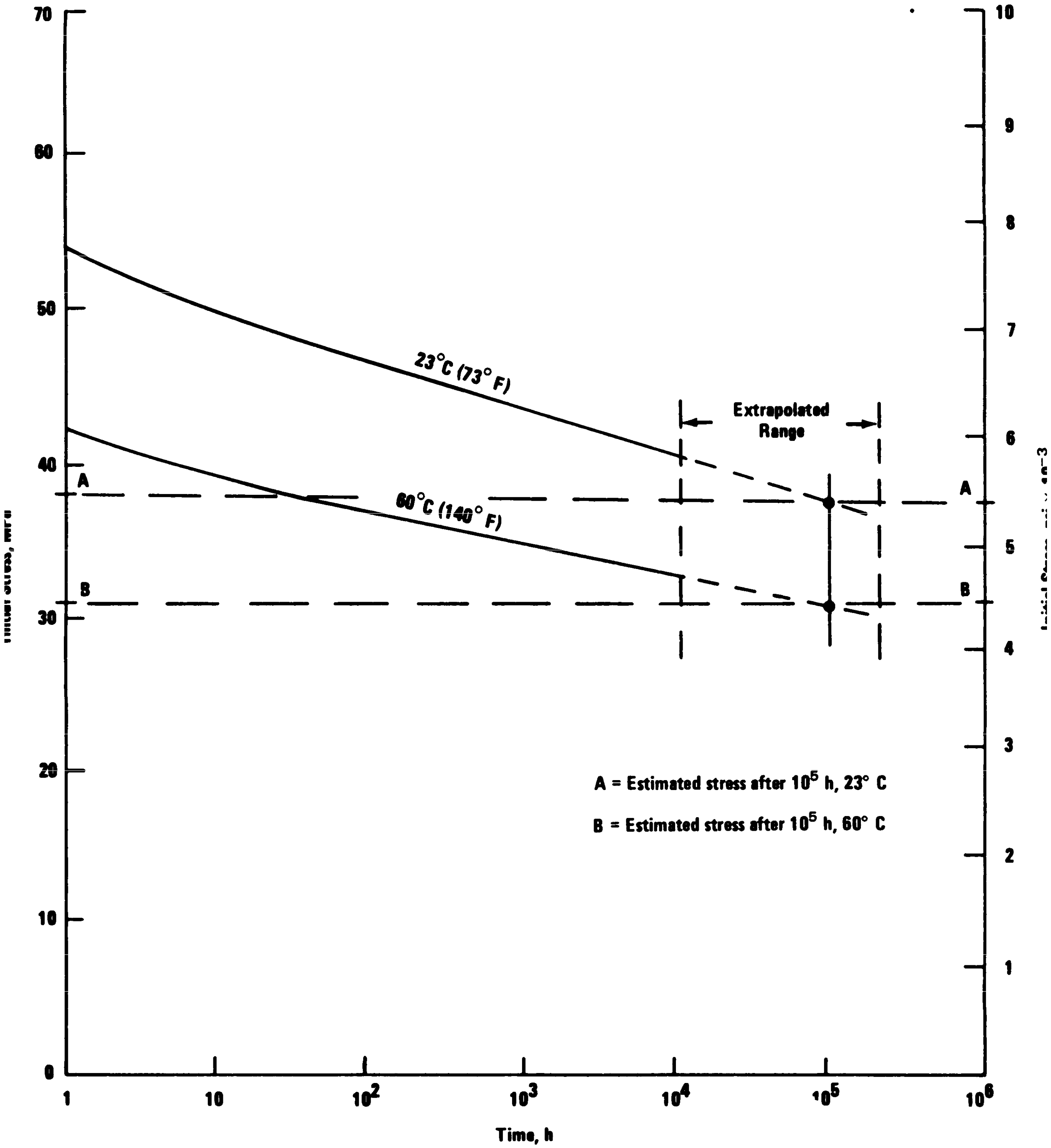

Figure 5-4. Extrapolation of Time to Rupture vs Applied Stress

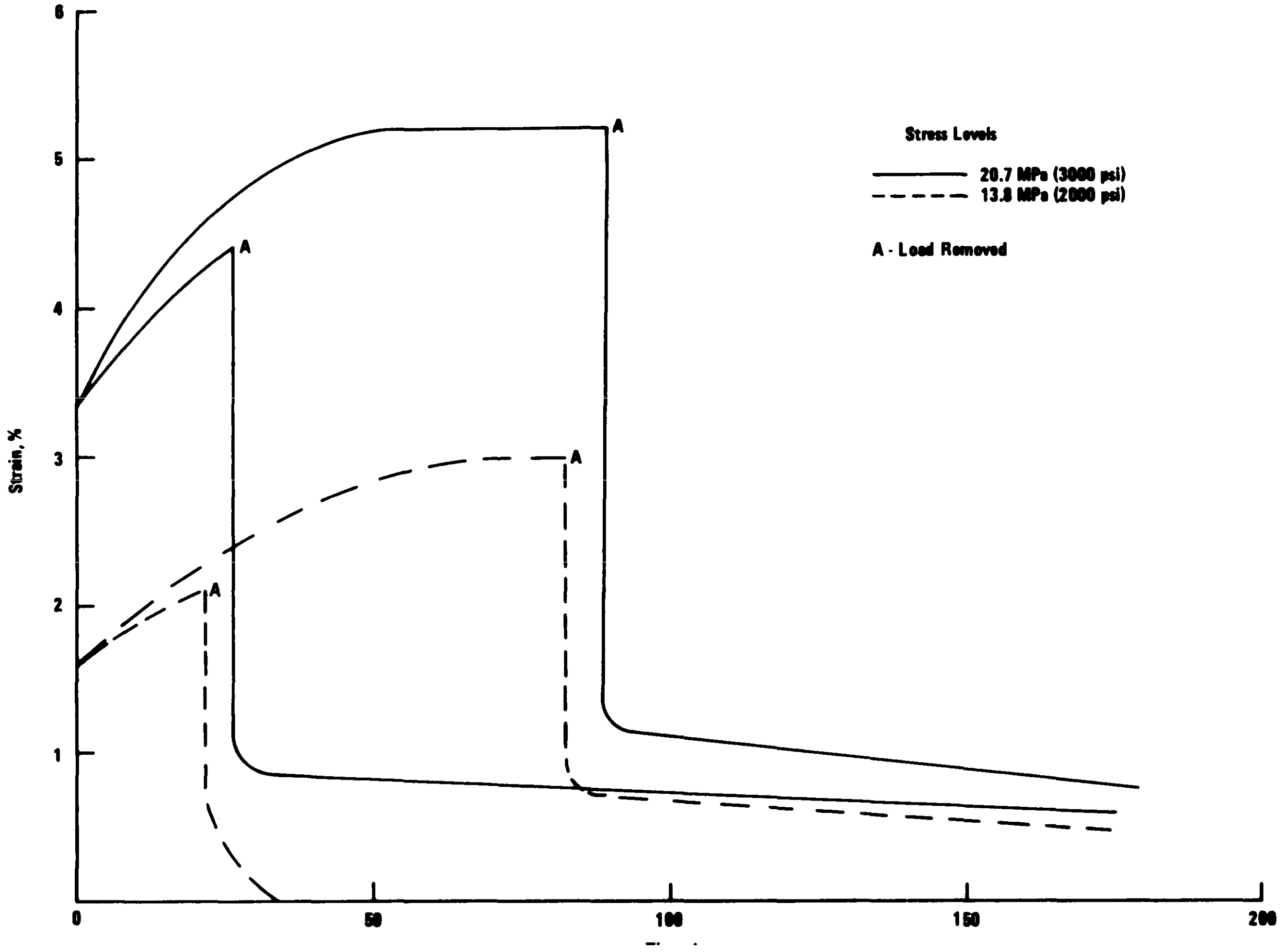

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Figure 5-5. Effect of Stress and Time Under Load on Stress Relation (Ref. 2)

Plastics, like most other materials, are notch sensitive. Conventional impact tests, employing notched specimens, tend to underestimate impact resistance. Unnotched specimens appear to approximate actual behavior more closely. However, such data are scarce. The impact resistances of several thermoplastics tested in an unnotched condition are listed in Table 5-1. The conclusion is reached from available published data that impact resistance cannot be predicted reliably by any single test. Improvised prototype tests under simulated service conditions are required to verify material performance in critical applications. Examples of such tests are falling ball impact, dart impact, tensile impacts at high loading rates, and drop tests.

The practical meaning of the basic engineering properties of plastics implied in stress-strain relations, creep behavior, and impact resistance is summarized in Table 5-2 along with criteria for evaluating these properties.

5-2.5 CHEMICAL RESISTANCE

The resistance of plastics to various chemicals is extremely variable, and no two resin types behave exactly alike. Even within one generic group, resins may react differently. Therefore, it is not a safe practice to assume the resistance of a plastic by analogy with a similar resin or by its reaction to a similar chemical. Test data for the specific plastic and chemical are required. Chemical resistance tests measure changes in weight, dimensions, and appearance at ambient and elevated temperatures and at times the loss of strength after chemical exposure.

Results of exposure tests and recommended maximum service temperatures for plastics subjected to various chemicals are usually furnished by material suppliers. Additional information on chemical resistance may be found in Refs. 2, 5, and 6. The compatibility of plastics with explosives is summarized in Ref. 7.

TABLE 5-1. UNNOTCHED IMPACT VALUES FOR SELECTED THERMOPLASTICS (Ref. 5)

Material	Impact Strength	
	J/m	ft-lb/in.
Polysulfone	3203	60
Polycarbonate	3203	60
Polyethersulfone	2135	40
Acetal homopolymer	1281	24
Nylon 6, 30% glass	1068	20
Acetal copolymer	1068	20
Nylon 6/6, 30% glass	907	17
Polycarbonate, glass	907	17
Polysulfone, glass	747	14
Nylon 6/6, carbon fiber	641	12
Polyethersulfone, glass	641	12
Polypropylene, glass	534	10
Polyester, glass	534	10
Nylon 6/6, mineral	427	8
Nylon 6, mineral	427	8
Acetal copolymer, glass	427	8
Polysulfone, mineral	374	7
Polysulfone, carbon fiber	320	6
Polyimide	320	6
Polyester, carbon fiber	214	4
Polyphenylene sulfide	160	3

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TABLE 5-2. PRACTICAL MEANINGS AND CRITERIA FOR ENGINEERING PROPERTIES OF PLASTICS

Property	Practical Meaning	Criteria
Strength	Ability to carry dead load	1. Yield strength for intermittent loading 2. Strength at specific strain level for materials with large elongations 3. For sustained loads. creep rupture
Stiffness	Ability to carry stress without excessive dimensional change	1. Initial modulus of elasticity for more brittle materials 2. Secant modulus for more ductile materials 3. Creep modulus for sustained loads
Elasticity	Ability to carry stress without permanent set	1. Yield point with more brittle materials 2. Stress relaxation for more ductile materials
Resilience	Ability to absorb energy without permanent set	1. Area under stress-strain curve up to yield point 2. Area under stress-strain curve up to elastic limit, as determined by stress relaxation
Toughness	Ability to absorb energy and undergo large permanent set without rupture	1. Total area under stress-strain curve 2. Unnotched impact strength 3. Prototype testing 4. Tensile impact tests

5-2.6 COMPARATIVE PROPERTIES

The mechanical properties of various plastic molding materials are summarized in Table 5-3. More complete data compilations are found in Refs. 2 and 8.

The type of data presented in Table 5-3 is useful for comparing materials and for preliminary design calculations. It is also possible to select materials for further screening or to eliminate others on the basis of the property values shown in Table 5-3. There are, however, limitations to data in this form that preclude their use for final design purposes and final material selection. Only average values are presented, statistical evaluations are ignored, and time, temperature, and loading rate effects are not considered. Finally, results obtained by specimen testing may differ markedly from the results obtained under actual production conditions.

5-2.7 COMMERCIAL AVAILABILITY

Plastics are produced as powders or pellets for molding, extruding, or casting and in fabricated forms, such as film, sheet, pipe, rod, extruded profiles, and foam, for further processing into components. All common TP, except polytetrafluoroethylene (PTFE), are available as molding and extrusion compounds, and all TS as molding compounds. PTFE is available as sheet or rod stock. The more prevalent materials supplied in fabricated form are listed in Table 5-4. Materials other than those listed in Table 5-4 are not stock items but can be procured as custom fabrications. A listing of commercial films and foams together with their physical properties is tabulated in Ref. 2.

5-2.8 COST CONSIDERATIONS

Raw material cost and manufacturing cost are the major factors determining the overall cost of a component. The price of plastics varies over a wide range and may be as low as $0.84/kg ($0.38/lb) or as high as $18.15/kg ($8.25/lb). Therefore, the total material cost must be carefully considered, and the use of a more expensive material must be justified by improved and necessary performance characteristics. Because manufacturing costs depend on numerous factors as well as on the design of a specific component, suggestions are offered to aid the designer in reaching a rough estimate of the fabrication costs and in comparing the costs of various processes.

5-2.8.1 Raw Material Costs

The list prices, based on unit weight and on unit volume, of a representative group of plastics are shown in Table 5.5. Since the specific gravities of plastics range from 0,90 to 2.00, the cost per unit volume is of greatest significance in comparing materials.

Resin prices have shown marked increases since 1974 and are subject to frequent change. The prices listed are intended to serve as a guide only. Relative material prices, also included in the table, tend to remain fairly constant, so they are most useful for comparative purposes.

5-2.8.2 Manufacturing Costs

Manufacturing costs are influenced by the number of parts being produced, the material being processed, tooling costs, the specific process, cycle times, the amount of scrap generated, and any finishing operations. In general, much of the information necessary for estimating costs is not available from published sources, and the designer must depend on custom fabricators and/or material suppliers to furnish the data.

A rough estimate of manufacturing costs can be made by multiplying the total material cost by a factor related to the process. Examples of such factors are given in Table 5-6. Generally, when the material costs are low, as with phenolics, polystyrene, polyethylene, and polypropylene, the factor range will be greater. Low factors apply to large volume production without finishing operations; the larger factors are applicable to low volume runs, low equipment productivity, and some finishing. When material prices are higher, the factor range is narrower. However, the probable average range can be used in most cases (Ref. 9).

Scrap losses are usually low with thermoplastic injection molding, blow molding, and extrusion and are estimated to be less than 10% in the majority of cases. Scrap generation in thermoforming thermoplastic sheet or in molding thermoset resins is greater and may be as high as 30%.

5-3 MANUFACTURING PROCESSES AND CONSIDERATIONS

The manufacturing processes, listed in Table 5-7, are classified as forming, machining, joining, and finishing operations. The forming processes, in which plastics are converted to finished components, are of primary concern in determining producibility. Machining, joining, and finishing are of secondary importance.

Injection molding, which is applicable to thermoplastic and thermosetting materials, is the most universal and versatile of the forming processes although compression and transfer molding are the traditional methods for fabricating thermoses. These three molding processes are capable of producing the most complicated component configurations and of holding part dimensions to the closest tolerances. All three can be used in high production or limited quantity modes. Thermoforming is a relatively cheap and fast method for producing simple shapes from thermoplastic sheet stock. Blow molding and rotational molding are limited to hollow shapes. Casting is useful for parts with thick sections, but it ‘is limited to a few material types and

TABLE 5-3. MECHANICAL PROPERTIES OF SELECTED PLASTICS (Refs. 2 and 8)

Material	Tensile Properties					Flexural Strength		Compressive Strength		Specific Gravity	Maximum Continuous Service Temperature	
	Yield Strength		Modulus of Elasticity		Elongation at Yield							
Thermoplastics	MPa	(psi × 10³)	GPa	(psi × 10⁵)	%	MPa	(psi × 10³)	MPa	(psi × 10³)		°C	(°F)
Acrylonitrile-butadiene-styrene (ABS)												
unfilled	35-55	(5-8)	1.7-2.6	(2.5-3.8)	2.5-3.5	59-100	(8.5-14.5)	——	——	1.04-1.06	——	——
20% glass	83-90	(12-13)	5.5-6.2	(8-9)	1.5-2.0	117-138	(17-20)	97	(14)	1.23	70-80	(155-180)
Acetal												
unfilled	61-69	(8.8-10)	2.8-3.1	(4.1-4.5)	3-45	90-97	(13-14)	34-90	(5-13)	1.41	——	——
20% glass	62-83	(9-12)	6.2-6.9	(9-10)	2-7	69-103	(10-15)	34-124	(5-18)	1.55	90-110	(195-230)
Acrylic												
unfilled	50-76	(7.3-11)	2.1-3.1	(3-4.5)	3.6-3.0	79-110	(11.5-16)	72-124	(10.5-18)	1.15-1.19	60-80	(140-180)
cast sheet	69-72	(10-10.5)	3.1	(4.5)	4.9-5.0	103-110	(15-16)	117-124	(17-18)	1.19	80-90	(180-200)
Nylon 6/6												
unfilled	55-83	(8.0-12)	2.1-4.1	(3.0-5.9)	30-70	83-124	(12-18)	76-138	(11-20)	1.13-1.16	65-120	(150-250)
30% glass	179	(26)	8.3	(12)	3-4	262	(38)	165	(24)	1.37	105-120	(225-250)
Nylon 6												
unfilled	59-38	(8.5-12)	1.7-3.1	(2.5-4.5)	25-110	83-117	(12-17)	55-100	(8-16)	1.12-1.14	80-105	(180-225)
30% glass	165	(24)	6.9	(10)	2.0	193	(28)	165	(24)	1.40	95-100	(200-215)
Polycarbonate												
unfilled	59-66	(8.5-9.5)	2.1-2.4	(3.0-3.5)	6-9	76-93	(11-13.5)	69-86	(10-12.5)	1.18-1.21	105-120	(220-250)
20% glass	110	(16)	6.9	(10)	4-6	172	(25)	138	(20)	1.34	115-125	(240-260)
Polyester												
unfilled	55	(8)	2.3-2.6	(3.3-3.7)	50-300	83-90	(12-13)	59-62	(8.5-9)	1.31-1.38	——	——
20% filled	121	(17.5)	7.2	(10.5)	4-5	165	(24)	117	(17)	1.43	140	(280)
Polyethylene												
Low-density, unfilled	8-16	(1.2-2.3)	0.1-0.3	(0.14-0.38)	90-600	——	——	——	——	0.91-0.93	55-90	(130-195)
High-density, unfilled	21-28	(3-4)	0.4-1.2	(0.6-1.8)	20-130	——	——	19-25	(2.7-3.6)	0.94-0.97	55-90	(130-195)
Polypropylene												
unfilled	31-37	(4.5-5.4)	1.2-1.6	(1.7-2.3)	6-20	41-55	(6-8)	38-55	(5.5-8)	0.90-0.91	95	(200)
40% glass	72	(10.5)	6.9	(10)	4-5	152	(22)	68	(9.8)	1.22	80-120	(180-250)

(cont'd on next page)

TABLE 5-3. (cont'd)

Material	Tensile Properties					Flexural Strength		Compressive Strength		Specific Gravity	Maximum Continuous Service Temperature	
	Yield Strength		Modulus of Elasticity		Elongation at Yield							
Thermoplastics	MPa	(psi × 10^3)	GPa	(psi × 10^5)	%	MPa	(psi × 10^3)	MPa	(psi × 10^3)		°C	(°F)
Polystyrene												
unfilled	37-54	(5.3-7.9)	2-4-3.4	(3.5-5)	1-2	55-97	(8-14)	79-110	(11.5-16)	1.04-1.05	65	(150)
20% glass	76	(11)	7.6	(11)	1-2	107	(15.5)	103	(15)	1.20	65	(150)
Polysulfone												
unfilled	70	(10.2)	2.6	(3.8)	50-100	106	(15.4)	96	(13.9)	1.24	—	—
20% glass	121	(17.5)	7.6	(11)	20	162	(23.5)	145	(21)	1.38	150	(300)
Polyvinyl chloride (PVC)												
unfilled	41-52	(6-7.5)	2.4-4.1	(3.5-6)	40-80	69-110	(10-16)	55-90	(8-13)	1.31-1.45	70	(130-160)
15% glass	90	(13)	6.6	(9.5)	2-3	117-138	(17-20)	—	—	1.52	—	—
Thermosets												
Alkyd												
mineral-filled	41	(6)	13.1	(19)	0.5-1	62	(9)	172	(25)	1.98		
Diallyl phthalate (DAP)												
glass-filled	55-69	(8-10)	9.7-15.2	(14-22)	2-4	76-207	(11-30)	172-241	(25-35)	1.5-1.9		
mineral-filled	34-60	(5-8.7)	8.3-15.2	(12-22)	2-4	59-76	(8.5-11)	138-221	(20-32)	1.6-1.9		
Epoxy												
glass-filled	34-138	(5-20)	20.7	(30)	4	55-207	(8-30)	124-276	(18-40)	1.86-1.92	95-200	(200-400)
mineral-filled	28-69	(4-10)	3.4-13.8	(5-20)	2-3	41-124	(6-18)	124-207	(18-30)	1.6-2.1	95-200	(200-400)
Melamine												
cellulose-filled	34-90	(5-13)	7.6-9.7	(11-14)	0.6-1.0	62-110	(9-16)	228-310	(33-45)	1.47-1.52		
glass-filled	34-72	(5-10.5)	11.0-16.5	(16-24)	0.6	97-159	(14-23)	138-241	(20-35)	1.5-2.0		
Phenolic												
wood-flour-filled	34-62	(5-9)	5.5-11.7	(8-17)	0.4-0.8	48-97	(7-14)	172-214	(25-31)	1.35-1.46		
glass-filled	48-124	(7-18)	13.1-22.8	(19-33)	0.2	103-414	(15-60)	179-483	(26-70)	1.7-2.0		
Polyester												
Sheet molding compound	55-172	(8-25)	9.7-17.2	(14-25)	3	69-248	(10-36)	103-207	(15-30)	1.65-2.6		

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TABLE 5-4. AVAILABLE MATERIAL FORMS

Films (TP): Thickness Range, 0.013 mm (0.0005 in.) to 0.25 mm (0.010 in.)
Polyethylene, Polypropylene, Acetal, Acrylic, Cellulosic, Nylon, Polycarbonate, Polystyrene, Polyvinyl Chloride, Polyester

Sheets (TP): Extruded or Calendered, Thickness Range 0.25 mm (0.010 in.) to approximately 20 mm (3/4 in.)
ABS, Acetal, Acrylic, Cellulosic, Nylon, Polycarbonate, Polyester, Polyethylene, Polypropylene, Polystyrene, Polysulfone, Polyvinyl Chloride, Styrene-Acrylonitrile (SAN)

Standard Pipe (TP):
Polyvinyl Chloride, ABS, Polyethylene, Polybutylene

Blanks and Slabs (TP):
Acrylic, Nylon, Polycarbonate, Polypropylene, Polystyrene

Casting Materials and Cast Rods, Tubes, Profiles (TP and TS):
Acrylic, Nylon, Polystyrene, Polyurethane, Polyester, Epoxy, Phenolic

Precast Foams (TP and TS):
Polyurethane, Polystyrene, Epoxy, Phenolic, Polyvinyl Chloride, Polyethylene

TABLE 5-5. BULK LIST PRICE OF PLASTIC Materials (Ref. 8)

Material	$/kg	$/lb	$/litre	¢/in^3	Comparative Price[b]
Fluorocarbon (FEP)[c]	18.15	8.25	38.93	63.8	*42.53*
Fluorocarbon (PTFE)[d]	11.00	5.00	23.62	38.7	*25.80*
Silicone	9.17	4.17	17.09	28.0	*18.67*
Nylon 6/12	5.13	2.33	5.49	9.0	*6.00*
33% glass	4.99	2.27	9.95	16.3	*10.87*
Nylon 6/6	3.17	1.44	3.60	5.9	*3.93*
30% glass	3.30	1.50	4.52	7.4	*4.93*
Polysulfone	7.85	3.57	9.70	15.9	10.60
Epoxy (liquid)	2.35	1.07	NA[e]	NA[e]	—
Polyurethane (TP)	3.39	1.54	4.03	6.6	4.40
Diallyl phthalate	4.18	1.90	7.69	12.6	8.40
Polycarbonate	3.17	1.44	3.84	6.3	4.20
30% glass	4.44	2.02	6.35	10.4	6.93
Cellulose acetate	2.35	1.07	2.99	4.9	3.27
Acetal	2.60	1.18	3.66	6.0	4.00
20% glass	3.15	1.43	5.00	8.2	5.47
Acrylic	1.61	0.73	1.89	3.1	2.07
Melamine	1.61	0.73	2.38	3.9	2.60
Alkyd	1.28	0.58	2.56	4.2	2.80
Polyester (liquid TS)	1.23	0.56	NA[e]	NA[e]	—
Polyester (TP)	2.55	1.16	3.36	5.5	3.67
ABS[f]	1.67	0.76	1.77	2.9	1.93
10% glass	2.09	0.95	2.32	3.8	2.53
Polyvinyl chloride	0.84	0.38	NA[e]	NA[e]	—
Polypropylene	0.97	0.44	0.92	1.5	1.00
30% glass	1.63	0.74	1.83	3.0	2.00
Phenolic	1.19	0.54	1.65	2.7	1.80
Urea	1.17	0.53	1.77	2.9	1.93
Polystyrene	1.01	0.46	1.04	1.7	1.13
Polyethylene					
Low-density	1.01	*0.46*	*0.92*	1.5	1.00
High-density	0.99	0.45	0.92	1.5	1.00

[a] Prices as of July 1980
[b] Based on Polyethylene = 1.0
[c] FEP—fluorinated ethylene propylene
[d] PTFE—polytetrafluoroethylene
[e] NA_Not Applicable
[f] acrylonitrile-butadiene-styrene

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TABLE 5-6. MATERIAL COST FACTORS (Ref. 9)

Process	Material Cost Factors	
	Overall Range	Probable Average Range
Compression molding	2-10	3-5
Injection molding	1.5-5	2-3
Blow molding	1.5-5	2-3
Extrusion	2-5	3-4
Thermoforming	2-10	3-5

Material Cost x Factor = Manufacturing Cost

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TABLE 5-7. MANUFACTURING PROCESSES FOR PLASTICS

Forming	Machining	Joining	Finishing
Injection molding	Drilling	Adhesive bonding	Electroplating
Extrusion	Milling	Mechanical fastening	Vacuum metallizing
Compression molding	Turning	Heat sealing	Painting
Transfer molding	Tapping	Ultrasonic bonding	
Thermoforming	Punching	Ultrasonic staking	
Blow molding	Grinding	Spin welding	
Rotational molding		Vibration welding	
Mechanical forming		Hot gas welding	
Casting		Electromagnetic bonding	

low quantity runs. Mechanical forming techniques are adaptations of metalworking processes and are geared to high production rates. Extrusion is applicable to the production of continuous lengths of piping, rods, sheets, and profiles. The general features of these methods are summarized in Table .5-8. The uses of selected groups of thermoplastics by process grade are summarized in Table 5-9. To give a more complete view, total plastic production figures are listed in Table 5-10.

The selection of a process for component fabrication is governed by the configuration of the part and to a lesser extent by the material, the size of the production run, and the cost of processing. The essential features of the part are its size. wall thickness, depth of draw, the dimensional accuracy required, and the inclusion of ribs, bosses, holes, inserts, etc. Material considerations are the type, i.e., thermoplastic or thermosetting, flow characteristics, and the availability of material grades for specific processes. The cost of matched metal dies for injection, compression, or transfer molding may be prohibitive in low quantity runs. Regardless of the selection, it should be realized that each process imposes restrictions on the design. These restrictions, or design rules, must be observed in component design if good producibility is to be achieved.

5-3.1 INJECTION MOLDING

Injection moldinq, originally developed to process thermoplastics, has been modified to handle thermosetting compounds as well. It is estimated that from 25 to 30% of all thermoplastics are injection molded. Corresponding figures for thermoses are not available, but an increased number of materials are now being injection molded. From the standpoint of equipment in use, nearly 45% of all plastic processing units are injection molding machines.

5-3.1.1 Injection Molding Thermoplastics

The basic injection molding process is relatively simple. A molding compound is metered into the feed port of the injection machine, conveyed through zoned heating sections to be melted, and forced into a closed single or multiple cavity mold. The material is cooled to solidification, the mold is opened, and the part or parts are

TABLE 5-8. CHARACTERISTICS OF FORMING PROCESSES

Method	Material Type	Practical Size Limitations	Wall Thickness mm	Wall Thickness (in.)	Minimum Practical Quantity[b]	Tool Cost	Product Cost	Reusable Scrap	Availability of Facilities
Injection molding	TP, TS	23 kg (50 lb)	See Table 5-13		100-10,000	High	Low	Yes (TP) No (TS)	Good
Compression molding	TS	23 kg (50 lb)	See Table 5-13		100-10,000	Med to high	Low	No	Good
Transfer molding	TS	0.6 m × 0.6 m (24 in. × 24 in.)	See Table 5-13		100-10,000	High	Low to med[a]	No	Good
Thermoforming	TP	1.2 m × 1.0 m (48 in. × 42 in.)	0.25-3.2	(0.010-0.125)	10-1000	Low	Low to med[a]	No	Good
Blow molding	TP	200-230 litres (7-8 ft^3)	0.25-5	(0.010-0.200)	1000	Low	Low to med[a]	Yes	Fair
Rotational molding	TP	230 kg (500 lb)	0.64-25	(0.025-1.0)	100-1000	Low	Low to med[a]	No	Poor
Mechanical forming	TP	0.25 mm to 305 mm (0.010 to 12.0 in.) thick billets	—		50-1000	Low	Low to med[a]	No	Fair to poor
Casting	TP, TS	0.5 m (18 in.) dia. rod 0.6 m (24 in.) dia. tube 230 kg (500 lb)	5-20	(0.18-0.75)	1-100	Low	Med	No	Poor
Extrusion	TP	0.6 m (24 in.) dia. tube 2.4 m (8 ft) sheet	0.30-5 0.25-20	(0.012-0.20) (0.010-0.75)	300 m (1000 ft)	Low to med	Low to med	Yes	Good

TP — Thermoplastic TS — Thermoset

[a] Varies with quantity

[b] Rough estimate, varies with mold cost

TABLE 5-9. USE OF SELECTED THERMOPLASTICS BY PROCESS GRADE (Ref. 10)

Material	Percent Use			
	Injection	Extrusion	Blow Molding	Other
LDPE[a]	11.0	77.2	1.0	10.8
HDPE[b]	23.2	18.8	41.5	16.5
Polypropylene	42.2	45.8	1.7	10.3
ABS[c]	50.6	38.8	—	10.6
Polystyrene	52.4	30.5	—	17.1
Nylon	65.6	31.9	—	2.5
PVC[d]	6.2	54.5	1.8	37.5

[a] Low density polyethylene
[b] High density polyethylene
[c] Acrylonitrile-butadiene-styrene
[d] Polyvinyl chloride
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TABLE 5-10. US PRODUCTION OF PLASTICS BY MATERIAL (Ref. 10)

Material	Production 1980		
	10^3 tonne	10^6 pounds	Percent
Epoxy	143	315	0.84
Phenolic	680	1499	4.01
Polyester	430	947	2.54
Urea	528	1165	3.12
Melamine	76	167	0.45
Total Selected Thermoses	1857	4093	10.96
ABS[a]	417	920	2.46
SAN[b]	50	111	0.30
HDPE[c]	1998	4405	11.80
LDPE[d]	3307	7291	19,52
Nylon	124	274	0.73
Polypropylene	1655	3648	9.77
Polystyrene	1597	3521	9.43
PVC[e]	2481	5470	14.65
Total Selected Thermoplastics	11630	25640	68.66
Total Selected Plastics	13487	29733	79.62
Other Plastics	3455	7614	20.38
Grand Total	16940	37347	100.00

[a] Acrylonitrile-butadiene-styrene
[b] Styrene-acrylonitrile
[c] High density polyethylene
[d] Low density polyethylene
[e] Polyvinyl chloride
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ejected. The mold closes, and the cycle is repeated. A schematic representation of the process is shown in Fig. 5-6.

The controls permit automatic and semiautomatic operation of the machine. The molded parts require little if any finishing. Processing costs per piece are low for large volume runs, and the machines are capable of high production rates.

There are several types of injection machines, of which the reciprocating screw version is by far the most common. It combines a rotational screw motion with plunger injection, transfers heat more efficiently, allows closer control of melt temperatures, and requires lower injection pressure than the older plunger-type machines.

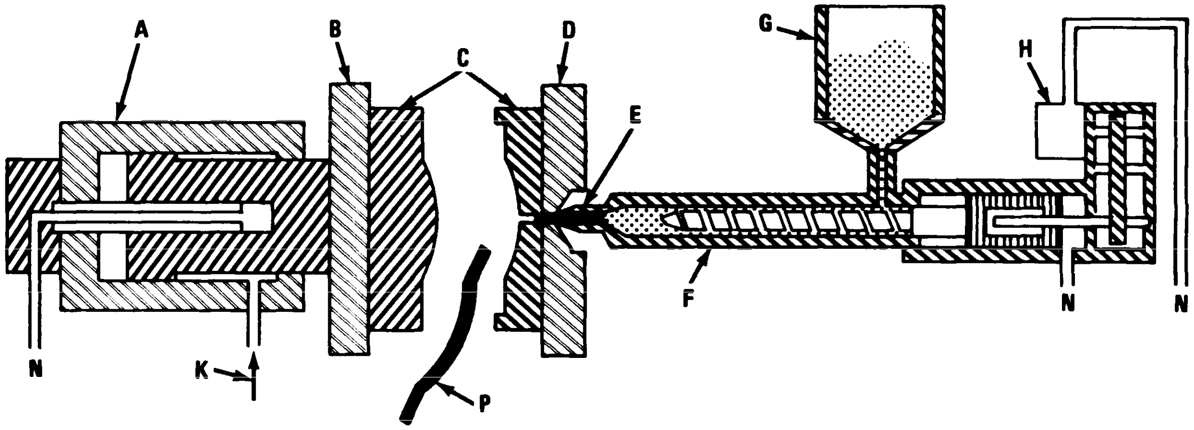
Machine capacities are rated by the weight of the injection shot and range from 0.03 kg (1 oz) or less to 23 kg (800 oz). Shot weights are based on polystyrene with a 1,04 specific gravity. Actual shot weights for other materials are calculated as the ratio of their specific gravity to that of polystyrene times the rated machine capacity. The recommended machine capacity for a specific part should exceed the total weight of the part, runners, and sprues by at least 10%, but not more than 80%. An excess capacity allows the melted plastic to be packed into the mold; too great an overcapacity y is inefficient and detrimental to control of the melt temperature.

The platen dimensions of a machine and the maximum mold size are included in machine specifications. The maximum depth of the mold depends on the daylight opening. To determine the maximum part depth for a machine, allowance must be made for part removal.

Injection pressures for most machines usually do not exceed 138 MPa (20,000 psi). This pressure is sufficient to mold the majority of plastics. However, materials such as ABS, acrylic, polyvinyl chloride, and some of the newer resins with higher melting points may be somewhat more difficult to process and may require greater injection pressures. High shear screws are designed to handle these materials. These screws lower the melt viscosity of the resin and permit injection at lower pressures. Table 5-11 lists the molding pressures and temperatures for a selected group of filled and unfilled resins.

Clamping pressure is an important consideration. The clamping mechanism locks the mold in a closed position and resists the injection pressure. Total clamping pressure is calculated as the injection pressure times the projected mold surface area. For example, a mold with a projected area of 0.064 m^2 (100 $in.^2$) and an injection pressure of 69 MPa (10,000 psi) at the mold cavity would require a theoretical clamping pressure of 454 tonne (500 tons). In actuality, pressure drops occur in the injection cylinder so that the effective pressure in the mold cavity might be from 25 to 50% of the original force. The approximate clamping force requirements are related to the shot size in Table 5-12.

Suggested sources for further information on injection molding are Refs. 2, 11, and 12.



A. Hydraulic Clamp Cylinder
B. Movable Platen
C. Mold
D. Fixed Platen

E. Injection Nozzle
F. Heating Cylinder and
Reciprocating Screw
G. Hopper
H. Screw Drive

P. Part Ejected
Oil Pressure:
K. Clamp Opening
N. No Pressure

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Figure 5-6. Schematic of Injection Molding-Part Ejection (Ref. 11)

TABLE 5-11. MOLDING PRESSURES AND TEMPERATURES FOR SELECTED THERMOPLASTICS (Ref. 2)

Materials	Molding Pressure		Molding Temperature	
	M Pa	(psi x 10^3)	‘ c	‘F
ABS				
Medium impact	55-172	(8-25)	205-275	(400-525)
20% glass	103-207	(15-30)	175-260	(350-500)
Acrylic				
Heat resistant	69-207	(10-30)	205-260	(400-500)
Nylon				
Type 6, unfilled	7-138	(1-20)	225-260	(440-500)
Type 6, 30% glass	21-69	(3-l0)	250-290	(480-550)
Type 6/6, unfilled	7-69	(l-l0)	270-325	(520-620)
Type 6/6, 33% glass	34-138	(5-20)	265-295	(510-560)
Polycarbonate				
High viscosity	69-138	(10-20)	295	(560)
30% glass	69-207	(10-30)	295-345	(560-650)
Polyethylene				
Low density	34-69	(5-l0)	150-230	(300-450)
High density	34-138	(5-20)	150-260	(300-500)
Polystyrene				
High impact	34-103	(5-15)	225-260	(435-500)
30% glass	69-172	(10-25)	230-260	(450-500)
Polyvinyl chloride				
Rigid	69-276	(10-40)	150-210	(300-415)
15’% glass	55-172	(8-25)	160-195	(320-385)
Polysulfone				
Unfilled	103-138	(15-20)	345-400	(650-750)
30% glass	103-138	(15-20)	345-400	(650-750)

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TABLE 5-12. APPROXIMATE CLAMP FORCE FOR VARIOUS INJECTION SHOTS (Ref. 11)

Shot Size		Clamp Force	
kg	oz	tonne	ton
up to 0.06	up to 2	9-23	10-25
0.03-0.11	1-4	23-45	25-50
0.06-0.28	2-10	45-91	50-100
0.09-0.43	3-15	91-136	100-150
0.11-0.71	4-25	136-181	150-200
0.17-0.85	6-30	181-227	200-250
0.23-1.13	8-40	227-272	250-300
0.28-1.42	10-50	272-317	300-350
0.57-1.70	20-60	317-363	350-400
0.85-2.27	30-80	408-454	450-500
1.13-2.83	40-100	454-544	500-600
1.42-3.40	50-120	544-635	600-700
1.70-3.97	60-140	635-726	700-800
1.98-5.10	70-180	726-816	800-900
2.27-5.67	80-200	816-907	900-1000

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5-3.1.2 Injection Molding Thermoses

The reciprocating screw injection machine, which has a reciprocating as well as a rotating action, has made possible the molding of a variety of thermoset compounds in an efficient manner. The major thermoset resins, namely, phenolic, urea, melamine, alkyd, polyester, epoxy, diallyl phthalate, and silicone, can be injection molded. Variations in the design of the reciprocating screw are made to prevent premature curing of the resins. The length to diameter (L/D) ratio and the compression ratio* are lower than is normal with rotating injection screws for thermoplastics. These measures reduce frictional heat and the length of time the material is exposed to heat in the machine cylinder. Injection and clamping pressures are generally higher compared to thermoplastic molding conditions. Molds are maintained at temperatures of from 160° to 205°C (320 °-4000 F), the normal curing range for thermoset resins. Since the phenolic, urea, melamine, and silicone resins release gases during curing, molds for these materials must be properly vented. Poor venting results in burnt parts, voids, or porosity in the finished component.

5-3.2 EXTRUSION PROCESSES

The extrusion process is used to convert thermoplastic compounds into continuous lengths of pipes, tubing, profiles, rods, sheets, films, monofilament, and coated wires or cables. Extruders also serve a number of other specialized functions, such as coating of various substrates, providing parisons for blow molding, blending fillers and colors into resins, and manufacturing pelletized compounds for molding or extruding. Generally, the designer is concerned with the extrusion of nonstandard piping, tubing, and profile sections.

The process consists of feeding the granular resin or extrusion compounds into the hopper of the extruder. Single or twin screws convey the material through a series of zones in which the plastic is mixed, the particles are consolidated into a mass, and the mass is heated to a melting range and forced through a die, which forms the desired configuration. Following passage through the die, the hot material may be expanded by internal air pressure to form thin-walled tubing or blown film, Alternately, the extrudate may be drawn down by controlled speed of the takeoff equipment as rod, sheet stock, thick-walled tubing, or profile sections. The formed product is cooled by air or water prior to take-up as continuous rolls or coils, or it may be cut into lengths. See Fig. 5-7 for a schematic of an extruder.

Single-screw extruders are more common due to their adaptability to most processing functions and their simplicity, which leads to lower processing costs. Extruders are rated by the nominal outside diameter of the screw flight and by an *L/D* ratio, which is the flight diameter. Most *L/D* ratios range from 24/ 1 to 32/1. In some applications ratios up to 40/1 are found. The bulk of extrusion is done with machine sizes from 64 to 152 (2.5 to 6 in.). Larger units are employed in resin compounding, pelletizing, and wire coating.

Production rates depend on the end product being extruded and the material type as well as the size of the screw diameter. Rates up to 225 kg/h (500 lb/h) are common for pipe, tubing, and profiles. Rates in excess of 9070 kg/h (20,000 lb/h) are achieved in pelletizing or compounding.

The geometry of an extruder screw is complex and extremely variable. Screws are designed to accommodate specific materials and specific products. The designs include variations in flight helix angle, flight depth, width of the flight land, and root diameter. These features control the feed rate, mixing, compaction, and melt temperature.

Although twin screw extruders can be used with most plastics, they are confined to processing rigid polyvinyl chloride (PVC) pipe and thick profiles and to compounding heat sensitive materials.

Material shrinkage during cooling is not a serious problem except in extruding profiles. For these shrinkage control is a difficult and tricky operation. The amorphous resin types, which shrink the least, are the most frequently extruded profiles. These resins include rigid and plasticized PVC, general purpose and high impact polystyrene, acrylics, and cellulose acetate. The crystalline resins, of which the most important are polyethylene, polypropylene, nylon, and acetal, have greater shrinkages and, consequently, are extruded as profiles less frequently and in smaller cross sections. A vacuum is usually applied during cooling to aid in controlling the sectional dimensions of profile extrusions.

The thermoset materials are not easily adapted to extrusion processes, and extruded rods, tubes, and profiles are rare. Extruders, however, serve as auxiliary equipment for compression and transfer molding of thermosets. Here the extruder function is simply to preheat and densify the material before it enters the mold (Refs. 2 and 13).

5-3.3 COMPRESSION MOLDING

In compression molding, the material, either as a preform or as a powder, is placed into a heated mold cavity. Pressure is applied to close the mold and fill the cavity. The part is then held under pressure and allowed to cure before removal. The actual process is, however, more complex than indicated. Presses are constructed to permit fully automatic operation with single or multiple cavity molds, and the closing pressure cycle is regulated to control material flow in the mold and to

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*The compression ratio is obtained by dividing the volume of the screw channel at the feed end by the volume at the discharge end.

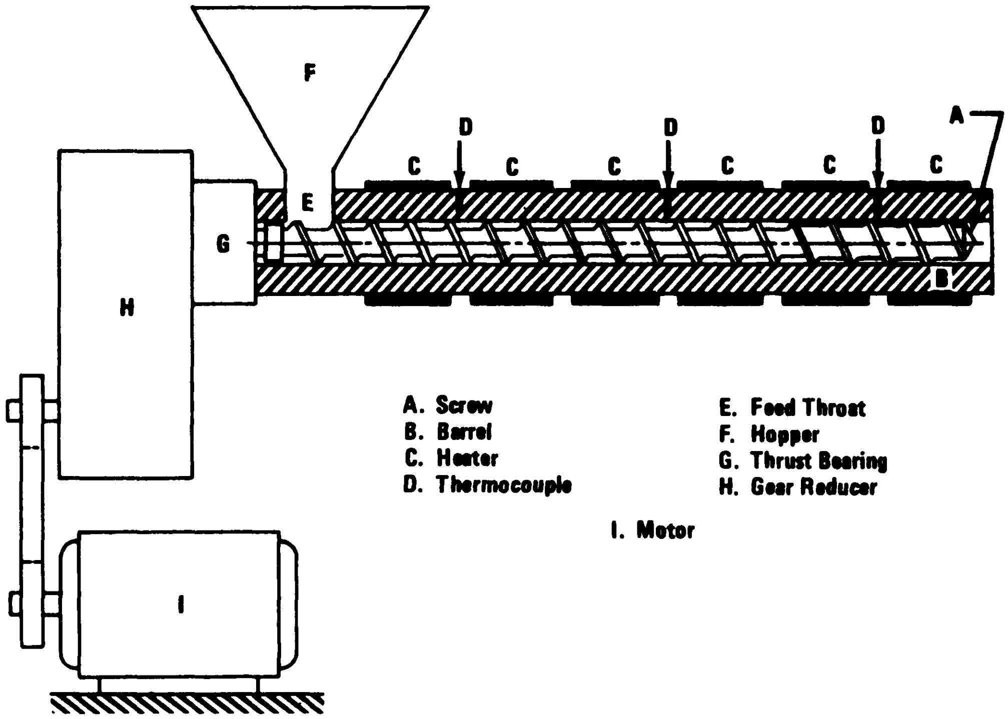

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Figure 5-7. Schematic of an Extruder (Ref. 13)

open the mold at fast speeds. A "breathing" cycle is included when necessary so that reaction gases can escape. With automatic operation, production rates are high and are comparable to injection molding.

The material is fed into the mold either as a cold powder or a preheated preform. Preheating reduces cure times, pressure requirements, and mold erosion. Radio frequency (RF) preheating units, ovens, or extruders are used to preheat materials. The extruder preheater has been particularly successful and has reduced cure times by as much as 75%.

Molding pressures vary with the material type and the configuration of the part. Generally, a part 25 mm (1 in.) deep and molded from a general purpose phenolic requires a pressure of 20.7 MPa (3000 psi). For example, a part having 0.064 m^2 (100 $in.^2$) of molding surface and being molded on a press with a 250-mm (l O-in.) diameter ram requires a pressure of 136 tonnes (150 tons) on the part of part depths up to 25 mm. The pressure on the ram will be 26 MPa (3820 psi). Each additional 25 mm of depth requires 4.8 MPa (700 psi) to fill the mold. The polyester-based bulk molding compounds (BMC) and sheet molding compounds (SMC) are molded at lower pressures ranging from 3.4 to 10.3 MPa (500 to 1500 psi). (See Ref. 14 for details of BMC and SMC.)

The range of mold temperatures is in the order of from 160°-205°C (320 °-4000 F). BMC and SMC are molded at temperatures ranging from 130°-175°C (265°-350°F). As a rough guide, the cure time for a phenolic part 3 mm (1/8 in.) thick and molded from cold powder is approximately 60 s.

Compression molds are of three types as shown in Fig. 5-8. Differences between the types are related to the clearance between the mold cavity and the force, the amount of flash (excess material) allowed to overflow from the mold, and the manner in which the force and the cavity come to a close. Flash molds, which are the cheapest, have the greatest clearances, permit more flash to escape from the mold, and give the poorest thickness control. Excess flash prevents the mold from closing completely, which results in overly thick parts. Flash molds, however, are adequate for prototype molding. Fully positive molds, the most expensive type, are used for extreme accuracy in part thickness because they are constructed with the tightest clearances between force and cavity and allow only minimal flash. Semipositive molds are intermediate to the flash and fully positive molds in regard to clearance and the amount of flash. They are the most common type and are used extensively with automatic molding presses and in molding BMC or SMC. Automatic loading chambers, used in conjunction with automatic presses, accurately control charge weights so that part thicknesses can be maintained with the semipositive molds.

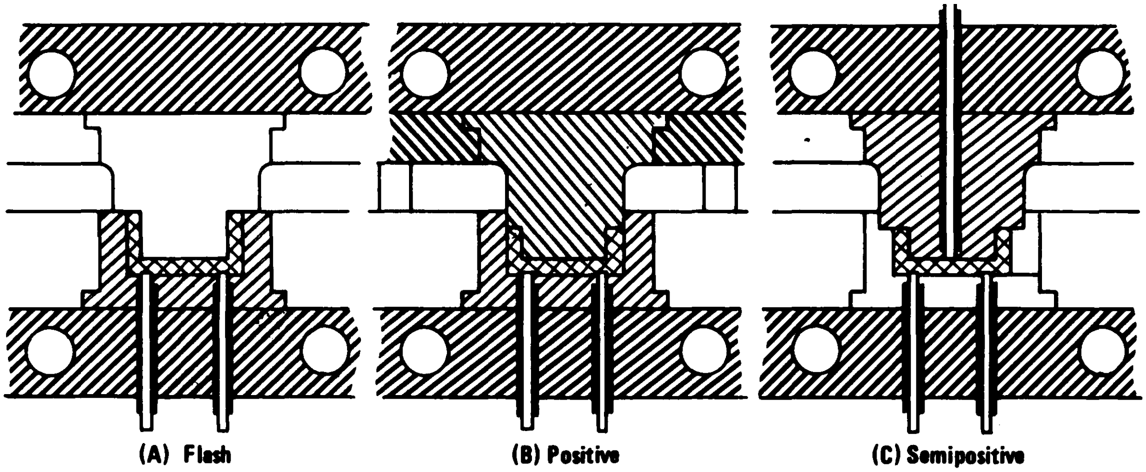

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Figure 5-8. Compression Mold Types (Ref. 15)

Although thermoplastics can be compression molded, the process is not conducive to high production rates. Heating and cooling must be performed in the mold cavity, unless a method can be devised to preheat and transfer material to a cold mold. Compression molding is satisfactory for molding thermoplastic prototypes or thick thermoplastic slabs that cannot be injection molded.

Information on hydraulically operated compression presses, their specifications, and general features are furnished in Refs. 8 and 14, and further details of the process are given in Ref. 16.

5-3.4 TRANSFER MOLDING

Transfer molding of thermosetting materials is roughly analogous to injection molding. The material is heated to plasticity in a transfer pot and then forced into a closed mold cavity or cavities through a system of sprues, runners, and gates. The part is held under heat and pressure until cured. Transfer molding has been automated for high-speed operation particularly suited to the production of small parts. Molding is usually conducted with preheating to reduce the cure time and required transfer pressure. Most hydraulic presses used for compression molding can be modified for transfer molding.

Compared to compression molding, transfer molding is advantageous when thin sections, delicate inserts, through-pins, and close tolerances are design requirements. The closed mold during the feed cycle prevents damage to inserts and pins, and cure times are slightly shorter because the material can be safely heated to higher temperatures without precure. Part size, however, is somewhat limited. Runners, sprues, and culls (the excess material in the transfer pot) are wasted material and add to the scrap total. Gates can create finishing costs unless designed for easy removal or located where they can be tolerated. Transfer molding fiberglass filled materials can result in some loss of strength, especially if the gates are restricted.

There is little difference between transfer or injection molding of thermoses. Finished properties, production rates, and mold costs are comparable. Selection of either process can be made on the basis of equipment availability.

5-3.5 THERMOFORMING

Thermoforming is a process for converting thermoplastic sheets into various shapes by the application of heat and pressure. Heating is by hot air or radiation; pressure is furnished by vacuum, air pressure, or mechanically by matched die molding. Commercial machines perform all process functions automatically at high production rates. Steps in the process include heating, forming, cooling, and trimming.

There are at least nine variations of the method (see Refs. *2* and 16), the simplest of which is straight vacuum forming as illustrated in Fig. 5-9. Drape forming is similar to vacuum forming except that the sheet is formed over a male mold. The depth of draw is limited in both cases, and variations in thickness occur over the surface of the part. The other process variations are designed to produce more uniform thicknesses, improve tolerances, and increase the output rates.

Normally, sheet thicknesses range from 0.38 to 3.18 mm (0.015-0.125 in.); occasionally, thicker sheets are thermoformed. Machine platen sizes are variable. The most popular sizes are approximately 0.6 X 0.6 m (24 X 24 in.), 0.9 X 0.9 m (36 X 36 in.) and 1.2 X 1.1 m (48 X 42 in.). Molds are frequently constructed of aluminum and are sometimes cored for part cooling. Wood, epoxy, and plaster molds are acceptable for low volume runs.

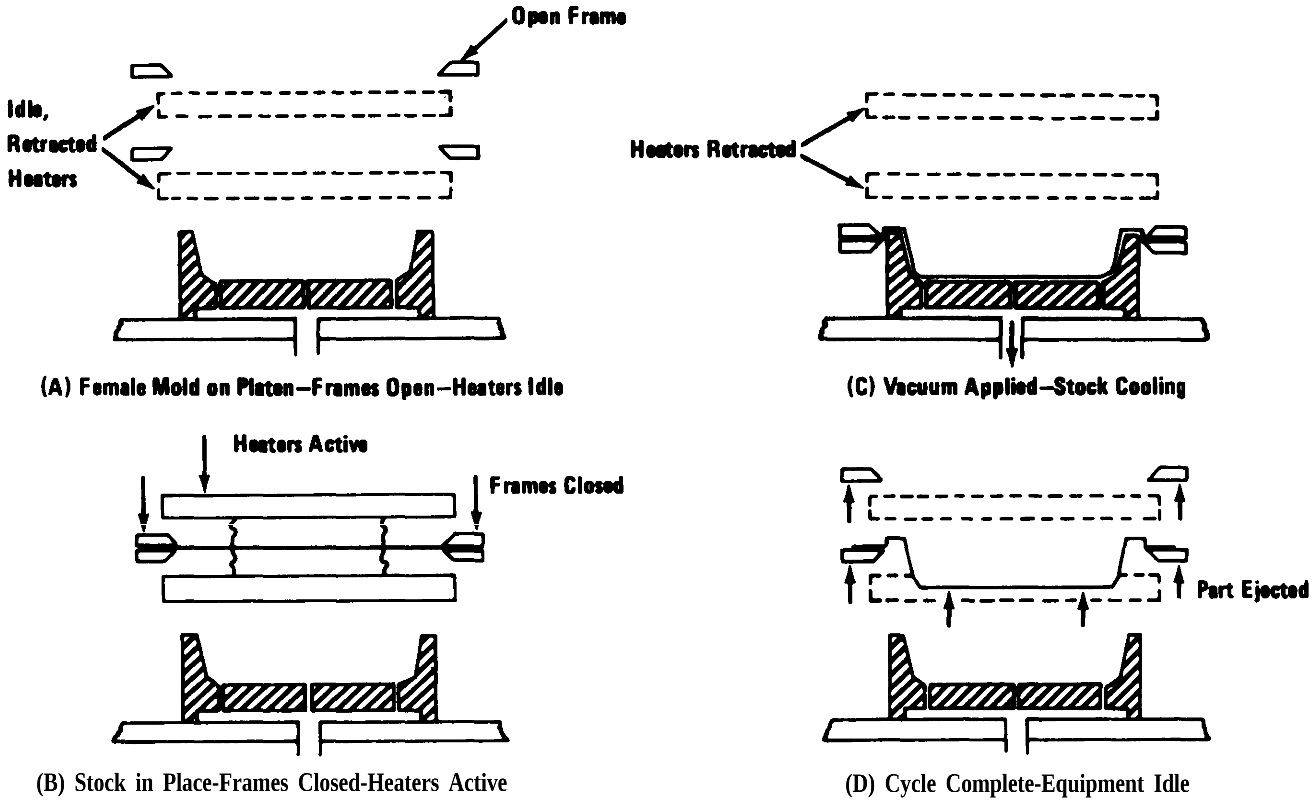

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Figure 5-9. Straight Vacuum Forming (Ref. 17)

Nearly all thermoplastic types have been thermoformed. The bulk of the processing has been with ABS, acrylic, impact polystyrene, polyester, polyvinyl chloride, and nylon sheet stock.

5-3.6 BLOW MOLDING

Blow molding is a process for the production of bottles, containers, drums, fuel tanks, and other hollow objects. The following steps comprise the process:

1. Form a parison, a tube of molten thermoplastic.
2. Position the parison in a mold, and seal the lower end.
3. Expand the parison by air pressure to fill the mold.
4. Cool the part in the mold.
5. Remove the part, and trim the flash.

The parisons are formed by conventional extruders (extrusion blow molding) and by injection machines (injection blow molding). Parisons can be programmed to control the weight and provide a uniform wall thickness of the part. In a modified version, called stretch blow molding, the parison is mechanically stretched during expansion. The resulting biaxially stretched material has increased strength, which permits thinner wall sections.

Extrusion blow molding has size capabilities for containers up to 208 1 (55 gal). Parts by injection blow molding have a capacity of a few millileters up to 1.4 1 (48 oz).

Air pressure rarely exceeds 1.03 MPa (150 psi); therefore, molds can be constructed from lower cost aluminum.

Although it is possible to blow mold many thermoplastics, the process has been limited to high and low density polyethylene, PVC, polypropylene, polycarbonate, and polyesters. These materials have been satisfactory as containers for a variety of products. Parts are also formed by coextrusion of two materials. One example is a container of polyethylene terephthalate (PET) with PVC. PET provides a barrier for carbon dioxide while the PVC prevents oxygen transmission.

5-3.7 ROTATIONAL MOLDING

Rotational molding is a process for the fabrication of hollow parts from thermoplastics and to a lesser extent thermosetting resins. Resin, either as a fine powder or a liquid dispersion, is placed in a heated mold and rotated about two perpendicular axes simultaneously. The resin melts and adheres to the mold surface in a homogeneous layer of uniform thickness. When resin flow ceases, the heating cycle is terminated, and the mold and the contents are cooled before part removal.

Generally, the process is limited to the fabrication of hollow parts that cannot be produced any other way. Equipment and tooling costs are low, and rotational molding is well adapted to low production runs of large pieces. It can be converted to higher production rates by increasing the number of molds. The amount of scrap produced is minimal, and molded parts are free from residual stresses.

Rotational molding has been restricted to a few materials. Polyvinyl chloride plastisols (a resin suspension in a liquid plasticizer) are used most frequently. Powdered polycarbonate, nylon, and acetal compounds have been developed specifically for this process. Cross-linked polyethylene, which behaves as a thermoset when heated, and polyurethane are the only thermoses that have been molded by this method (Refs. 2, 16, and 18).

5-3.8 MECHANICAL FORMING

Forming methods, such as stamping, forging, and blanking, have been adapted to the fabrication of parts from thermoplastic feedstock. Existing metalworking presses are used in these operations. Normally, processing requires material heating prior to forming. In melt flow forming, the plastic is heated to a temperature slightly above its melting point, but in solid phase forming, the temperature is kept at least 10°C (50°F) below the melting point. Glass-fiber-filled compositions are melt formed; unfilled materials are formed in the solid phase or in some instances are cold formed.

Sheet stock for forming is fabricated by conventional extrusion up to approximately 20 mm (0.75 in.) in thickness. Thicker forging blanks are obtained by slicing extruded rod or from compression molded slabs.

The more common thermoplastics for forming include polyethylene, polypropylene, ABS, PVC, and nylon 6. Materials that are difficult to process by other methods have been mechanically formed. One such example is ultrahigh molecular weight polyethylene.

Maximum part size, as with metals, is limited by press bed dimensions. Some of the larger parts formed to date are automotive engine oil pans, fender liners, and backings for bus seats (Refs. 2 and 19).

5-3.8.1 Blanking

Three die types are used in blanking:

1. Progressive dies—individual operations are performed consecutively as the material is fed through a series of dies in a common die set.
2. Compound dies—a complete set of operations is performed in a single die in one die set.
3. Steel rule dies—operations are performed in a low-cost sheet metal die.

The selection of a die depends on the material, configuration of the part, required accuracy, and quantity of the production run. Progressive dies are feasible in very high production runs but require accurate control of the press feed. Compound dies offer extreme accuracy, and they are suited to intermediate quantity production. Feed control is less critical, but fast ram action is needed for cleaner shear edges and ease of ejection. Steel rule dies are employed in smaller quantity runs for simple operations with thin sheet stock and for prototypes,

5-3.8.2 Stamping

The stamping of thermoplastics employs the rapid application of force upon the material, which is held in a matched steel die. The process includes both melt flow stamping and solid phase stamping. Part thicknesses normally do not exceed 6.4 mm (0.25 in.) (Ref. 19).

Melt flow stamping requires material temperatures approximately 25°C (77° F) above the melting point of the material. Pressures of from 3.4 to 13.8 MPa (500 to 2000 psi) are typical and are maintained for 10 to 30 s to permit cooling of the part before removal from the die. Total cycle time ranges from 20 to 45 s. Parts can be formed with ribs, bosses, and abrupt changes in thickness. Stamping compositions are usually reinforced with long glass fibers (50 mm (2 in.) or greater). This increased fiber length tends to improve impact strength, rigidity, and creep resistance over short-fiber reinforcements. The longer fibers are not oriented during flow, so the parts are essentially isotropic (uniform properties in all directions).

Solid phase forming produces a deformation rather than a flow of the plastic. As a result, orientation of the polymer chains occurs and increases strengths in the direction of orientation. Wall thicknesses remain uniform but cannot be changed abruptly. Pressures may be as high as 27.6 to 69 MPa (4000 to 10,000 psi), and die dimensions must be adjusted to account for elastic recovery after pressure release.

5-3.8.3 Forging

In the forging of thermoplastics, two opposing shaped punches mate in a common floating ring to form a closed die. The upper punch is raised, and a preheated billet is placed on the lower punch in the die ring. The upper punch is then closed, and pressure is applied to form the desired part shape. Forging is also conducted with the material in either a melt flow phase or a solid phase. Melt flow pressures are in the same range as melt flow stamping. Solid phase pressures, although in a 27.6- to 69-MPa (4000- to 10,000-psi) range, tend to be on the higher side compared to solid phase stamping. The greater thickness of forging billets mandates closer control of the heating stage and a uniform temperature. Variations of temperature within the billet can result in residual stresses and differential recovery, or spring-back.

5-3.9 CASTING

Casting is an economical method for low quantity runs and for fabricating models and prototypes. The process consists of pouring a resin monomer or a catalyzed liquid resin into a mold in which the resin is cured and hardened. The part is cooled in the mold before removal. Casting can be accomplished in open molds without pressure or in flexible molds for parts with undercuts. Low-pressure, closed molds are sometimes used to minimize high mold shrinkage. Trimming, drilling, and other finishing operations may be required. The process has not been adapted to automation, but production capabilities can be improved by adding automatic weighing, mixing, and dispensing equipment to the system.

5-3.9.1 Casting Acrylics

Acrylics are cast from liquid monomers or partially polymerized monomers in the form of viscous syrups. Heating initiates the polymerization, and the curing reactions are marked by large volume reductions and are extremely exothermic after approximately a 20% monomer conversion. Cooling is initiated at this point to dissipate the heat and to control the reaction. At about 85% of conversion, the reaction rate slows down, and posturing may be required to complete the reaction.

Acrylic sheets are fabricated by batch casting. A related process produces continuously cast sheets from a partially polymerized monomer. Batch sheets, in a full spectrum of colors, are cast in sizes up to 3.0 by 3.7 m (10 X 12 ft) and from 0.8 to 108 mm (0.03 to 4.25 in.) thick. Continuous sheets are cast in thicknesses up to 9.5 mm (0.375 in.) and widths to 2.7 m (9 ft).

Acrylic rods are cast in open aluminum *or* nylon molds, but tubes are made in metal molds and centrifugally cast to control wall thickness.

5-3.9.2 Casting Nylon

Nylon castings are made by polymerizing a monomer in two-piece molds at atmospheric pressure or at a low applied pressure. Depending on the shape and allowable tolerances, parts are cast to size or may require machining. Blind or through-holes can be molded if they are in a direction parallel to the mold opening and closing. Multiple cavity molds are permissible. Low-pressure molding, in addition to compensating for shrinkage, allows greater length-to-thickness ratios and more detailed parts than atmospheric casting. Mold costs, however, are greater. The thickness of castings varies from 4.8 to 19 mm (3/16 to 3/4 in.). Normal tolerances are ± 1% or ± 0.76 mm (0.030 in.), whichever is greater.

5-3.9.3 Casting Epoxy

Epoxies are cast from catalyzed liquid resins. The mixture of resin and catalyst is poured into a mold, preferably one under vacuum to prevent air entrapment. The casting may be cured at room temperature using the exothermic heat of reaction or at elevated temperatures in the range of 50°-150°C (120 °-3000 F); the choice depends on the catalyst type.

Available liquid resins and catalysts form low viscosity systems that are easy to process and modify with fillers. An added advantage of epoxy systems is the low mold shrinkage—in the order of 0.5 to 1.0%. Epoxy castings are used to encapsulate electronic components and for various plastic toolings, such as metal forming and vacuum forming dies (Ref. 20).

5-3.10 MACHINING

There are occasions when parts can be produced more efficiently by machining or by combining machining operations with one of the basic forming processes. Machining should be considered for all relatively simple shapes in low volume runs; however, complex parts in significant volumes are usually made more economically by molding,

Many flat-shaped parts without ribs or bosses can be fabricated inexpensively from sheet stock by sawing, routing, punching, and drilling. Large items, such as box-like structures, are possible by joining machined sections, using one of the techniques described in par. 5-3.12. Molding and forming methods usually are limited to thicknesses not exceeding 3 mm (1/8 in.), so machining may be the only alternative for thick sectioned parts. Rods, slabs, and heavy walled tubing serve as feedstock for machining.

At other times molding may require expensive, complex tooling to accommodate side holes, undercuts, critical dimensions, and other features. It is possible to simplify mold designs and reduce costs by combining machining with molding, and such changes should be considered.

Machining is used extensively to fabricate prototypes and experimental parts. Test results with machined parts should be viewed with caution because the properties may differ considerably from molded samples. Orientation during molding, nonuniform shrinkage, built-in stresses, and process variables contribute to the differences.

Possible machining operations with plastics include sawing, drilling, reaming, threading and tapping, turning, milling, punching, grinding, sanding, and buffing. The differences between plastic machining and metal machining are in the design of cutting tools, feed rate, and machine speeds. Coolants are frequently required to prevent excessive heating of the plastic material. For additional information on plastic machining, see Ref. 21.

5-3.11 DESIGN AND PRODUCIBILITY

Compliance with design rules established for plastic components—discussed in pars. 5-3.11.1 and 5-3.11.2—can be a determining factor in meeting producibility requirements. These rules apply to design features such as wall thickness, draft, tolerances, and to the mold design. The objective is to coordinate the design with the selected process and to prevent design errors, which lead to inefficient processing and reduced producibility.

5-3.11.1 Molded Components

Wall thickness limitations for injection, compression, and transfer molded parts are listed in Table 5-13. The minimum wall thickness depends on the flow characteristics of a material and the ability of it to fill the mold under pressure. Excessive thicknesses require longer cycle times and add to the total cost of the part. In addition, thicker parts may be undercured (thermoses) or contain thermally induced stresses (thermoplastics). When greater stiffness is required, ribs should be considered rather than added thickness. Abrupt changes in thickness should be avoided to prevent stress concentrations.

Allowances must be made for draft to facilitate part removal. There are no precise rules for the amount of taper, which varies with the material type. For example, sheet molding compounds, bulk molding compounds, and many glass-filled thermoplastics require a minimum draft of from 0.017 to 0.052 rad (1 to 3 deg) for depths up to 152 mm (6 in.) and 0.052 rad (3 deg) for greater depths. Unfilled materials can be molded with 0,009 rad (0.5 deg) taper.

In general, undercuts are to be avoided; however, small undercuts can be tolerated with some of the more flexible materials. There are techniques for providing undercuts, but at increased mold costs.

An inside corner can also act as a stress concentration point. The radius for such corners should not be less than 1.6 mm (1/16 in.) for filled materials and 0.8 mm (1/32 in.) for unfilled materials.

A major consideration in design is to specify all dimensional tolerances for a component, It is essential in designing with plastics that the tolerances be kept as liberal as possible because excessively close tolerances add to mold and production costs and lead to higher rejection rates, and component producibility may very well be jeopardized by insistence on tight tolerances. The tolerances that can be met in production runs depend on the specific fabrication process, the mold construction associated with each process, and the type of material being processed. Injection, transfer, and compression molding, which use matched metal dies, are capable of maintaining closer tolerances than are possible with rotational molding, blow molding, or thermoforming. Molding compounds with high filler contents are more difficult to control and require greater tolerances than unfilled or lightly filled materials. The variability related to materials and processes makes it advisable for the designer to consult with mold designers, custom fabricators, and material suppliers regarding tolerances for specific parts. Typical tolerances for injection molded thermoplastics are shown in Table 5-14. Comparable tolerances would be acceptable for transfer and compression molded parts. These design practices are treated in depth in Refs. 22 and 23.

5-3.11.2 Mold Design

Mold design usually is not the responsibility of the product designer. However, consultation with the mold designer at an early stage is desirable and may aid in eliminating design errors. Shrinkage during molding is probably the most troublesome aspect of mold design; it is influenced by the material composition and molding parameters, such as pressure, temperature, gate size, and others. Mold shrinkages listed in company property sheets are for comparisons only and are not reliable for design purposes. The part designer must depend on the experience of the mold designer for this information. It is good practice to test run a mold for shrinkage prior to finishing the mold surface. Mold cavities are made undersize and cores oversize so that corrections can be made in the mold dimensions. When several candidate materials are to be compared, the mold should be test run first with the material having the greatest shrinkage (Ref. 24).

The location of parting lines, gates, and ejector pins requires careful consideration. They should be located to minimize flash removal and finishing operations. Another critical aspect of mold design is the need to assure adequate flow of fiber fill to thin sections of a piece that have the greatest need for the strengthening afforded by the fibers.

Extreme care must also be taken when scaling up from a single-cavity to a multicavity mold. The heat losses occasioned by different mold wall thickness must be calculated as carefully as possible and then verified in actual practice. Many a plastic part successfully made in a single-cavity mold has failed miserably or at least brought the manufacturer much grief in scaling up to a multicavity mold. Computer programs should be used to facilitate these calculations whenever possible. (References on mold design are 5, 11, 12, and 25.)

TABLE 5-13. WALL THICKNESS OF MOLDED PARTS (Ref. 22)

Material	Thickness Range					
	Minimum		Average		Maximum	
	mm	(in.)	mm	(in.)	mm	(in.)
Thermoses						
Alkyd						
glass-filled	1.1	(0.040)	3.2	(0.125)	12.7	(0.500)
mineral-filled	1.1	(0.040)	4.7	(0.187)	9.5	(0.375)
Diallyl Phthalate						
mineral-filled	1.1	(0.040)	4.7	(0.187)	9.5	(0.375)
Epoxy						
glass-filled	0.8	(0.030)	3.2	(0.125)	25.4	(1.000)
Melamine						
cellulose-filled	0.9	(0.035)	2.5	(0.100)	4.7	(0.187)
Urea						
cellulose-filled	0.9	(0.035)	2.5	(0.100)	4.7	(0.187)
Phenolic						
wood-flour filled	1.3	(0.050)	3.2	(0.125)	25.4	(1.000)
flock-filled	1.3	(0.050)	3.2	(0.125)	25.4	(1 .000)
glass-filled	0.8	(0.030)	2.4	(0.093)	19.0	(0.750)
mineral-filled	3.2	(0.125)	4.7	(0.187)	25.4	(1.000)
Silicone						
glass-filled	1.3	(0.050)	3.2	(0.125)	6.3	(0.250)
Polyester						
SMC	1.3	(0.050)	—	—	25.4	(1.000)
BMC	1.6	(0.060)	—	—	25.4	(1.000)
Thermoplastics						
Glass-filled	0.9	(0.035)	3.2	(0.125)	12.7	(0.500)
Acetal	0.4	(0.015)	1.6	(0.062)	3.1	(0.125)
ABS	0.8	(0.030)	2.3	(0.090)	3.1	(0.125)
Acrylic	0.7	(0.025)	2.4	(0.093)	6.3	(0.250)
Cellulosics	0.7	(0.025)	1.9	(0.075)	4.7	(0.187)
FEP	0.3	(0.010)	0.9	(0.035)	12.7	(0.500)
Nylon	0.4	(0.015)	1.6	(0.062)	3.1	(0.125)
Polycarbonate	1.1	(0.040)	2.4	(0.093)	9.5	(0.325)
Polyethylene L.D.	0.6	(0.020)	1.6	(0.062)	6.3	(0.250)
Polyethylene H.D.	0.9	(0.035)	1.6	(0.062)	6.3	(0.250)
Ethylene vinyl acetate	0.6	(0.020)	1.6	(0.062)	3.1	(0.125)
Polypropylene	0.7	(0.025)	2.0	(0.080)	7.6	(0.300)
Polysulfone	1.1	(0.040)	2.5	(0.100)	9.5	(0.375)
Polyphenylene oxide	0.8	(0.030)	2.0	(0.080)	9.5	(0.375)
Polystyrene	0.8	(0.030)	1.6	(0.062)	6.3	(0.250)
SAN	0.8	(0.030)	1.6	(0.062)	6.3	(0.250)
PVC (rigid)	1.1	(0.040)	2.4	(0.093)	9.5	(0.375)
Polyurethane	0.7	(0.025)	1.6	(0.062)	19.0	(0.750)
Ionomer	0.7	(0.025)	1.6	(0.062)	19.0	(0.750)

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TABLE 5-14. TYPICAL TOLERANCES FOR AN INJECTION MOLDED THERMOPLASTIC

Part Dimension	Tolerance, ± Dimension					
	Fine		Standard		Coarse	
	mm	(in.)	mm	(in.)	mm	(in.)
Sidewall Thickness [1 to 6 mm (0.039-0.25 in.)]						
to depth of 25 mm (1 in.)	0.05	0.002	0.08	0.003	0.10	0.004
depth over 25 mm, add per mm (1 in.)	0.001	0.001	0.002	0.002	0.003	0.003
Bottom Wall Thickness						
0 to 2.5 mm (0 to 0.1 in.)	0.05	0.002	0.10	0.004	0.15	0.006
2.5 to 5.0 mm (0.1 to 0.2 in.)	0.10	0.004	0.13	0.005	0.18	0,007
5.0 to 7.5 mm (0.2 to 0.3 in.)	0.15	0.006	0.18	0.007	0.20	0.008
External Height						
Single cavity, to 25 mm (1 in.)	0.05	0.002	0.10	0.004	0.15	0.006
Multiple cavity, to 25 mm (1 in.)	0.08	0.003	0.13	0.005	0.18	0.007
Height over 25 mm, add per mm (in.)	0.002	0.002	0.003	0.003	0.004	0.004
Internal Length and Height						
to 25 mm (1 in.)	0.05	0.002	0.08	0.003	0.13	0.005
at 75 mm (3 in.)	0.10	0.004	0.15	0.006	0.25	0,010
at 100 mm (4 in.)	0.15	0.006	0.20	0.008	0.30	0.012
at 150 mm (6 in.)	0.20	0.008	0.30	0.012	0.41	0.016
over 150 mm, add per mm (in.)	0.001	0.001	0.002	0.002	0.003	0.003

5-3.12 ASSEMBLY AND JOINING TECHNIQUES

Joining plastics to themselves or to other materials is frequently necessary to complete an assembly or to provide access holes in a component. The various techniques currently in use include adhesive bonding, mechanical fastening, and melt processes in which the plastic is heated and subjected to pressure to effect a bond. The more important methods are described in this subparagraph.

5-3.12.1 Adhesive Bonding

Adhesive bonding is an efficient and economical method for joining plastics to themselves or to other materials. Adhesives are classified as elastomeric, thermoplastic, or thermosetting types. The elastomeric are used to impart flexibility in the joint. The thermoplastic adhesives are easy to use and are readily adapted to high-speed production and are applied as resin melts or as solvent solutions of the resin. However, the thermosetting types are the most durable and versatile. Best results are obtained by curing under pressure at elevated temperatures, but some thermosetting and elastomeric systems are curable at room temperature.

For effective bonding both surfaces must be compatible with the adhesive. The polyethylene, polypropylene, and fluorocarbons are difficult to bond and require surface treatments, such as etching or oxidation, to insure adherence to the plastic. Surface treatments for other materials involve removal of mold release agents and all foreign matter.

The strengths of adhesive bonds are influenced strongly by the joint design as well as the adhesive. Typical joint designs for adhesives are shown in Fig. 5-10 (Refs. 16 and 26).

5-3.12.2 Mechanical Fastening

Mechanical fasteners are widely used to secure plastics to other materials. The advantages of this method are fast installation, low cost, minimal tooling, and reliability. The choice of a fastener depends on the plastic type, loading conditions at the joint, the environment to which the assembly will be exposed, and whether disassembly is a requirement. The more common fastener types are discussed in this subparagraph.

5-3.12.2.1 Screws

Common machine screws made to National Coarse and National Fine Thread Standards are employed in conjunction with threaded metal inserts. Pretapped holes are rare and suited only to extremely hard plastics. Thread-forming screws are specified for ductile plastics having an elastic modulus below 2.8 GPa (400,000 psi) and thread-cutting screws for more brittle

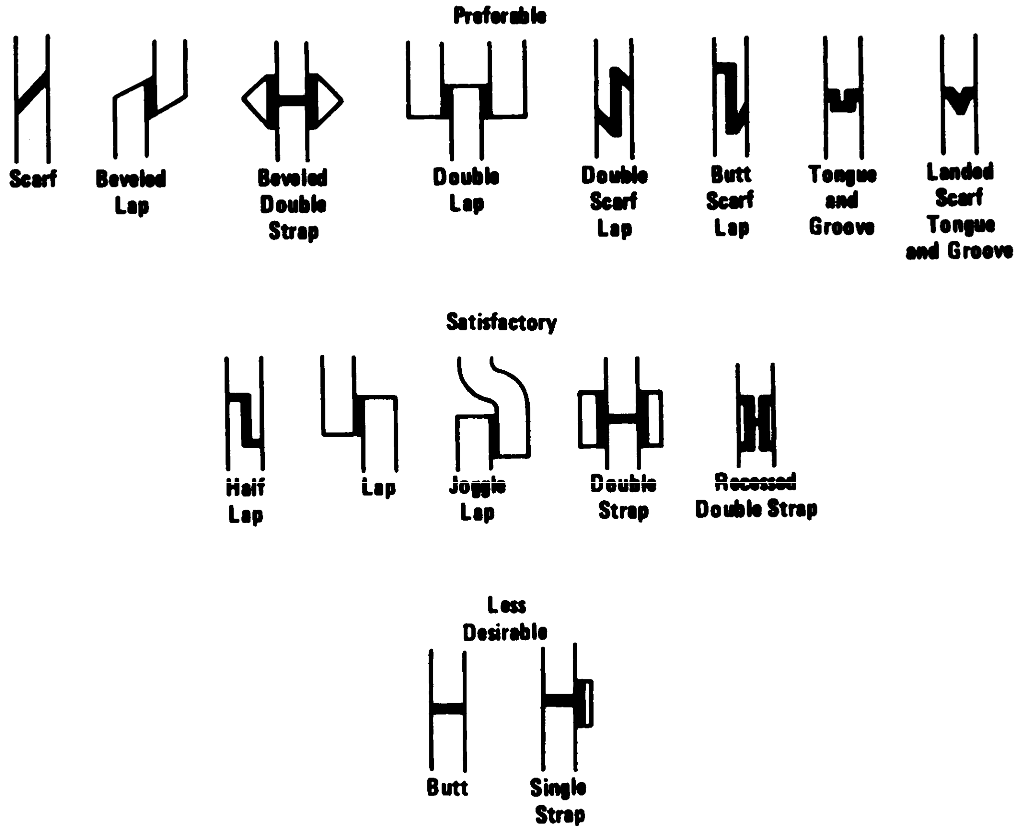

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Figure 5-10. Bonded Joint Configurations (Ref. 26)

materials. When holes are located on bosses, the diameter of the boss should be from 2.5 to 3 times the hole diameter.

Stripping torques can be increased by reducing hole size, increasing the length of thread engagement, and increasing screw diameter. A common failure is cracking of the plastic boss; corrective measures are to increase the boss radius where it joins the base material or to increase the boss hole diameter, to decrease screw diameter or thread engagement, or to change the configuration of the screw threads.

5-3.12.2.2 Threaded Metal Inserts

Internally metal inserts have tapped threads, and externally they have configurations of various designs to anchor into plastics. Inserts may be incorporated in many ways, and they are frequently added to the mold and integrally molded into the part. Although this is a costly method, the insert becomes well anchored, and stresses in the plastic are kept to a minimum normally. However, in extreme environments the inserts can induce stresses due to differing shrinkage rates. Other types of inserts are pressed into bosses, threaded in place, ultrasonically inserted, expanded in place, or glued in place.

The installed cost of a metal insert and a machine screw is greater than it is for a tapping screw, but they have the advantage over tapping screws of having greater load distribution areas, and the screw can be assembled and disassembled a greater number of times. It is also possible to incorporate thread locking features in the insert.

5-3.12.2.3 Stamped Metal Screw Receivers

These receivers add reinforcement to molded or stamped holes, are easy to install, and can be adjusted to component misalignments. The screw and receiver are clipped, latched, or pressed into position and are reusable.

5-3.12.2.4 Drive Pin Fasteners

Solid drive pins with knurls or splines are pressed in place or ultrasonically inserted. They are designed to fasten components without the use of screws. The pins are either solid, single pieces or solid with a tubular receiver. The tubular pins can be inserted to provide interference fits or can be flared over for positive retention.

5-3.12.3 Heat Sealing

Heat sealing is a method for joining two layers of plastic film by applying heat and pressure. Sufficient heat is furnished to fuse the layers into a single mass. The process is known as RF sealing or thermal sealing, depending on the heat source. RF heating brings the plastic to melting temperature rapidly, but it is possible only with those materials having high dielectric losses. These include cellulose acetate, nylon, polyurethane, PVC, and other vinyl polymers. Electrical elements supply the heat for thermal sealing. In both cases pressure is applied by pneumatic or hydraulic activation of sealing bars or plates.

RF and thermal sealing units are automated for high-rate production, or they can be operated manually for low quantity production runs. Operational costs are low. Films up to 0.25 mm (0.010 in.) in thickness are easily sealed. Thicker sections are best sealed with electrically heated hot plates. The pieces to be sealed are held against the plate until melted and are then pressed together until cooled. Such methods can be completely manual, semiautomatic, or fully automatic for high-rate production.

5-3.12.4 Ultrasonic Bonding

Ultrasonic techniques are based on the fact that materials subjected to high-frequency mechanical vibrations absorb energy and rise in temperature. Most thermoplastics can be melted and bonded by ultrasonic means. The equipment for this process is automated and capable of handling high-volume runs at fast rates.

The equipment converts electrical energy into high-frequency mechanical energy in the form of an axial vibration, normally at 20 kHz. A "horn" transmits the vibrations to the plastic and also is used to apply a slight clamping force so that the melted plastic is cooled under pressure. In addition to bonding, ultrasonics are used for other operations requiring localized heating and light pressures. Examples include staking, swaging, positioning inserts, spot welding, and forming.

Performance in bonding depends on the material type and the joint configuration. Rigid thermoplastics readily transmit vibrations and are easy to melt, but flexible materials require higher amplitude vibrations for melting and bonding. Materials with low melting points and specific heats are easier to process. The crystalline resins, acetal, nylon, polyethylene, polypropylene, polyester, and polyphenylene sulfide require additional heat to account for the heat of fusion at melting and, consequently, are more difficult to bond. Higher energy input and higher amplitudes are necessary with these materials. The amorphous resins, particularly ABS, polycarbonate, and polystyrene, are easier to bond. Materials that absorb moisture—nylon and polycarbonate are examples—must be dried prior to bonding. Materials with glass or mineral fillers up to 30 to 35% can be bonded, but they tend to cause excessive wear of the horn. Dissimilar materials can be bonded together provided their melting points are in the same range and they are chemically compatible. Some combinations are ABS and acrylic, polycarbonate and acrylic, and polystyrene and phenylene oxide base resins.

The design of joints for ultrasonic bonding depends on the type of plastic, the geometry of the part, and the function of the bond, i.e., tack, strong bond, hermetic seal, etc. A basic requirement of all joints is a small, uniform contact area. In the most common design a triangular section, known as an energy director, concentrates the vibrations for a rapid heat buildup at the bond line as shown in Fig. 5-11. Design types include the butt, modified butt, step, tongue and groove, shear, and stud-welding joints. Details of joint designs may be found in Refs. 23 and 27.

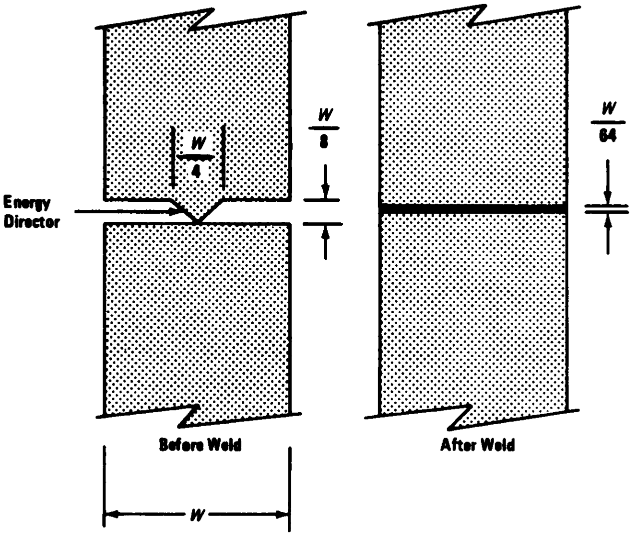

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Figure 5-11. Modified Butt Joint With Energy Director (Ref. 27)

5-3.12.5 Ultrasonic Staking

Ultrasonic staking is a method for joining plastics to metals or other dissimilar materials. A typical staking joint is shown in Fig. 5-12. A hole is drilled in the material to be joined to the plastic. A stud or boss previously molded into the plastic part is fitted into the hole. Vibrations are transmitted through the horn, which shapes the melted plastic and maintains pressure until the joint is cooled. Various stud and cavity designs are used in ultrasonic staking. These include hollow, domed, knurled, and flush stakes and are depicted in Fig. 5-13.

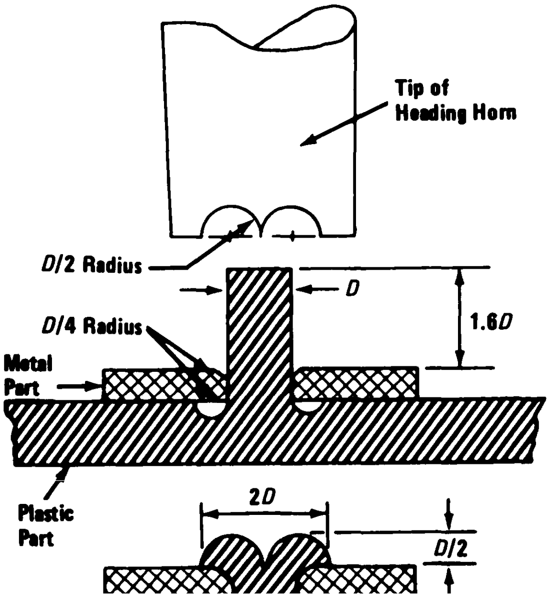

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Figure 5-12. Typical Ultrasonic Staking (Ref.27)

5-3.12.6 Spin Welding

Spin welding is a technique for rapidly bonding circular surfaces of thermoplastics. Spin welds are made by rotating one part at high speeds against the surface of the second part; frictional heat is generated in a few seconds and is sufficient to melt both surfaces. When rotation stops, the parts are held together under pressure until cooled.

Prototype or low volume runs can be carried out with rotation provided by standard drill presses. Equipment for automatic operation can be custom-built to fit specific assemblies if warranted by the number of parts to be produced (Ref. 23).

5-3.12.7 Vibration Welding

Vibration welding, like spin welding, depends on frictional heat to melt the thermoplastic pieces to be joined. One surface is vibrated while in contact with the other until a melted film is formed at the interface. Melting usually occurs within two to three seconds. Vibration is then stopped, and pressure is applied as the surfaces are cooled. Vibration may be in a linear or angular mode. With linear motion, several pieces can be bonded at the

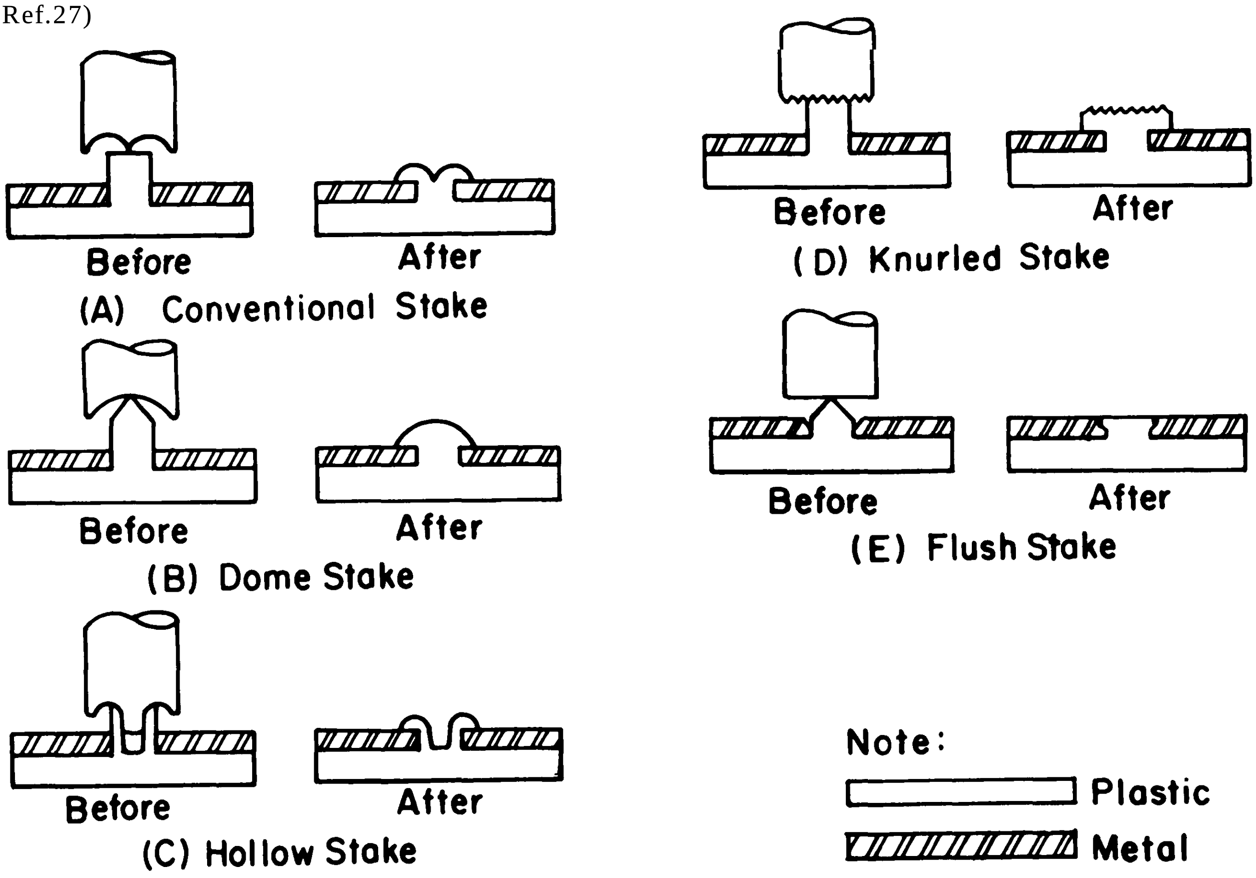

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Figure 5-13. Stud Cavity Designs for Staking (Ref. 27) same time, and angular vibration is used when linear surface contacts cannot be made. The major advantages of vibration over spin welding are that joint sections other than circular can be bonded and that the mating surfaces need not be in the same plane. The method is applicable to large surfaces. Parts as long as 559 mm (22 in.) and as wide as 305 mm (12 in.) have been welded on standard equipment (Refs. 2 and 23).

5-3.12.8 Hot Gas Welding

Thick thermoplastic sections have been joined by hot gas welding, a process somewhat similar to acetylene welding of metals. The plastic surfaces at the joint and the welding rod to be inserted in the joint are melted by heated, pressurized gas. An electrically heated welding gun serves as a heat source and is used to apply pressure to the melt. The welding rods are made from the same plastic as the parts to be joined, and the gas is usually air. Inert gases, such as nitrogen, may be required for materials subject to oxidative degradation. Joint types are similar to those in metal welding, and beveled edges are essential for sound joints. The process is generally suited to low volume runs and has not been automated (Ref. 26).

5-3.12.9 Electromagnetic Bonding

Electromagnetic techniques are based on the fact that magnetic materials develop heat when subjected to high-frequency induction sources. Plastics to be bonded by this method are made magnetic by the dispersion of metallic particles within them. Only one of the layers to be joined must be magnetic. Alternately, a magnetic film may be placed between two nonmagnetic surfaces. In either case, exposure to a magnetic field develops rapid heating and melting at the interface. A slight pressure is applied to complete the bond.

Standardized equipment, with a pneumatic press for pressure application, permits automation and high-volume production. Parts with thicknesses up to 50 mm (2 in.) have been bonded by this method. It is applicable to irregular surfaces and develops heat at the interface only, so there is little distortion of the external surfaces (Refs. 2 and 26).

5-3.13 FINISHING PROCESSES

The surfaces of molded or formed components normally do not need further treatment. There are some applications, however, for which surface finishing is used to improve properties or overcome deficiencies. Of the existing finishing methods, electroplating, vacuum metallizing, and painting may offer specific advantages. These and other surface finishing processes should be considered and applied only when a functional purpose would be served.

5-3.13.1 Electroplating

The principle advantage of plated surfaces is that they are electrically conductive and can be employed for the shielding of electronic components, grounding, electrical contacts, and as replacements for printed circuit boards. Plated surfaces can also function as mirrors and as light or heat reflectors, particularly in corrosive environments. The hardness and wear resistance of plastics are improved by plating, and these improvements may warrant the additional cost of plating in some instances.

Electroplating is accomplished by subjecting a plating grade material to a series of cleaning, etching, and preplating stages before final deposit of the metal. Each plastic type requires a different treatment, and each part must be designed to meet plating conditions. Corners and edges require large radii; deep or small recesses are to be avoided. The metals that have been successfully deposited on plastics include copper, nickel, chrome, and silver. The bulk of electroplating has been in decorative automotive applications, in which the plastic is ABS on which a chrome finish is applied. Other resins for plating are ABS/polycarbonate alloy, nylon 6/6, polysulfone, phenolic, and urea. For further details on electroplating plastics, see Refs. 2 and 28.

5-3.13.2 Vacuum Metallizing

In vacuum metallizing, a metal is evaporated by heating in a high vacuum and is deposited as a thin film on the plastic parts stacked in the vacuum chamber. Aluminum is deposited most frequently due to its lower cost and ease of vaporization. Practically all plastics may be metallized by this process.

The plastic parts must receive a basecoat prior to metallizing and a topcoat afterward to protect the metal deposit. Various organic coatings, such as acrylic or alkyd base enamels or lacquers, are used for these purposes. The metal surface coating acts as a shield against electromagnetic interference and as a heat reflector. Metallized films provide improved moisture and vapor barriers as well as resistance to ultraviolet or infrared penetration. They are used in critical packaging applications.

5-3.13.3 Painting

Air spraying is the most widely used method for applying paints to plastics. Other methods include dipping, roller coating, and flow coating. The coatings are either acrylic or alkyd base enamels or lacquers and are most frequently supplied as solutions with organic solvents. As a result of pollution laws, low-solvent-content and water-base paints are becoming available. Since some solvents attack plastics, material suppliers should be consulted as to the compatibility of specific plastic materials with specific paint systems. Surfaces to be painted must be free of mold release agents for good adhesion; however, some plastics do not permit paint adhesion without pretreatment. Flame impingement, acid etch, or chemical etch are common methods of treating these surfaces. The painted plastics usually require a heat cure; air drying at room temperature generally results in inferior coatings.

The functional advantages of painting are to improve outdoor weathering and to increase resistance to chemicals, moisture, and ultraviolet radiation. It also serves as a protection for machined surfaces.

5-4 TESTING AND EVALUATION

The selection of appropriate test and evaluation procedures is a major consideration in establishing producibility. Tests are required to perform the following functions:

1. Compiling data for design purposes, such as failure criteria and allowable stresses
2. Identifying materials
3. Compliance of materials with specifications
4. Determining optimum processing conditions, quality control, and process reliability
5. Evaluating the performance of finished components.

A testing program is normally included in the overall design and procurement package. Some of the stated test phases may not be necessary in all cases, and some may be the responsibility of the custom molder or part fabricator. It is good practice, however, to specify criteria for the performance of finished components. A sufficient number of tests should be allocated to insure quality and reliability, but they should not be excessive because many test procedures are expensive and can result in substantial cost increases.

In general, tests are classified as standardized procedures or as practical tests designed for specific components under specific conditions. Both types may be required.

5-4.1 STANDARDIZED TEST PROCEDURES

Standard methods for testing plastics have been developed by the American Society for Testing and Materials (ASTM) and have been universally accepted throughout the plastics industry. Test procedures have been established for determining mechanical, thermal, electrical, optical, and permanence properties. Procedures include the preparation of test specimens, conditioning prior to testing, design of test fixtures, and description of acceptable equipment for conducting the tests. Specimens for testing thermoplastics are generally injection molded in specially designed molds. Thermosetting materials are compression molded to the test configuration. Alternately, specimens can be machined from sheet stock. A partial listing of ASTM tests is given in Table 5-15. A complete list of ASTM tests and test procedures is found in Ref. 1.

5-4.1.1 Mechanical Properties

The mechanical properties of greatest significance are tensile strength and modulus, flexural strength and modulus, compressive strength, creep in tension, compression or flexure, and impact resistance. The significance of these properties is discussed in pars. 5-2.1 through 5-2.4.

5-4.1.2 Thermal Properties

Tests for deformation under load and the deflection temperature give some indication of the behavior of the material at elevated temperatures. They are not intended as criteria for establishing the maximum service temperature of a material; their chief function is to compare materials under similar conditions.

The tests listed under process-related thermal properties in Table 5-15 are also for comparative purposes. Tests D 1525, D 1238, and D 731 are useful in estimating processing temperatures and the flow characteristics of a material during molding. Mold shrinkage (ASTM Test Number D 955) is discussed in par. 5-3.11.2.

5-4.1.3 Electrical Properties

The standard tests for electrical properties include determination of dielectric strength, dielectric constant, loss factor, resistivity, and arc resistance. These properties vary considerably with temperature, humidity, moisture content of the plastic, and the geometry of the part. Test results therefore do not correlate well with actual performance and are limited to material comparisons and quality control.

5-4.1.4 Permanence Properties

The important permanence properties are chemical resistance, accelerated weathering, and outdoor weathering.

Outdoor testing is the most accurate method for evaluating the effects of weather on plastics. However, the disadvantage of these tests is that up to three years may be required before the results indicate significant changes. Accelerated testing does not always correlate with outdoor test results, but it is a widely accepted expedient.

5-4.2 PRACTICAL TESTING OF COMPONENTS

Nonstandardized tests are designed to stimulate or duplicate the environmental and service conditions to which a component may be exposed. The purpose of these tests is to verify performance, to detect any unforeseen defects, and to provide an estimate of the life of the component.

TABLE 5-15. A PARTIAL LIST OF ASTM TEST METHODS FOR PLASTICS* (Ref. 1)

	ASTM No.	Property Tested
Mechanical Properties		
	D 953	Bearing Strength
	D 1180	Bursting Strength of Rigid Plastic Tubing
	D 695	Compressive Properties
	D 2236	Dynamic Mechanical Properties by Means of Torsional Pendulum
	D671	Flexural Fatigue by Constant Amplitude of Force
	D 790	Flexural Properties
	D 2583	Hardness by Means of a Barcol Impresser
	D 785	Hardness, Rockwell
	D 256	Impact Resistance
	D 732	Shear Strength
	D 2990	Tensile, Compressive and Flexural Creep and Creep Rupture
	D 1882	Tensile Impact Energy to Break
	D 638	Tensile Properties
	D 2289	Tensile Properties at High Speeds
Thermal Properties		
	D 696	Coefficient of Linear Thermal Expansion
	D611	Deformation Under Load
	D 648	Deflection Temperature Under Flexural Load
	c 177	Thermal Transmission (Conductivity)
Thermal Properties Related to Processing		
	D 1525	Vicat Softening Temperature
	D 1238	Flow Rates of Thermoplastics by Extrusion Plastometer
	D 955	Shrinkage from Mold Dimensions
	D731	Molding Index of Thermosetting Powders
Electrical Properties		
	D 150	Dielectric Constant and Loss Characteristics
	D 149	Dielectric Strength and Breakdown Voltage
	D 495	Arc Resistance
	D 257	DC Resistance or Conductance (Resistivity)
Optical Properties		
	D 542	Index of Refraction of Transparent Plastics
	D 1003	Haze and Luminous Transmission of Transparent Plastics
Physical Properties		
	D 792	Specific Gravity
	D 570	Water Absorption
Permanence Properties		
	D 543	Chemical Resistance
	G 23	Accelerated Weathering
	D 1435	Outdoor Weathering

* Abbreviated titles

There are no fixed rules for the types of tests to be conducted, and each case must be evaluated individually. Properly designed practical testing can be relatively inexpensive and can yield conclusive information on the overall performance of a component (Ref. 17).

Some examples of nonstandardized tests are

1. Temperature and humidity cycling at accelerated rates
2. Rough handling and storage tests
3. Bending, tensile, and drop tests

4. Fatigue and vibrational tests
5. Exposures to various oils and chemicals followed by strength tests
6. Mechanical testing of coupons taken from various sections of the component
7. Density measurements.

5-5 NONTRADITIONAL PLASTICS AND PROCESSES

The materials and processes discussed to this point are well established and traditional. Although new plastics are constantly being introduced, most appear to be in the traditional mode. These materials are usually variations of existing polymers or compounds and show no radical differences. Similarly, the basic fabrication processes are not substantially altered despite the continuous improvements in equipment design. Occassionally, new materials are developed that extend the applicability of plastics into newer areas. One such example is the recent development of thermoplastic elastomers. Processes sometimes undergo significant changes to handle a new material type, or conversely, materials are varied to fit an innovation in processing. An example of this type is reaction injection molding (RIM).

Thermoplastic elastomers and RIM permit greater design latitudes, easier fabrication, and lower overall costs in applications requiring toughness combined with resiliency.

5-501 THERMOPLASTIC ELASTOMERS

The properties of thermoplastic elastomers tend to bridge the gap between rubbers and plastics. They combine the resiliency of rubbers with the toughness and processibility of thermoplastics; they can be processed by extrusion, blow molding, injection, compression, and rotational molding methods. Unlike rubbers, however, there is no need for vulcanization, and scrap is reusable. It is possible to incorporate fillers into the compounds, or they can be added during extrusion or molding. The principal types now available, their properties, and costs are listed in Table 5-16. From a design standpoint, they can be considered replacements for parts traditionally made from metals, leather, cork, and wood. Current applications include automotive exterior shapes, gears, hoses, belting, electrical insulation, and jackets (Refs. 24 and 29).

5-5.2 REACTION INJECTION MOLDING

RIM is a relatively new molding process in which liquid monomers or the liquid components of a resin system are polymerized and molded in a single operation. The application is in areas in which the economical processing techniques allow effective competition with traditional, foamed, rigid thermoplastic materials, The production equipment consists of three main components: storage supply and dispensing unit, a mixing head, and the mold and clamping unit. Each component is maintained at a controlled temperature in the supply tank from which it is fed into the dispensing unit. The dispensing units use high-capacity metering pumps, which deliver the components to the mixing head at pressures of from 6.9 to 20.7 MPa (1000 to 3000 psi). The mixing head contains a small chamber in which the components undergo an impingement-type mixing before entering the mold cavity. A clamping

TABLE 5-16. THERMOPLASTIC ELASTOMERS, COST AND PROPERTIES (Ref. 24)

	Olefinics	Styrene Block Polymers	Thermoplastic Urethane	Polyester Copolymers
Specific gravity, dimensionless	0.9-1.02	1.00-1.16	1.10-1.25	1.17-1.25
Cost—dollars/kg*	0.99-2.54	0.88-2.65	2.87-4.30	3.31-3.64
Cost—dollars/lb*	0.45-1.15	0.40-1.20	1.30-1.95	1.50-1.65
Hardness, durometer D	35-50	75(A)-35	50-60	40-72
Tensile strength, MPa	10.3 -13.8	6.9-15.2	31.0-37.9	24.1-44.8
psi	1500-2000	1000-2200	4500-5500	3500-6500
Ultimate elongation, %	150-300	350-750	400-500	300-650
Flexural modulus, MPa	138-241	28-103	138-172	55-517
psi x 10^3	20-35	4-15	20-25	8-75
Compression set, **%	80-90	45-55	25-35	35-50
Melt flow, gm/10 min	0.4-8.0	0.3		6-8
Brittle point, °C	–51 to –71	–101	–59 to –73	–73
°F	–60 to –95	–150	–75 to –l00	–l00

l as of January 1979
**22 h at 70°C (158°F)
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force is applied to the mold while the components complete the polymerization reaction.

The process advantages are

1. Lower mold pressures, normally not over 0.35 MPa (50 psi), and correspondingly low clamping pressures
2. Reactions are exothermic and little additional heat is supplied to the mold.
3. Low mold and equipment costs
4. Design flexibility permitting the molding of large parts with variable and thick wall sections
5. Fillers, such as fiberglass, can be added to the resin.

The process requires liquid resin intermediates, which can be catalyzed to produce rapid polymerization without volatile reaction products. Several polyurethane compositions meet these requirements: rigid foams, low modulus elastomers, or high modulus elastomers. All commercial production to date has been with polyurethane systems. Nylon 6, polyester, and epoxy systems are presently being developed for RIM applications.

5-6 EXAMPLES OF PRODUCIBILITY

There are occasions when relatively minor errors in design or material selection result in unnecessary production costs and lower producibility. Examples of such errors and the corrective measures taken are presented here.

5-6.1 TOLERANCES

Invariably, the tightest tolerance is the dominant criterion for all tolerances on any given part. Thus if the most severe tolerance is ± 0.08 mm (± 0.003 in.), that becomes the tolerance for all close fitting areas. If the next level of tolerance is ± 0.25 mm (± 0.010 in.), then that becomes the tolerance for all other dimensions. This forces very high tooling cost and also requires many adjustments in process control.

Designers should examine every surface and every dimension of their designs to assure that only the degree of control needed is specified. If a particular surface can stand a ± 0.51-mm (± 0.020-in.) tolerance, it should be specified as such even if it occurs only once in the drawing because this can significantly enhance producibility.

5-6.2 CORRECT MATERIAL GRADE

The design engineer wanted a rigid nylon container with a burst strength of approximately 0.46 MPa (66 psi), so he selected a specific material based on this criterion. He knew that nylon could be blow molded, which was exactly what he wanted. Unfortunately, the material he selected turned out to be an injection molding grade. The producer acquired the material and proceeded to begin building the injection molding tooling. Several thousand dollars later the error was discovered, but not until the program budget was overrun, and significant time had been lost.

Once the error was discovered, it was an easy matter to select a blow molding grade of material that actually exceeded the mechanical properties required. There are many grades of plastic materials. The designer should always check the processing requirements of his selected material to assure compatibility with his preferred production process.

5-6.3 LOCATION OF GATES

Gates are the points in an injection mold at which the material enters the cavity. Normally, these are rather thin sections that can be broken off and sanded to smooth the surface. In this particular case the gates were located on a surface that had a 0.25-mm (0.010-in.) tolerance, and this necessitated a secondary machining operation to maintain the tolerance.

The normal production practices of breaking and sanding are usually capable of holding only a 0.38- to 0.5 l-mm (0.01 5- to 0.020-in.) tolerance. Gates should always be located on surfaces compatible with normal production processes.

5-6.4 PRODUCTION PROCESS PLANNING

The design specified a vacuum formed polyethylene hemisphere with a 2.54-mm (0.100-in.) undercut in the open end of the hemisphere. The original female tooling was made from machined aluminum. After several attempts met with failure, it was concluded that the undercut was too large to permit removal of the part from the cavity. The tooling was rebuilt, and the reduction was decreased to 1.91 mm (0.075 in.) with the same unsatisfactory results. A third set of tooling was built with a 1.27-mm (0.050-in.) undercut, and the job was completed,

The problem here was twofold. First, the amount of undercut in the tooling exceeded normal practice recommendations. In forming high-density polyethylene into a female tool, it is possible to have a 1.27-mm (0.050-in.) undercut per side and still successfully strip the part from the cavity. Secondly, using machined aluminum for the first batch was premature. When preparing a large quantity run, it is always wise to make the first parts on temporary tooling. This will prove the tooling concept and provide prototypes of the final production part before the commitment to harder, more expensive, permanent tooling.

5-6.5 OVERSTRESSED THREADS

The design called for a plastic component with threaded holes to be assembled to a metal part with metal machine screws engaging the threaded holes. The screws were drawn up too tight, the threads were overstressed, the plastic deformed, and the component failed.

Whenever threads are used in plastic components, it is good practice to state the torque level for screw engagement, In this case the screw assembly was discarded in favor of bonding.

5-6.6 MOLD PARTING LINES

The design specified a product with a series of sharp corners all' located in different planes. Tool designers always try to make sharp corners of a product coincide with the parting lines of the tooling. In this instance this practice resulted in a very complex tool whose cost was far out of range with the simplicity of the part.

The estimate of tooling cost and the explanation of what caused the high cost resulted in reexamination of the part and the subsequent elimination of several sharp corners. The necessary ones were maintained, and the tooling was ultimately produced at about one-half the original estimate.

5-6.7 INCREASED PRODUCIBILITY WITH PLASTIC

The marforming process, a metal forming operation, historically used hardened tool steel for tooling. This made it expensive to test parts from the actual process in the prototype stage. To circumvent this problem, prototype tooling was made from aluminum-filled epoxy. It was originally planned to make 200 pieces from this tooling, and once the part was proven, the subsequent quantity of 10,000 was to be made from steel tooling. The epoxy tooling was not only good enough to produce the first 200, but it subsequently produced 5000 more parts, and a second set of relatively low-cost epoxy tooling was built for the balance of the production. These two sets of epoxy tooling proved substantially lower in cost than one set of steel tooling and produced equally high quality parts.

As another example, the design of a spherical liquid container specified the material as an aluminum alloy. The parts were needed in large quantities, and the cost was high. The container was 3.18 mm (0.125 in.) thick and had to withstand an internal pressure of approximately 690 kPa (100 psi) and had to have a relatively high resistance to impact. The design was changed to specify an ABS general purpose injection molding resin. The same wall thickness was used. The new material was an unqualified success. The strength-to-weight ratio was improved, the product provided the necessary physical characteristics, and most significantly, it resulted in a cost reduction of approximately 10:1 over its aluminum counterpart.

5-6.8 STRESS CONCENTRATION

A rectangular, box-shaped light reflector was designed in high-density polyethylene. The initial parts developed cracks either during installation or after a short service time. Wall thicknesses were increased by 30'%, but failures continued.

Examination of the parts revealed that cracks were initiated at the intersection of the side walls and base. Increasing the radius at these points eliminated the failures. It was not feasible, however, to reduce the wall to its original thickness.

5-6.9 FIBER ORIENTATION

An aerodynamic fin for a rocket application was designed to be compression molded from a fiberglass-reinforced epoxy compound. The design required a flexural strength of 172 MPa (25,000 psi), which is close to the limit of the material. An alternate material, glass-cloth-reinforced epoxy, was more difficult to mold and necessitated machining. The first attempt was to mold the fin in a vertical position with the base at the top of the mold, but it took excessive pressure to fill the mold, and the parts showed separation of resin from the fiber at the bottom of the mold cavity.

The mold was redesigned to function in a horizontal position. The resulting parts indicated random fiber orientation over the entire surface and successful?' met the strength requirements. The subject of reinforced plastics is discussed more extensively in Chapter 6.

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CHAPTER 6

PRODUCIBILITY CONSIDERATIONS FOR COMPOSITE COMPONENTS

The fiber-reinforced, resin base composites are the subject of this chapter. The properties of the major reinforcements and resin systems are discussed in r-elation to the properties of the composite; properties are also listed for both the short fiber (discontinuous) reinforced composites and the filamentary (continuous) reinforced composites. The principal fabrication processes for converting composites into components are described, and the advantages and limitations of each process are delineated. Methods for machining, joining, and testing composites are also included. Component design is discussed in relation to producibility. Design guides are given for several of the important fabrication methods. A distinction is made throughout the chapter between the fabrication of components from commercial grade composites and the fabrication practices followed in the aerospace industry for the class of composites generally designated as "high performance" or "advanced" composites.

6-1 INTRODUCTION

Composites are defined as material systems consisting of two or more constituents, each of which is distinguishable at a macroscopic level. These constituents retain their identity in the composite and are separated by a distinct interface. The properties of the composite are a combination of the properties contributed by the constituents and modified by their synergistic effects. It follows that composites can reconstructed having specific characteristics by selecting appropriate constituents. In the simplest composite structures one constituent acts as a reinforcing agent or filler while the other serves as a matrix or binder.

The way composites are classified depends on the type and form of the individual constituents. The materials of primary interest in this chapter are described as fiber-reinforced, polymer-based composites. Specifically, these materials include the traditional reinforced plastics and the more recent composites, which are generally referred to as "advanced", "high modulus", or "high performance" composites.

The fiber reinforcements in these composites may be continuous or discontinuous, aligned or random, woven or nonwoven. The matrix materials are thermosetting resins for the most part but also include a few thermoplastics. Selection of the reinforcement and the resin, the proportions of each in the composite, and the distribution and alignment of the reinforcement within the composite are essential features in the design of a composite and are therefore important to its ultimate use in fabrication of a component. Although almost any combination of resin and reinforcement is possible, cost or processing restrictions have limited the number that are commercially acceptable. The more prominent material combinations are listed in Table 6-1. Fiberglass and polyester resin are the most frequently used materials, and they form the backbone of the reinforced plastics industry. Other materials, notably graphite, aramid and boron reinforcements, and polyimide resins are limited to aerospace applications.

It is apparent that production practices vary widely between commercial and aerospace manufacturers, and a clear distinction must be made between "commercial grade" and "high performance grade" composites. The commercial fabricators rely upon the less expensive fiberglass products and the higher production rate processes associated with these materials. Commercial quality control and reproducibility standards are less stringent than is customary in the aerospace industry. To meet mission requirements, the aerospace manufacturers have developed the high performance grade materials. Designs and processing have been refined to attain the degree of reliability required in aerospace structures, and higher production costs are tolerated for the sake of this increased reliability. Consequently, producibility criteria applied to high performance composites will differ significantly from the commercial grades, and what is acceptable in aerospace may be impractical commercially.

It is safe to assume that most military components based on composites will use commercial grade materials to be cost-effective. To date, high performance grades in Army applications have been used only for rotor blades and other helicopter parts, radomes, missiles, and bazooka-type weapon systems. However, materials and fabrication technology developed in the aerospace industry can be of advantage in other design areas. Of particular interest are the analytical methods applied to composites and their failure mechanisms, improved fabrication controls, and consolidation or

TABLE 6-1. REINFORCEMENT/RESIN COMBINATIONS FOR COMPOSITES

Reinforcement		Matrix		
Form	Material	Type[1]	Resin	Use and Orientation
Continuous				
Roving	Fiberglass, graphite, aramid	TS	Polyester, epoxy	Filament windings, pultrusions
Nonwoven[2]	Fiberglass, graphite, aramid, boron	TS	Epoxy, polyimide	Unidirectional or crossplied laminates
Nonwoven[2]	Graphite, aramid	TP	Polysulfone	Unidirectional or crossplied laminates
Woven fabric	Fiberglass	TS	Polyester, epoxy, polyimide, phenolic, silicone	Orthotropic laminates
Woven fabric	Graphite, aramid	TS	Epoxy, polyimide	Orthotropic laminates
Woven fabric	Nylon	TS	Phenolic	Orthotropic laminates
Mat	Fiberglass	TS	Polyester, epoxy	Partially aligned (swirled) laminates
Discontinuous				
Mat	Fiberglass	TS	Polyester, epoxy	Random laminate
Mat[3]	Fiberglass	TP	Polypropylene, nylon	Random laminate
Chopped fiber	Fiberglass, graphite, aramid	TS	Polyester, epoxy	Random laminate
Chopped fiber	Fiberglass	TS	Polyester	Random sheet or bulk molding compounds
Chopped fiber	Fiber-glass, nylon	TS	Phenolic, epoxy	Random molding compounds

[1] TS= thermoset, TP = thermoplastic
[2] Broad goods or tapes
[3] May also contain continuous fibers

other improvements in component design that increase efficiency. It is also probable that the price of certain materials, such as graphite and aramid fibers, will be reduced, which will permit their use in structural components. Graphite already is being considered as a lighter weight replacement for automotive parts, Effective use of these materials will require the close controls developed in the aerospace industry.

6-2 MAJOR MATERIAL CONSIDERATIONS

The major advantage of the fiber-reinforced composites is their high strength and rigidity, which favor their use in structural applications. The mechanical properties are functions of the reinforcing agent and the way it is used in the composite. The reinforcement-related variables of greatest significance are the volume, length, and orientation of the fiber within the composite. Fiber diameter and the uniformity of fiber distribution and spacing are secondary factors affecting mechanical properties. The primary role of the resin is to absorb and transmit loads to the fiber. At the same time, the resin controls the viscoelastic behavior (par. 5-2), temperature, loading rate, and time dependence of the strength properties implied in viscoelasticity. Creep, stress relaxation, in-plane shear, and interlaminar shear are directly dependent on the resin system. The chemical, electrical, and thermal characteristics of the composite are controlled primarily by the resin and the fillers that are sometimes added to it.

The principal reinforcing agents and resin systems are compared before consideration of composite properties. The continuously reinforced (filamentary) composites are treated separately from the short fiber composites.

Maximum strength and stiffness are attained in the filamentary composites. The short fiber composites have a range of properties intermediate to the filamentary materials and glass-filled molding compounds (Chapter 5).

Composite raw material and fabrication costs, which depend chiefly on the reinforcement type, vary widely. Generally, the more expensive reinforcements incur the highest fabrication costs; consequently, the overall component cost is the decisive factor in material selection and in establishing producibility.

6-2.1 REINFORCEMENTS

The major reinforcing agents for composite use are fiberglass, graphite, and Kevlar 49* (DuPont's aramid). Boron filament, because of its high cost, has limited application. The reinforcements are produced as continuous filaments and are converted later into other forms as required for fabrication. The properties of the reinforcements, including specific strength and modulus, are listed in Table 6-2.

Fiber tensile strengths, as reported, are strongly influenced by the test procedure and the physical form of the fiber being tested, and results are often misleading. As an example, monofilament strengths are never attained in the composite. Unidirectional composites, tested at equivalent fiber volumes, provide more accurate evaluations of strength and modulus. Such values are presented in par. 6-2.5.1.

6-2.1.1 Fiberglass Reinforcements

In the United States fiberglass is made almost exclusively from E-glass (a lime-alumina-borosilicate glass) with limited production of S-glass (silica-alumina-magnesia glass) fiber. E-glass fiber is the most important reinforcement in the plastics/composites industry. S-glass has a somewhat higher strength and modulus but is more expensive; it is used mostly in high performance aerospace applications.

Fiberglass is produced as a continuous monofilament bundle by drawing molten glass through a multihole bushing. The size of the hole determines the fiber diameter. The diameters produced for composite use are shown in Table 6-3. The monfilaments are gathered into a single strand or end, which is the basic unit for the construction of other fiberglass products. The definitions for different strand groupings are as follows:

1. *Rovings*. A number of parallel ends without twist, gathered as a flat ribbon; rovings are designated by end count, such as 12, 20, 30, or *60* ends. Each end contains at least 204 monofilament and may contain 408, 612, or 816 monofilament. Recent practice is to disregard end count and number of monofilament and to designate roving by yield in yards per pound.
2. *Multifilament Strand.* A single end formed by drawing 2000 to 4000 monofilament from one bushing; this strand is used chiefly for filament winding or pultrusions.
3. *Chopped Strands.* Rovings are cut into uniform lengths usually not exceeding 50 mm (2 in.); chopped strands may be purchased from the fiberglass manufacturers or may be chopped from rovings during processing.
4. *Reinforcing Mat.* Mat is made from roving and is either chopped strand mat or continuous strand (swirled) mat. It is held together by a resinous binder, which dissolves in the resin during processing. Mats are designated by the weight per unit area, which ranges from 0.23 to 1.83 kg/m^2 (0.75 to 6 oz/ft^2).
5. *Yarns.* These are assemblages of strands suited for weaving. Yarn construction varies and may consist of "singles" or two or more plies with twist.
6. *Woven Fabrics (Broad Goods).* Various fabric styles are woven for use with reinforced plastics; typical constructions are shown in Table 6-4. Some fabrics are directional and contain more yarns in the warp direction (length) than in the fill (crosswise) direction.
7. *Woven Roving.* This is a plain weave fabric made from rovings. Weights range from 0.41 to 1.36 kg/m^2 (12 to 40 oz/yd^2).
8. *Nonwoven Fabrics (Broad Goods).* These fabrics are composed of parallel rovings held together by occasional transverse strands; in a second version, collimated rovings or strands are held together by a resin matrix. Fabrics in widths from 300 to 600 mm (12 to 24 in.) are known as broad goods. In widths from 75 to 300 mm (3 to 12 in.), they are known as tapes.

The fiberglass reinforcements, as is customary with other reinforcement types, are subjected to surface treatments to promote resin adhesion. Coupling agents are applied as a "size" or "finish" and are compatible with specific resin systems. Surface treatments and the resin/fiber interracial bond have a strong influence on composite strength retention, failure mechanisms, and moisture penetration. There are numerous reports in the literature dealing with the interface; specific sources are the annual conferences of the Society of the Plastics Industry (SPI) and Refs. 1 and 2.

6-2.1.2 Graphite Reinforcements

Most graphite fibers are produced by pyrolyzing polyacrylonitrile (PAN) fibers under tension at temperatures of 1760°-2760°C (3200°-5000°F) in a controlled atmosphere. The properties of the fibers are functions of the tension and temperature during pyrolysis. Typical properties indicate that as the elastic modulus is increased, the strength and ultimate elongation are decreased. The fibers are classifed roughly as low-cost,

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*The use of product names does not constitute an endorsement of the product or the company that manufactured the product by the US Army.

TABLE 6-2. COMPARATIVE PROPERTIES OF COMPOSITE REINFORCEMENTS

Reinforcement	Tensile Strength		Specific Tensile Strength		Elastic Moldulus		Specific Elastic Modulus		Elongation,	Density	
	GPa	psi × 10^3	MPa/(kg/m^3)	[psi (lb in.^{3})] × 10^6	GPa	psi × 10^6	MPa/(kg/m^3)	[psi/(lb/in.^{3})] × 10^6	%	kg/m^3	lb/in^3
E-glass											
Monofilament	3.45	500	1.35	5.4	72.4	10.5	28.4	11.4	4.8	2550	0.092
Strand	3.34	485	1.31	5.3							
Roving[1]	1.93	280	0.76	3.0							
Roving[2]	1.38	200	0.54	2.2							
S-glass											
Monofilament	4.59	665	1.84	7.4	86.9	12.6	34.9	14.0	5.3	2490	0.090
Strand	3.79	550	1.52	6.1							
Roving[3]	3.45	500	1.39	5.6							
Roving[4]	2.76	400	1.11	4.4							
Graphite											
Celion GY-70[5]	1.86	270	0.94	3.8	517	75.0	262	105.6	0.4	1970	0.071
Celion 3000[5]	2.76	400	1.56	6.3	234	34.0	132	53.1	1.2	1770	0.064
Magnamite AS[6]	3.10	450	1.69	6.8	234	34.0	128	51.5	1.3	1830	0.066
Magnamite HTS[6]	2.90	420	1.75	7.0	269	39.0	162	65.0	1.1	1660	0.060
Magnamite HMS[6]	2.21	320	1.21	4.8	365	53.0	199	80.3	0.6	1830	0.066
Thornel 300[7]	2.76	400	1.59	6.3	234	34.0	134	54.0	1.2	1740	0.063
Thornel P-55[8]	2.07	300	1.02	4.1	379	55.0	188	75.3	0.5	2020	0.073
Aramid											
Kevlar 49[9]	2.76	400	1.92	7.7	131	19.0	91.0	36.5	2.0	1440	0.052
Boron											
4 mil	3.45	500	1.33	5.3	400	58	154	61.7	0.9	2600	0.094
8 mil	3.65	530	1.08	4.3	400	58	118	47.5	0.9	3380	0.122
4 2 mil[10]	3.28	475	1.56	6.3	365	53	174	69.7	0.9	2100	0.076

[1] G. dia. MIL-R-60346

[2] Above G. dia. MIL-R-60346

[3] MIL-R-60346

[4] General purpose, MIL-R-60346

[5] Celanese Corp.

[6] Hercules, Inc.

[7] Union Carbide Corp.

[8] Union Carbide, pitch base

[9] I. E. Du Pont

[10] Carbon core

TABLE 6-3. FIBERGLASS FILAMENT DIAMETERS AND CODE DESIGNATION

Code	Diameter Range	
	μm	10^{-5} in.
D	5.1-6.4	20-25
DE	5.8-7.1	23-28
G	8.8-10.2	35-40
J	11.4-12.7	45-50
K	12.7 -14.0	50-55
M	15.2 -16.5	60-65
T	22.9 -24.1	90-95

high-strength (LHS), intermediate modulus (IM), or high modulus (HM). Fibers are marketed as continuous length tows consisting of filaments in multiples of 1000 up to 12,000 and designated as lk, 3k, 6k, etc. Fibers are also produced from a pitch precursor at lower cost, but also at lower strengths. Additional information on graphite reinforcements is given in Refs. 3 and 4.

High performance applications are mostly with LHS fiber, which offers the best balance of cost and properties. IM and HM fibers have low strains at failure, which limit their use. It is anticipated that pitch base fibers will find increased use in commercial grade applications.

Graphite reinforcements are also available as woven and nonwoven broad goods. Typical fabric constructions are listed in Table 6-5.

6-2.1.3 Aramid Reinforcements

Aramid is a generic term denoting a class of polyamide fibers produced by conventional textile spinning methods. Kevlar 49 is the only aramid fiber currently available for composite use. The fiber is characterized by a high tensile strength and modulus combined with a low density. Kevlar composites, however, exhibit low compressive strengths, a deficiency attributed to a poor resin-to-fiber bond.

Kevlar 49 rovings are produced in deniers of 4560 and 7100, with filament counts of 3072 and 7100, respectively. (Denier is a textile unit indicating the weight in grams of 9000 m of yarn or roving; it corresponds to yield in yards per pound, used in the fiberglass industry.) The yields for 4560 d and 7100 d are 979 yd/lb and 629 yd/lb, respectively.

Kevlar 49 fabrics are also available (Table 6-5) and are woven with yarns of 195d, 380d, and 1420 d (Ref. 4).

6-2.1.4 Boron Reinforcements

Continuous boron filament is manufactured by a deposition process in which the boron is deposited on a tungsten core. Fiber diameters, controlled by the deposition rate, are standardized at 0.10, 0.14, and 0.20 mm (0.004, 0.0056, and 0.008 in.). The fiber usually is supplied as a prepreg tape.

Although the fiber has excellent strength and modulus properties, its high cost limits the use to hybrid constructions with graphite reinforcements. Here the function of the boron is to provide increased bearing or compressive strength and localized stiffening.

In an attempt to reduce the production costs, boron has been deposited on a carbon substrate, which is less

TABLE 6-4. TYPICAL E-GLASS WOVEN FABRICS FOR REINFORCED PLASTICS

Style	Count[1]	Warp Yarn[2]	Fill Yarn[2]	Weave[3]	Weight	
					g/m^2	oz/yd^2
120	60 X 58	ECD 450-1/2	ECD 450-1/2	Crowfoot	108	3.2
143	49 X 30	ECE 225-3/2	ECD 450-1/2	4 HS	302	8.9
1543	49 X 30	ECG 150-2/2	ECD 450-1/2	4 HS	319	9.4
7743	120 X 20	ECDE 75-1/0	ECG 150-1/0	8 HS	346	10.2
181	57 X 54	ECE 225-1/3	ECE 225-1/3	8 HS	302	8.9
1581	56 X 54	ECG 150-1/2	ECG 150-1/2	8 HS	322	9.5
7781	56 X 54	ECDE 75-1/0	ECDE 75-1/10	8 HS	305	9.0

[1] warp yarn X fill yarn

[2] E = E-glass; C = continuous; D, DE, G = fiber diameter (see Table 6-3)
numbers: First set X 100 = yield, yd/lb; example, 450 = 45,000 yd/lb
Second set: numbers of strands twisted together/twisted strands plied together; example, 1/2 = one strand of two strands plied together
Note: 450 X 1/2 = <u>4500</u> yield/lb= 22,500 yd/lb

(1/2) - no. strands twisted together twisted strands plied together

[3] 4 HS = harness satin, 1 over 4
8 HS = harness satin, 1 over 8

TABLE 6-5. TYPICAL GRAPHITE, KEVLAR, AND HYBRID FABRICS

	Style	Count	Warp Yarn	Fill Yarn	Weave	Weight	
						g/m²	oz/yd²
Kevlar 49							
	120	34 X 34	195 d	195 d	Plain	61	1.8
	143	100 X 20	380 d	195 d	Crowfoot	190	5.6
	181	50 X 50	380 d	380 d	8 Harness satin	170	5.0
	243	38 X 18	1140 d	380 d	Crow foot	227	6.7
	328	17 X 17	1420 d	1420 d	Plain	231	6.8
	1050	28 X 28	1420 d	1420 d	4 X 4 basket	356	10.5
Graphite							
	—	24 X 24	T300-3K[1]	T300-3K	8 Harness satin		
	—	48 X 48	T300-1K	T300-1K	12 Harness		
	—	72 X 18	T50[2]	T50	Plain		
	—	36 X 0	T300-3K	Dacron tie	Unidirectional		
Hybrids							
	105	24 X 24	75% T300-3K 25% Kevlar 49, 1420 d	75% T300-3K 25% Kevlar 49, 1420 d	8 Harness satin	346	10,2
	107	24 X 24	50% T300-3K 50% Kevlar 49, 1420 d	50% T300-3K 50% Kevlar 49, 1420 d	8 Harness satin	329	9.7

[1] Thornel 300
[2] Thornel 50

expensive than the tungsten core. The boron-carbon version, however, is still considered a developmental material. (Refs. 3 and 4).

6-2.1.5 Hybrid Reinforcements

Reinforcements are combined at times to reduce cost, improve handling qualities or to compensate for a weakness in one of the reinforcements. Hybrids are constructed by interspersing plies of one material within the layered plies of another or by combining reinforcements in the warp or fill of fabrics and tapes. Examples are shown in Table 6-5. Other examples are dry, woven boron tape with nylon or fiberglass in the fill direction.

6-2.1.6 Miscellaneous Reinforcements

Reinforcements, such as cotton, paper, asbestos, or nylon, are used in combination with phenolic, silicone, or epoxy resins. These reinforcements may be in the form of woven fabrics, cotton ducks, felts, or flocks. Nylon/phenolic and asbestos/phenolic have been used in heat-resistant or ablative applications. Cotton, paper, and asbestos materials are fabricated into sheet stock, rods, or tubes and can be purchased as finished (molded) products.

6-2.2 RESIN SYSTEMS

The physical properties, processing characteristics, and comparatively low cost of the polyester, vinylester, and epoxy resins have led to their acceptance as the principal matrix materials for the composites. These resins are supplied as low viscosity liquid systems that can be adjusted to meet a variety of fabrication conditions. Their curing mechanisms permit relatively fast cures at ambient or elevated temperatures and at low molding pressures. Curing occurs by addition reactions without the evolution of volatile by-products. Each resin type can be formulated for the enhancement of specific properties or a combination of properties. Available commercial variations include flame-retardant, impact, heat, and corrosion-resistant grades.

Polyesters and the somewhat similar vinylesters are used most frequently and comprise over 80% of the total reinforced plastic production. (See Table 6-6.) The application of epoxies in commercial grades is limited. In aircraft and other high performance composites, the preference is reversed and epoxies are the major resin system. Polyester or vinyl ester usage in aerospace is rare.

Other thermosetting resins—phenolics, polyimide, and silicone–are limited to specific elevated tempera-

TABLE 6-6. RESIN CONSUMPTION FOR REINFORCED PLASTICS IN 1977 (Ref. 5)

Resin	Tonne X 10^3	lb X 10^6	Total, %
Polyester	369	814	82.6
Epoxy	22	48	4.9
Phenolic	41	90	9.1
Urea[2].	15	33	3.4
Total	447	985	100.0

[1] Includes vinyl esters
[2] Includes melamines

Source: SPI *Facts and Figures of the US Plastics Industry — 1982* Edition.

TABLE 6-7. PROPERTIES OF CURED POLYESTER, VINYL ESTER, AND EPOXY LAMINATING RESINS

Property	Polyester	Vinyl Ester	Epoxy
Tensile strength			
M Pa	55.2-82.7	62.1-82.7	41.2-107.7
10^3 psi	8.0-12.0	9.0-12.0	6.1-15.6
Tensile modulus			
GPa	2.7-3.4	3.1-3.4	2.1-3.4
10^5 psi	3.9-5.0	4.5-5.0	3.0-5.0
Maximum strain			
%	4.0-12.0	4.5-7.0	1.5-8.0
Water absorption			
%	0.1-0.3	0.1-0.3	0.4-1.5
Heat deflection temprature			
°C	104-121	104-121	135-177
°F	220-250	220-250	275-350

ture or electrical applications. These resins are furnished as solvent solutions or "varnishes" and can be processed only as B-staged (partially cured) preimpregnated materials (prepregs), In addition, these resins cure by condensation reactions (excepting one polyimide type) and release volatiles that must be removed during molding. Pressure requirements are greater than for the addition-type resins.

A recent development is the application of polysulfone or polyarylsulfone thermoplastics to high performance composites. The advantages of these resins are an increased resistance to moisture penetration at elevated temperatures and reduced molding times because no chemical curing reactions are involved.

Thermoplastic stamping compounds, currently limited to polypropylene or nylon 6, are used in commercial applications. These materials are supplied in sheet form containing varying amounts of continuous fiberglass, chopped glass, and other additives. Components are fabricated by melt flow stamping, essentially compression molding, in which reduced cycle times are achieved compared to the curing of thermoset resins. (The mechanical properties of polyester, vinyl ester, and epoxy resins are shown in Table 6-7.)

6-2.2.1 Polyester Resins

The liquid polyester resins for reinforced plastics are solutions of a prepolymer in a reactive monomer. The prepolymer and monomer combine during cure to form the solid resin. The catalyst type used in the reaction determines the curing temperature. For example, a mixture of methyl ethyl ketone peroxide (MEKP) with cobalt naphthanate (CON) is a typical ambient temperature catalyst system. Tertiary-butyl perbenzoate, alone or combined with benzoyl peroxide (BPO), initiates cures at 95°-150°C (200°-300°F). Viscosity is varied by the amount of monomer in the solution as dictated by the fabrication requirements. Alternatively, viscosity can be controlled by the addition of thixotropic agents or inorganic fillers. Resin properties are modified by variations in the chemical structure of the prepolymer and, to a lesser degree, by the monomer type. The resin may contain pigments, extenders, ultraviolet absorbers, or flame retardants. Mold shrinkage is relatively high, i.e., 7-10% for unmodified resins. Small amounts of thermoplastic resins are sometimes added to reduce this shrinkage. Maximum operational temperatures for continuous service of items containing polyester resins are from 95°- 105°C (200°-225° F). More detailed information about polyesters is given in Refs. 2 and 6.

6-2.2.2 Vinyl Esters

Although the vinyl ester resins differ from the polyesters in chemical structure, they are cured by the same catalyst systems and are also furnished as solutions in liquid monomers. Viscosity is controlled in the same manner as the polyester, and the mechanical properties of the two resin types are equivalent. The principal use of the vinyl ester resins is in corrosion-resistant applications. Newer versions do not contain monomers, but they are cured by the same catalysts. The advantage is that air pollution by monomer vapors is avoided; the disadvantage is that processing viscosity is harder to control.

6-2.2.3 Epoxy Resins

Traditionally, epoxies have been used in aircraft, space, and military applications, which tend to be strength and weight critical. Selection of this resin rather than cheaper polyesters is justified by its superior mechanical properties, fatigue resistance, heat resistance, stronger bond to reinforcements, and lower curing shrinkage. A history of satisfactory performance and reliability has been the decisive factor favoring the continued use of epoxies in high performance composites.

Conventional epoxy, the diglycidyl ether of bisphenol-A (DGEBA), is the most important polymer type. Epoxy novolacs are used less frequently. Other available types include brominated epoxies for improved ignition resistance, resorcinol ethers for extended processibility, and flexible epoxies for impact resistance and greater elongations.

Although cures are possible at ambient temperatures, most epoxy systems are cured at elevated temperatures from 120°-175°C (250°-350°F) to obtain optimum properties. A variety of curing agents and catalysts are available. Of these nadic methylanhydride (NMA) and metaphenylene diamine (MPDA) are the most popular. Cured properties vary with the type of curing agent.

Most epoxy systems can be obtained as liquids. Viscosity is controlled by the addition of reactive diluents or by applying heat. Too viscous a resin causes fuzzing of the reinforcements, uneven fiber coating, and entrapment of air. If the system is too fluid, resin migration and nonuniform distribution of the resin are apt to occur. A complete discussion of epoxy resin systems can be found in Ref. 7.

6-2.2.4 Polyimide Resins

The polyamides currently in use with high performance composites include addition- and condensation-type resins. An addition-type system, based on bismaleimide, is capable of service temperatures in the 125°-230°C (260°-450°F) range. Bismaleimide based resins can be cured at about 175°C (350°F) but require a higher temperature postcure. Other addition-type polyamides are available for service temperatures up to 315°C (600°F) and are cured at 315°C (600°F) and at higher pressures than are necessary for epoxy systems. A condensation-type polyimide, press cured at 370°C (700°F) has a service life above 315°C (600°F). As a general rule, the polyamides are more difficult to process than the epoxies because they are characterized by high melt temperatures and low volubility. Also they are processed as prepregs and require closely controlled B-staging (partial curing), curing, and posturing to insure the production of sound composites (Ref. 3).

6-2.3 PREIMPREGNATED MATERIALS

Preimpregnated materials, or prepregs, are combinations of a reinforcement and a complete resin system in a condition ready for molding. Available prepregs include woven or nonwoven fabrics, tapes, mats, and rovings coated with epoxy, polyimide, polyester phenolic, or silicone resins. All of the principal reinforcing agents, i.e., fiberglass, graphite, Kevlar 49, and boron can be prepreged.

Prepregs are manufactured by a specialized group of processors who also act as suppliers. Continuous webs of reinforcement are passed through a resin solution containing the appropriate curing agents, catalysts, and other additives. The coated materials are oven dried to remove solvents and partially cure, or B-stage, the resin. Controlled solvent removal and B-staging are required to produce a prepreg with proper “tack” and flow for molding. Some of the heat-resistant epoxies and polyamides are solid resins and are combined with the reinforcement by a hot melt roller application. Shelf life of the prepregs normally ranges from six months to a year, and refrigeration may be necessary to prevent resin reaction.

The main advantages of the prepregs are that they provide closer control of the resin content, a more uniform resin distribution, and are more likely to produce void-free laminates. Closely controlled and standardized prepregs have been developed for the high performance aerospace components. Practically all aerospace composites are fabricated from prepregs. The additional cost of impregnation, however, precludes their use in most commercial grade molding.

6-2.4 METAL MATRIX COMPOSITES

Up to this point, only resin matrix composites have been considered. In this paragraph, a second type, the fiber-reinforced, metal matrix composite is briefly reviewed. Complete discussions are given in Refs. 3, 8, and 9.

Of the existing metal matrix composites, boron/aluminum appears to offer the greatest potential. Tapes or broad goods of continuous boron fiber with aluminum are produced by attaching the boron to aluminum foil either by plasma-sprayed aluminum or by fugitive organic binders. The tapes or broad goods are then cut into plies, stacked, and oriented as required before being formed into the desired configuration by diffusion bonding. Other processes, such as brazing, can be used to consolidate the plies into finished parts. In these cases, the conventional boron filament is replaced by a silicon-carbide-coated boron (Borsic) since uncoated boron is degraded by contact with molten aluminum.

In general, the high cost of the metal matrix composites has discouraged their use, particularly in Army applications. Typical products made from metal matrix composites are turbine engine parts such as blades and vanes.

6-2.5 COMPOSITE PROPERTIES

Composite evaluations normally are based on their mechanical properties; chemical, electrical, and thermal properties are secondary considerations. Specific strength and modulus values cannot be assigned to a composite as is the case with metals. The numerous variables associated with composites necessitate that each material be examined separately with regard to the reinforcement and the resin matrix. Analytical procedures have been developed to determine the theoretical strength and stiffness of a composite by using existing elastic theory. These values are adequate for comparative purposes and for preliminary calculations in structural design equations.

The theoretical values apply to the filamentary composites only. Methods for treating the short fiber composites are not developed sufficiently to be used with confidence. Properties for the short fiber materials must be determined experimentally. Strength and modulus properties are most useful when determined as functions of the fiber volume in the composite.

6-2.5.1 Filamentary Composites

The basic structural unit for the filamentary composites is the monolayer made from nonwoven broad goods or tapes and consisting of filaments in a parallel array as shown in Fig. 6-1. The fiber spacing is relatively uniform, and a fixed number of filaments is contained per unit of width. The monolayer is anisotropic, i.e., the mechanical properties vary with the direction of applied loads. Maximum strength and modulus of elasticity are in the longitudinal (fiber) direction and are minimum in the transverse (perpendicular to the fiber) direction. Other laminates consisting of any number of plies are constructed from the monolayer. The following ply combinations are identified:

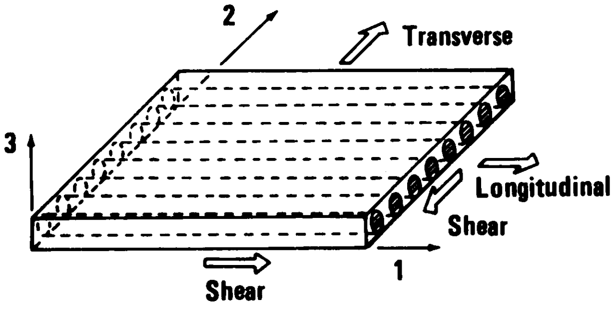


Figure 6-1. Schematic of a Single Ply (Ref. 10)

1. *Unidirectional Laminate. A* number of monolayer plies, all in a longitudinal direction

2. Angle-Ply *Laminate.* Two or more monolayer alternately oriented at plus and minus an angle θ as shown in Fig. 6-2

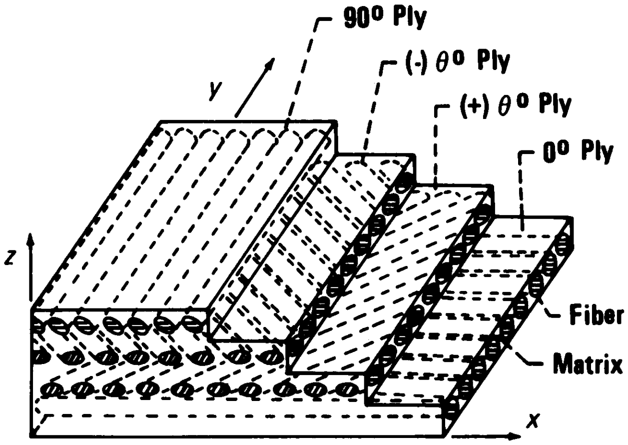


Figure 6-2. Schematic of an Angle-Ply Laminate (Ref. 10)

3. *Cross-Ply (Orthotropic) Laminate.* An angle-ply laminate in which the plies are at right angles to each other (0°, 90°)

4. *Quasi-Isotropic Laminate.* An angle-ply laminate consisting of several pairs of plies at several different angles so that the directional properties are no longer distinguishable and it approaches an isotropic material. For example, two pairs of plies, one at 0°, 90° and the other at ± 45°, would constitute the minimum number of plies for isotropy; adding two more pairs at ± 30° and ± 60° would bring the laminate closer to isotropy. Isotropy exists only in the plane of the laminate and not in the thickness direction.

5. *Balanced Laminate.* A laminate containing a symmetrical plying order in which the ply sequence forms a mirror image about the midplanes; an example is a plying order of 45°, 135°, 0°, 90°, 90°, 0°, 135°, 45°.

The mechanical properties of the monolayer are determined experimentally, and these values are used to calculate the properties of multilayered laminates containing plies at various orientations. The empirical values include the longitudinal and transverse tensile modulus, the shear modulus, Poisson's ratios, the tensile failure stresses in the longitudinal and transverse directions, and the shear failure stress. In some cases, the stresses and moduli for compressive loading are included as well. When not determined, compressive stress is assumed to have the same value as tensile stress. The shear stress is for in-plane loading and is designated at times as intralaminar shear. The monolayer properties of the principal reinforcing agents with epoxy and polyimide resin are listed in Table 6-8.

The "transformation equations", based on well-established elastic theory, permit the calculation of the elastic constants (moduli and Poisson's ratio) for angle-ply (± θ) laminates. Such results are shown graph-

TABLE 6-8. TYPICAL PROPERTIES OF UNIDIRECTIONAL FIBER COMPOSITES AT ROOM TEMPERATURE (Ref. 10)

Property	Reinforcement	Boron	Boron	Fiberglass	Graphite[1]	Graphite[1]	Graphite[1]	Kevlar 49
	Resin	Epoxy	Polyimide	Epoxy	Epoxy	Polyimide	Epoxy	Epoxy
Fiber volume, %		50	49	72	45	45	70	54
Specific gravity		2.02	1.99	2.13	1.55	1.55	1.61	1.36
Longitudinal modulus								
GPa		201	221	61	190	216	181	84
10^6 psi		29.2	32.1	8.8	27.5	31.3	26.3	12.2
Transverse modulus								
GPa		22	14	25	7	5	10	5
10^6		3.2	2.1	3.6	1.0	0.7	1.5	0.7
Shear modulus								
GPa		5.4	7.7	12.0	6.2	4.5	6.9	2.8
10^6 psi		0.78	1.11	1.74	0.90	0.65	1.00	0.41
Major Poisson's ratio		0.17	0.16	0.23	0.10	0.25	0.28	0.32
Minor Poisson's ratio		0.02	0.02	0.09	—	0.02	0.01	0.02
Tensile strength, longitudinal								
MPa		1372	1041	1289	841	807	1503	1186
10^3 psi		199	151	187	122	117	218	172
Compressive strength, longitudinal								
MPa		1600	1089	820	883	655	1703	290
10^3 psi		232	158	119	128	95	247	42
Tensile strength, transverse								
MPa		56	11	46	42	15	41	11
10^3 psi		8.1	1.6	6.7	6.1	2.2	5.9	1.6
Compressive strength, transverse								
MPa		123	63	174	197	70	246	65
10^3 psi		17.9	9.1	25.3	28.5	10.2	35.7	9.4
Intralaminar shear								
MPa		63	26	45	61	22	68	28
10^3 psi		9.1	3.8	6.5	8.9	3.2	9.8	4.0

[1] Modmor

[2] Thornel 300

ically for S-glass, graphite, and Keviar 49 with epoxy in Figs. 6-3, 6-4, and 6-5, respectively. Properties of the multilayered laminates are established by combining the properties of the angle-ply layers within the laminate. Carrying the calculations farther, laminate failure stresses can be approximated by using one of several failure criteria. With the "maximum stress first ply failure" criterion, the laminate fails when a ply stress equals the corresponding uniaxial strength for that material. The stresses are readily obtained from the elastic constants of the ply by assuming a maximum allowable strain somewhat below the failure strain of the monolayer. All possible failure modes must be examined. For example, a ply that has sufficient strength in the longitudinal direction may fail in the transverse direction as in intralaminar shear induced by a tensile load.

Computer programs are available for solving transformation equations and for calculating the properties of any multilayered laminate. These programs can handle laminates made from two or more different monolayer. Details of one such program may be found in Ref. 11; a simplified method that can be solved using a pocket calculator is described in Ref. 10. Table 6-9 lists the properties of angle-ply laminates of E-glass, S-glass, graphite, and Kevlar 49 with epoxy. These

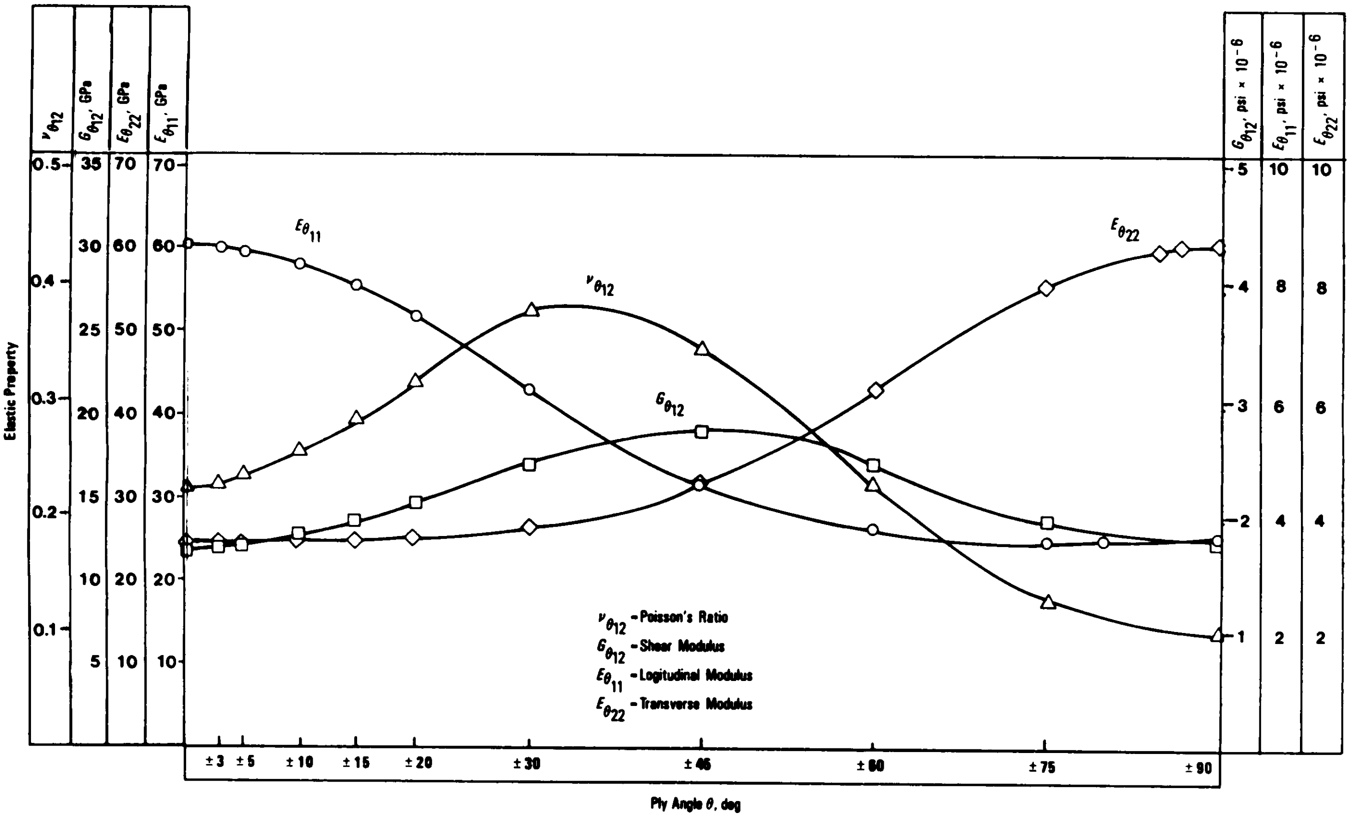


Figure 6-3. Elastic Properties of S-Glass Fiber/Epoxy $\pm\theta$ Laminates (Ref. 10)

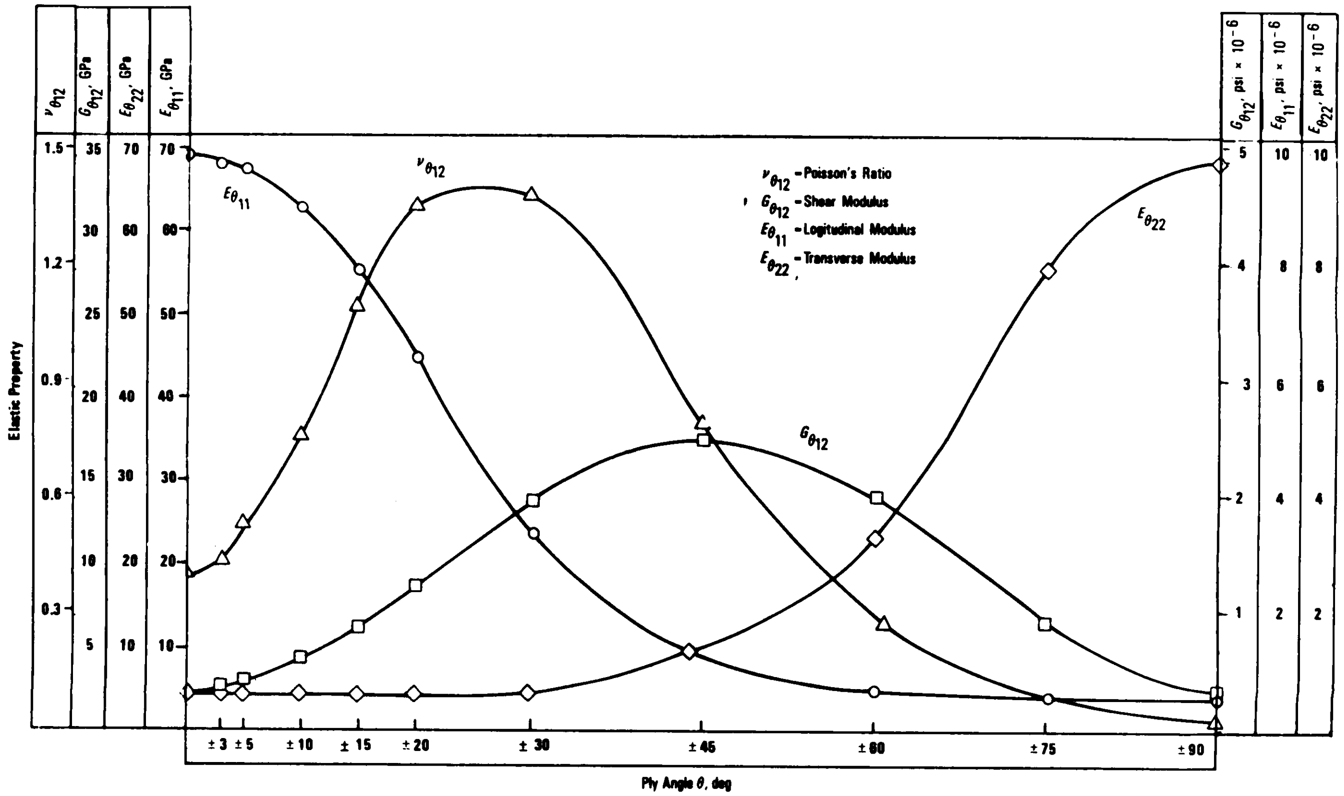


Figure 6-4. Elastic Properties of Kevlar Fiber/Epoxy $\pm\theta$ Laminates (Ref. 10)

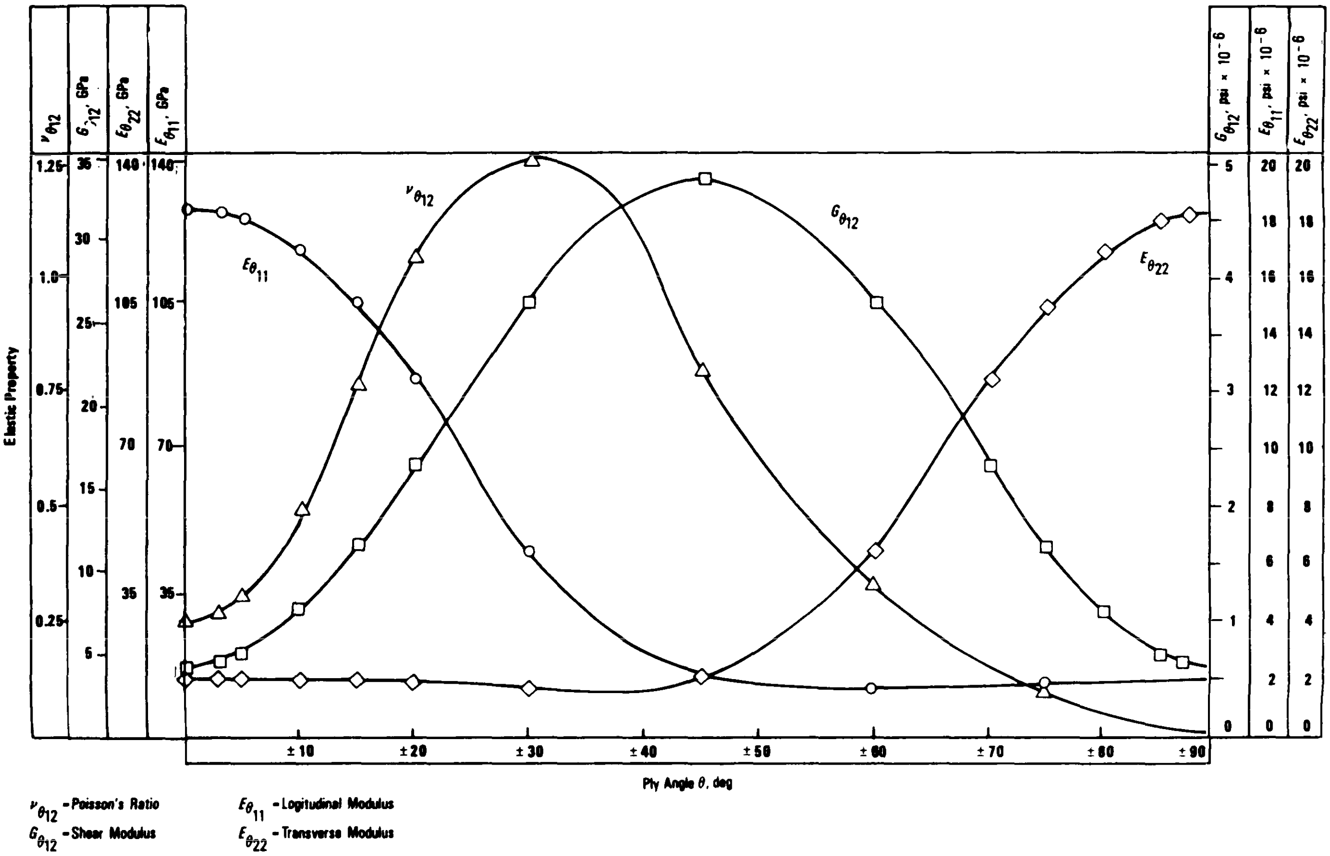


Figure 6-5. Elastic Properties of Graphite Fiber/Epoxy $\pm\theta$ Laminates (Ref. 10)

results are from a computer program and are taken from a different source than those shown in Figs. 6-3, 6-4, and 6-5. The monolayer strength and elastic properties for each material are given at 0 = 0°. When 0 exceeds 45°, the properties in the longitudinal and transverse direction are reversed, i.e., the longitudinal modulus *Ex* for 0 = 60° is the same as the transverse modulus *Ey* for 0 = 30°. In this program the transverse strength properties were assumed to be negligible at 0° and are listed as zero at that angle. A second point to be noted is that the values listed are for a fiber volume of 50%. Different values would be required for other fiber contents. Derivation of the basic equations and a full treatment of lamination theory are presented in Refs. 12, 13, and 14.

Woven fabrics essentially are orthotropic although some fabrics may have directional properties due to the construction of the weave. In both cases properties are determined experimentally, preferably in the 0° and 90° directions. Properties at other directions can be calculated by the transformation equations. The accepted practice is to test a specific prepreg system at a specified resin content. Data from one system usually are not applicable to other systems even though they may contain comparable resins and curing agents. Available data for such systems are limited. Typical data may be found in Military Handbook (MIL-HDBK) 17 (Ref. 12) or may be obtained from prepreg and resin suppliers. Properties of one system, an epoxy with a style 7781 fiberglass fabric, are summarized in Table 6-10 and Fig. 6-6.

Tensile stress-strain curves for various unidirectional laminates are shown in Fig. 6-7. The elastic response indicates linear behavior to failure. However, in compression, flexure, or shear, nonlinearity is evident. Bidirectional or multidirectional laminates constructed either from monolayer or woven fabrics also exhibit a nonlinear response. These stress-strain curves have an initial linear portion followed by secondary and sometimes tertiary inflection points or “knees”. A stress-strain curve of this type is illustrated in Fig. 6-8 for a quasi-isotropic laminate. Slope changes at two points of this curve are attributed to a resin debonding of the 90° fibers, followed by debonding of the 45° fibers. These manifestations do not necessarily imply a failure of the laminate either in intermittent or-cyclic loadings; the laminate is still capable of sustaining loads. Loading cycles may be repeated up to approximately 80% of the failure load without significant changes in the stress-strain curve.

TABLE 6-9. PROPERTIES OF ± Θ ANGLE-PLY LAMINATES AT 50% FIBER VOLUME (Ref. 15)

Θ	Ex		Ey		Gxy		Fxt		Fyt		Fxc		Fyc		Fxy		Uxy	Uyx
deg	GPa	10^6 psi	GPa	10^6 psi	GPa	10^6 psi	MPa	10^3 psi	MPa	10^3 psi	MPa	10^3 psi	MPa	10^3 psi	MPa	10^3 psi		
E-Glass/Epoxy—Specific Gravity 1.85																		
0	37.9	5.5	12.4	1.8	2.1	0.3	951.5	138	0	0	641.2	93	199.9	29	41.4	6	0.29	0.09
10	35.2	5.1	11.7	1.7	2.8	0.4	813.6	118	4.1	0.6	599.8	87	193.1	28	68.9	10	0.38	0.13
20	27.6	4.0	10.3	1.5	5.5	0.8	558.5	81	20.7	3	475.7	69	172.4	25	117.2	17	0.63	0.23
30	16.5	2.4	7.6	1.1	9.0	1.3	344.7	50	55.2	8	289.6	42	131.0	19	179.3	26	0.86	0.42
40	8.3	1.2	6.2	0.9	11.0	1.6	199.9	29	110.3	16	144.8	21	110.3	16	213.7	31	0.87	0.66
45	6.2	0.9	6.2	0.9	11.0	1.6	151.7	22	151.7	22	117.2	17	117.2	17	220.6	32	0.78	0.78
S-Glass/Epoxy—Specific Gravity 1.83																		
0	44.8	6.5	12.4	1.8	2.1	0.3	1123.8	163	0	0	744.6	108	206.8	30	34.5	5	0.29	0.08
10	42.1	6.1	11.7	1.7	3.4	0.5	937.7	136	5.5	0.8	696.4	101	193.1	28	68.9	10	0.40	0.11
20	32.4	4.7	10.3	1.5	6.2	0.9	613.6	89	20.7	3	544.7	79	172.4	25	131.0	19	0.68	0.22
30	18.6	2.7	8.3	1.2	10.3	1.5	365.4	53	55.2	8	317.2	46	131.0	19	199.9	29	0.93	0.41
40	8.3	1.2	6.2	0.9	12.4	1.8	206.8	30	117.2	17	144.8	21	103.4	15	248.2	36	0.91	0.67
45	6.9	1.0	6.9	1.0	13.1	1.9	158.6	23	158.6	23	110.3	16	110.3	16	255.1	37	0.80	0.80
Kevlar 49/Epoxy—Specific Gravity 1.30																		
0	66.9	9.7	5.5	0.8	1.4	0.2	1123.8	163	0	0	241.3	35	20.7	3	6.9	1	0.29	0.02
10	61.4	8.9	5.5	0.8	3.4	0.5	841.2	122	3.4	0.5	220.6	32	20.7	3	20.7	3	0.63	0.05
20	42.7	6.2	4.8	0.7	8.3	1.2	468.8	68	13.8	2	158.6	23	20.7	3	48.3	7	1.34	0.15
30	20.0	2.9	4.8	0.7	13.8	2.0	248.2	36	34.5	5	75.8	11	13.8	2	82.7	12	1.50	0.34
40	8.3	1.2	4.8	0.7	17.2	2.5	131.0	19	68.9	10	27.6	4	20.7	3	103.4	15	1.09	0.64
45	6.2	0.9	6.2	0.9	17.2	2.5	96.5	14	96.5	14	20.7	3	20.7	3	110.3	16	0.85	0.85
Graphite/Epoxy—Specific Gravity 1.44																		
0	118.6	17.2	6.2	0.9	3.4	0.5	1123.8	163	0	0	744.6	108	34.5	5	27.6	4	0.29	0.02
10	108.9	15.8	6.2	0.9	6.9	1.0	889.4	129	4.1	0.6	682.6	99	41.4	6	55.2	8	0.77	0.04
20	81.4	11.8	6.2	0.9	14.5	2.1	530.9	77	20.7	3	475.7	69	41.4	6	103.4	15	1.57	0.14
30	36.5	5.3	7.6	1.1	23.4	3.4	296.5	43	41.4	6	234.4	34	48.3	7	186.2	27	1.55	0.31
40	17.2	2.5	9.7	1.4	29.6	4.3	158.6	23	89.6	13	110.3	16	62.1	9	248.2	36	1.04	0.60
45	12.4	1.8	12.4	1.8	30.3	4.4	117.2	17	117.2	17	82.7	12	82.7	12	255.1	37	0.80	0.80

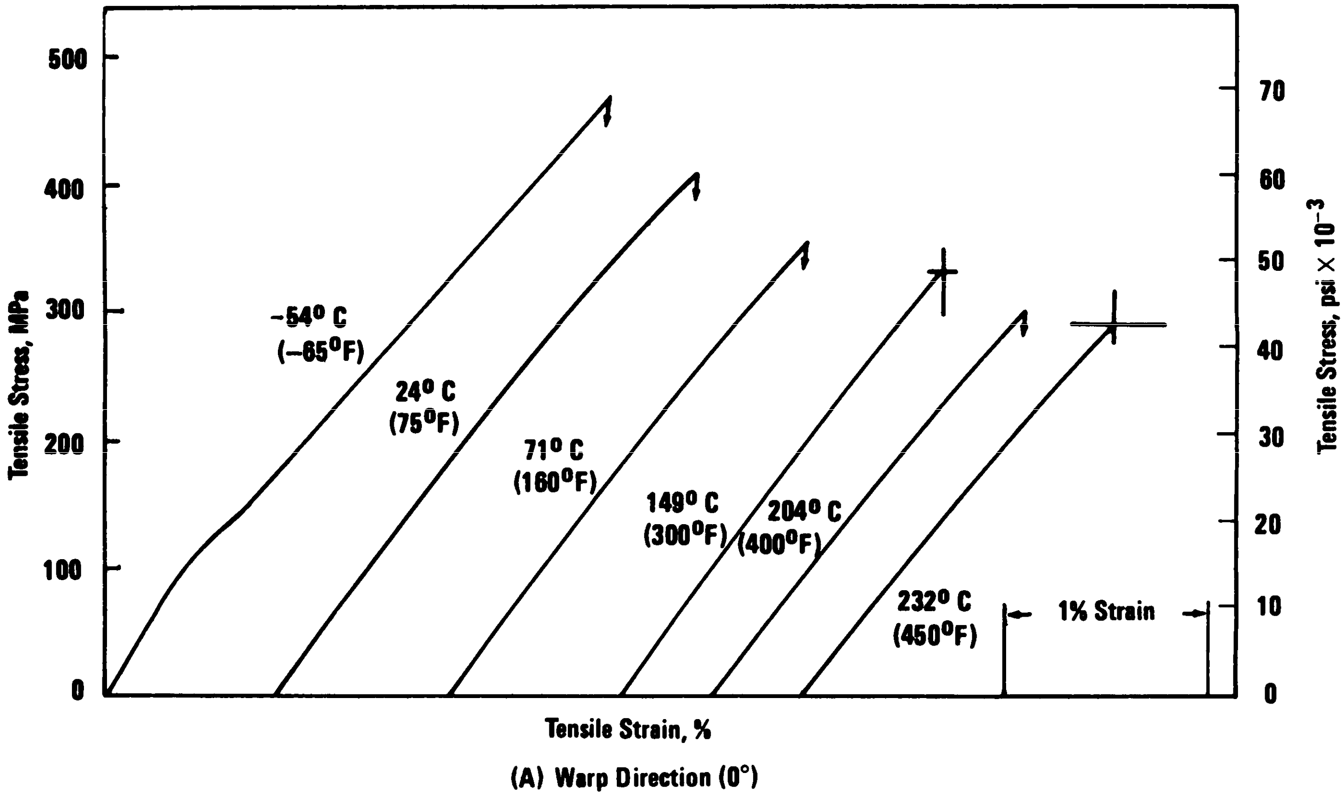
Ex = Longitudinal Modulus
Ey = Transverse Modulus
Gxy = Shear Modulus

Fxt = Tensile, Ultimate, Longitudinal
Fyt = Tensile, Ultimate, Transverse
Fxc = Compression, Ultimate, Longitudinal
Fyc = Compression, Ultimate, Transverse

Fxy = In-Plane Shear
Uxy = Major Poisson's Ratio
Uyx = Minor Poisson's Ratio

TABLE 6-10. MECHANICAL PROPERTIES OF EPOXY/FIBERGLASS FABRIC (US POLYMERIC E-720-E RESIN, STYLE 7781 FABRIC) (Ref. 12)

Temperature	−54°C (−65°F)	24°C (75°F)		71°C (160°F)		204°C (400°F)
Condition	Dry	Dry	Wet	Dry	Wet	Dry
Tension						
Ultimate, MPa, (10^3 psi) 0°	477.1 (69.2)	416.4 (60.4)	384.0 (55.7)	362.0 (52.5)	295.8 (42.9)	308.9 (44.8)
90°	386.1 (56.0)	337.8 (49.0)	316.5 (45.9)	291.6 (42.3)	254.4 (36.9)	240.6 (34.9)
Ultimate strain, % 0°	2.93	2.43	2.12	2.05	1.61	1.80
90°	2.92	2.33	2.04	1.98	1.70	1.72
Initial modulus, GPa, (10^6 psi) 0°	22.8 (3.3)	21.4 (3.1)	21.4 (3.1)	20.7 (3.0)	19.3 (2.8)	17.9 (2.6)
90°	20 (2.9)	19.3 (2.8)	19.3 (2.8)	17.2 (2.5)	18.6 (2.7)	15.9 (2.3)
Secondary modulus, GPa, (10^6 psi) 0°	15.9 (2.3)	17.2 (2.5)	17.2 (2.5)	17.2 (2.5)	16.5 (2.4)	—
90°	13.1 (1.9)	14.5 (2.1)	15.2 (2.2)	13.8 (2.0)	13.8 (2.0)	—
Compression						
Ultimate, MPa, (10^3 psi) 0°	531.6 (77.1)	446.8 (64.8)	395.1 (57.3)	372.3 (54.0)	318.5 (46.2)	164.1 (23.8)
90°	394.4 (57.2)	346.1 (50.2)	311.6 (45.2)	281.3 (40.8)	249.6 (36.2)	101.4 (14.7)
Ultimate strain, % 0°	2.48	2.14	1.99	1.86	1.62	1.12
90°	1.93	1.70	1.58	1.46	1.37	0.91
Initial modulus GPa (10^6 psi) 0°	24.1 (3.5)	22.8 (3.3)	21.4 (3.1)	22.1 (3.2)	20.7 (3.0)	17.3 (2.5)
90°	22.1 (3.2)	22.1 (3.2)	20.7 (3.0)	20.7 (3.0)	20.0 (2.9)	13.1 (1.9)
Shear						
Ultimate, MPa, (10^3 psi) 0°	120.7 (17.5)	98.6 (14.3)	—	77.2 (11.2)	—	—
Flexure						
Ultimate, MPa, (10^3 psi) 0°	797.0 (115.6)	632.2 (91.7)	—		—	—
Initial modulus, GPa, (10^6 psi) 0°	20 (2.9)	22.1 (3.2)	—		—	—
Bearing						
Ultimate, MPa, (10^3 psi) 0°	510.9 (74.1)	419.2 (60.8)	—		—	—
Interlaminar Shear						
Ultimate, MPa, (10^3 psi)	49.0 (7.1)	40.6 (5.9)	—		—	—



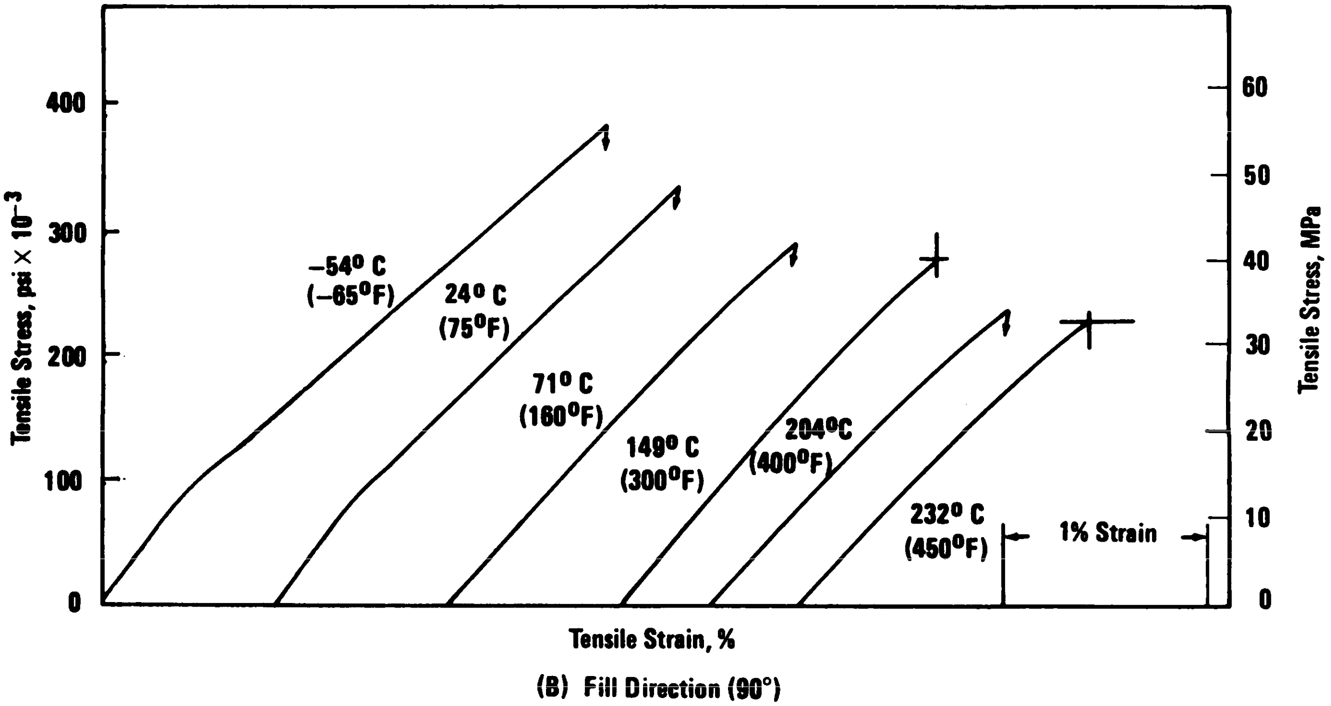


Figure 6-6. Tensile Stress-Strain for a Fiberglass (7781 Fabric)/Epoxy (Warp and Fill Directions) At Several Temperatures (Ref. 12)

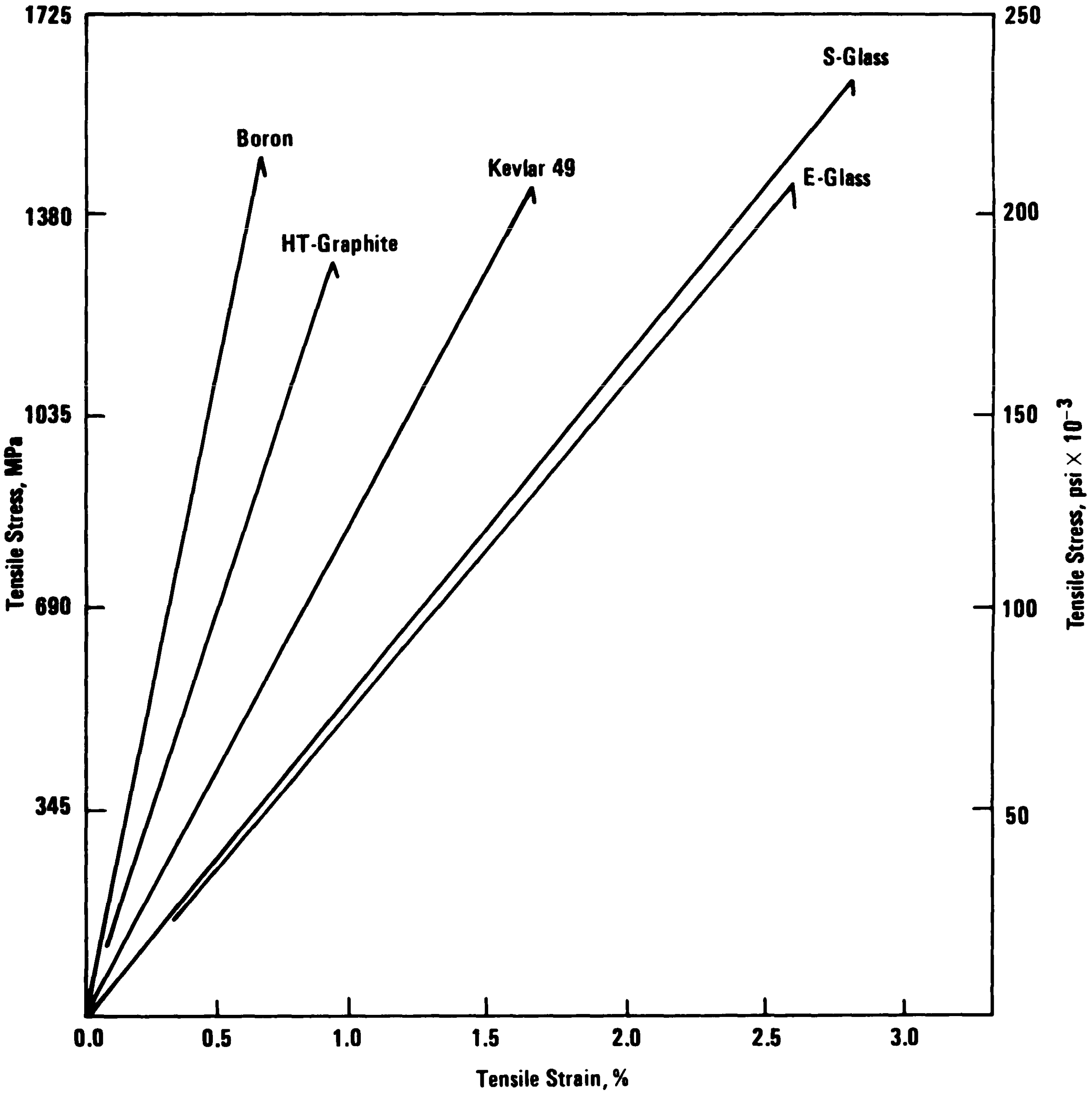


Figure 6-7. Unidirectional Composites Stress-Strain at 60% Fiber Volume (Epoxy Resin)

The effect of increased temperature on the properties and stress-strain relations is shown in Table 6-10 and Fig. 6-6. Such changes resulting from the viscoelasticity of the resin can be expected in all composites. An increased loading rate results in a more brittle response as noted in Fig. 5-2, and creep behavior follows the patterns indicated in Fig. 5-3b. As a general rule, the effects of viscoelasticity are less marked with the fibrous composites, especially when the resin is a thermoset, than would be expected for other plastic materials.

Composite strength and stiffness increase as the amount of reinforcing agent is increased. The limiting factor for the maximum fiber content is the processibility of the composites; some processes tolerate greater amounts of reinforcement than others. For example, filament winding permits the highest fiber loadings. Insufficient resin leads to higher voids content and, consequently, lower interlaminar shear strength (ply separation), Excess resin results in nonuniform laminate thickness and poor reproducibility. Fiber and resin contents are more meaningful when expressed as volume fractions. Property comparisons of composites constructed from different reinforcements should be made at equal fiber volume fractions. All properties are

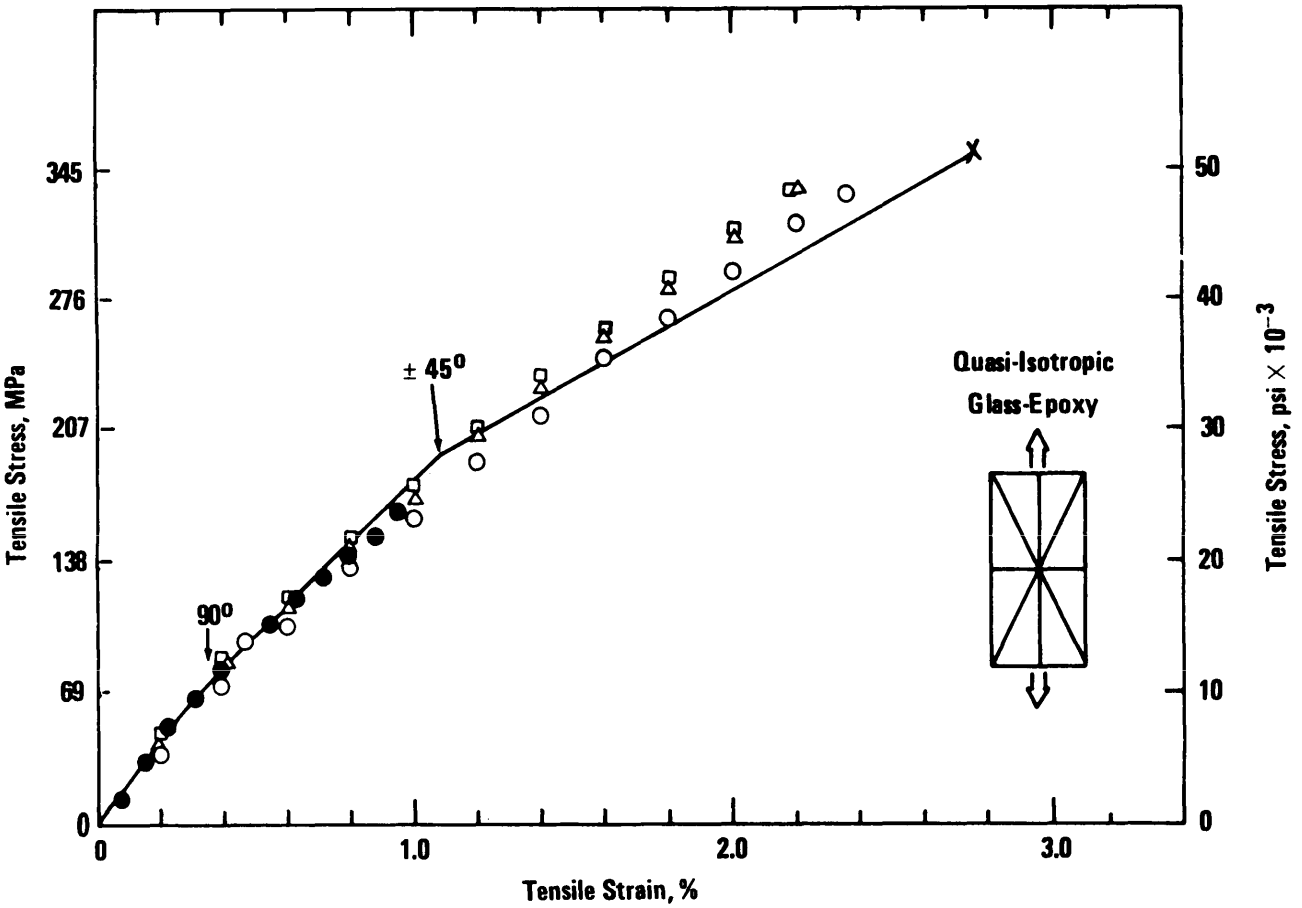


Figure 6-8. Stress-Strain for a Quasi-Isotropic Laminate With a Maximum Strain Theory Prediction (Ref. 16)

not optimum at the same fiber volumes. To illustrate this point, tensile strength increases linearly with fiber content; compressive strength will increase in a similar manner, but at a certain fiber content it will reach a maximum. Experience has shown that an optimum balance of structural properties is obtained at fiber volumes as listed in Table 6-11 and with void contents not in excess of 2%.

Fiber weight fractions are used frequently in expressing fiber contents. The weight fraction W_f is related to the volume fraction V_f in the following manner:

$$W_f = \frac{V_f \times G_f}{V_f \times G_f + (1 - V_f)\, G_r} \qquad (6\text{-}1)$$

where

V_f = volume fraction of fiber
G_f = specific gravity of fiber
G_r = specific gravity of resin
W_f = weight fraction of fiber.

TABLE 6-11. RECOMMENDED REINFORCEMENT CONTENTS FOR OPTIMUM FILAMENTARY COMPOSITES

Reinforcement	Volume Fraction
1. Boron on fiberglass carrier (scrim) (style 104 fabric)	0.50
2. Bidirectional woven fabrics	0.55
3. Directionally woven fabrics	0.60-0.65
4. Crossplied woven fabrics	0.55-0.60
5. Nonwoven unidirectional broad goods	0.65
6. Crossplied nonwoven broad goods	0.60-0.65

6-2.5.2 Short Fiber Composites

The short fiber composites most frequently used are combinations of fiberglass and polyester resins. Occasionally, graphite or Kevlar 49 reinforcements and epoxy resins are used in applications requiring increased strength or rigidity. The fiberglass/polyester composites include sheet molding compounds (SMC), bulk molding compounds (BMC), thick molding compounds (TMC), and composites fabricated by such methods as spray up, preform molding, and centrifugal casting, in which roving is cut into short lengths during, processing.

The fiber distribution in these composites is random or nearly random. Although a slight fiber orientation may occur during molding, the composite is considered isotropic for all practical purposes. Strength and stiffness are uniform in all loading directions.

Several methods have been developed to predict the elastic constants and failure stresses of short fiber composites and are based on adaptations of lamination and elastic theory (Refs. 16, 17, and 18).

These methods are useful in setting theoretical strength and stiffness limits but have not progressed so far that they can be used in design calculations. Evaluation of short fiber composite properties must depend on available test values obtained experimentally.

Property data related to SMC and BMC can be obtained from resin suppliers. Fiberglass manufacturers have limited data on short fiber composites fabricated by various methods. The annual conference proceedings of the Society of the Plastics Industry, Reinforced Plastics/Composites Institute, contain numerous articles dealing with short fiber composites. Other services are listed in Refs. 1, 2, and 19.

The general property trends are that composite strengths and moduli increase linearly with fiber content up to approximately 40% fiber volume. Over 40% the increase is less pronounced, and maximum values are reached at about 50’% fiber volume. Beyond this amount strengths begin to decrease. Variations in tension and flexure with glass content are shown in Figs. 6-9 and 6-10. Increased fiber length results in increased strengths and moduli as indicated in Table 6-12 for two resin systems.

Nonlinear behavior is observed in the stress-strain relations as illustrated in Fig. 6-11 for SMC. Stress-strain curves for nearly all short fiber composites exhibit a distinct knee, which may be associated with resin failure and observable cracking. Maximum allowable strains should account for such possible failures. The use of toughened resin systems alleviates this condition and permits greater strains (Ref. 22).

The effect of temperature on flexural strength and modulus is shown in Fig. 6-12 for a general purpose polyester with short glass fibers. Similar results occur in tension, compression, and shear. The sharp decrease in strength and modulus at about 100°C (212°F) is typical of many polyesters. Other polyester and epoxy resins are available for improved high-temperature performance.

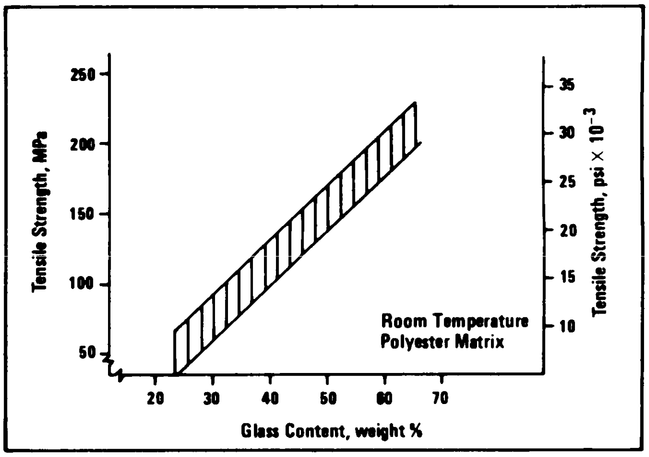


Figure 6-9. Tensile Strength Variation With Fiberglass Content (Short Fiber) (Ref. 20)

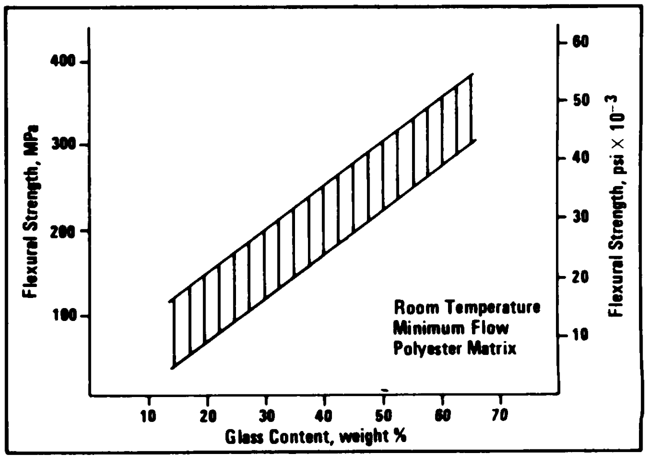


Figure 6-10. Flexural Strength Variation With Fiberglass Content (Short Fiber) (Ref. 20)

Creep behavior of short fiber composites is primarily a function of the resin system, but creep strains tend to be lower at higher fiber contents. As with the filamentary composites, the short fiber reinforced materials show greater resistance to creep than do the molding compounds of Chapter 5. The creep of a vinyl ester resin with a mixture of glass mat and woven roving is illustrated in Fig. 6-13. Additional data on creep may be found in Ref. 24.

6-2.5.3 Comparative Properties

The properties of fiber reinforced composites, as noted, vary with reinforcing agents, the form of the reinforcement, and the fabrication process. These prop-

TABLE 6-12. VARIATION IN PROPERTIES WITH FIBER LENGTH FOR A SHEET MOLDING COMPOUND AT 25% FIBER WEIGHT AND POLYESTER AND VINYL ESTER RESINS (Ref. 21)

TENSILE STRENGTH, MPa (10^3 psi)

Fiber Length		Polyester		Vinyl Ester	
mm	in.	RT*	99°C (210°F)	RT*	99°C (210°F)
12.7	0.5	63.4 (9.2)	42.7 (6.2)	69.6 (10.1)	58.6 (8.5)
25.4	1.0	79.3 (11.5)	66.9 (9.7)	81.4 (11.8)	84.1 (12.2)
38.1	1.5	102.7 (14.9)	86.7 (11.7)	126.2 (18.3)	100.7 (14.6)
50.8	2.0	112.4 (16.3)	91.7 (13.3)	122.0 (17.7)	103.4 (15.0)
FLEXURAL STRENGTH, MPa (10^3 psi)					
12.7	0.5	191.7 (27.8)	105.5 (15.3)	207.5 (30.1)	128.9 (18.7)
25.4	1.0	213.0 (30.9)	136.5 (19.8)	235.1 (34.1)	171.0 (24.8)
38.1	1.5	245.5 (35.6)	154.4 (22.4)	262.0 (38.0)	232.4 (33.7)
50.8	2.0	276.5 (40.1)	171.0 (24.8)	288.2 (41.8)	220.6 (32.0)
FLEXURAL MODULUS, GPa (10^6 psi)					
12.7	0.5	14.1 (2.04)	4.1 (0.6)	15.9 (2.31)	6.3 (0.91)
25.4	1.0	14.3 (2.07)	5.2 (0.76)	15.5 (2.25)	6.6 (0.95)
38.1	1.5	14.3 (2.07)	5.9 (0.85)	15.0 (2.18)	8.1 (1.17)
50.8	2.0	17.0 (2.47)	6.3 (0.92)	16.2 (2.35)	7.9 (1.15)

RT = room temperature

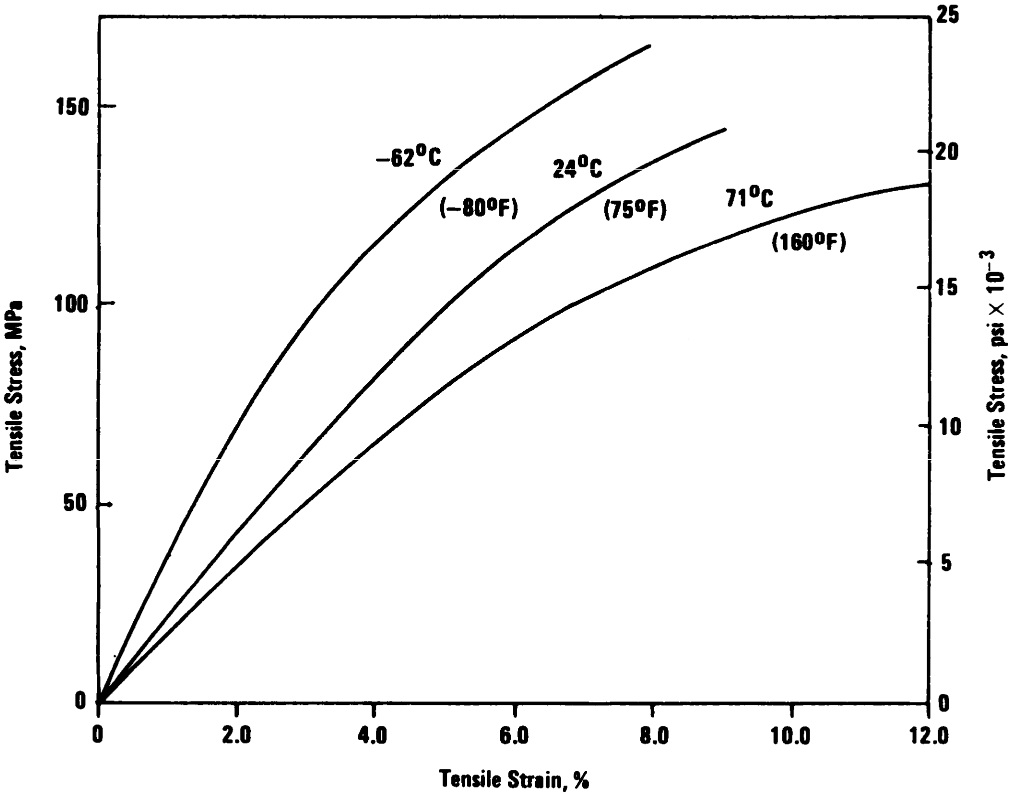


Figure 6-11. Tensile Stress-Strain for a Sheet Molding Compound at Several Temperatures (Ref. 19)

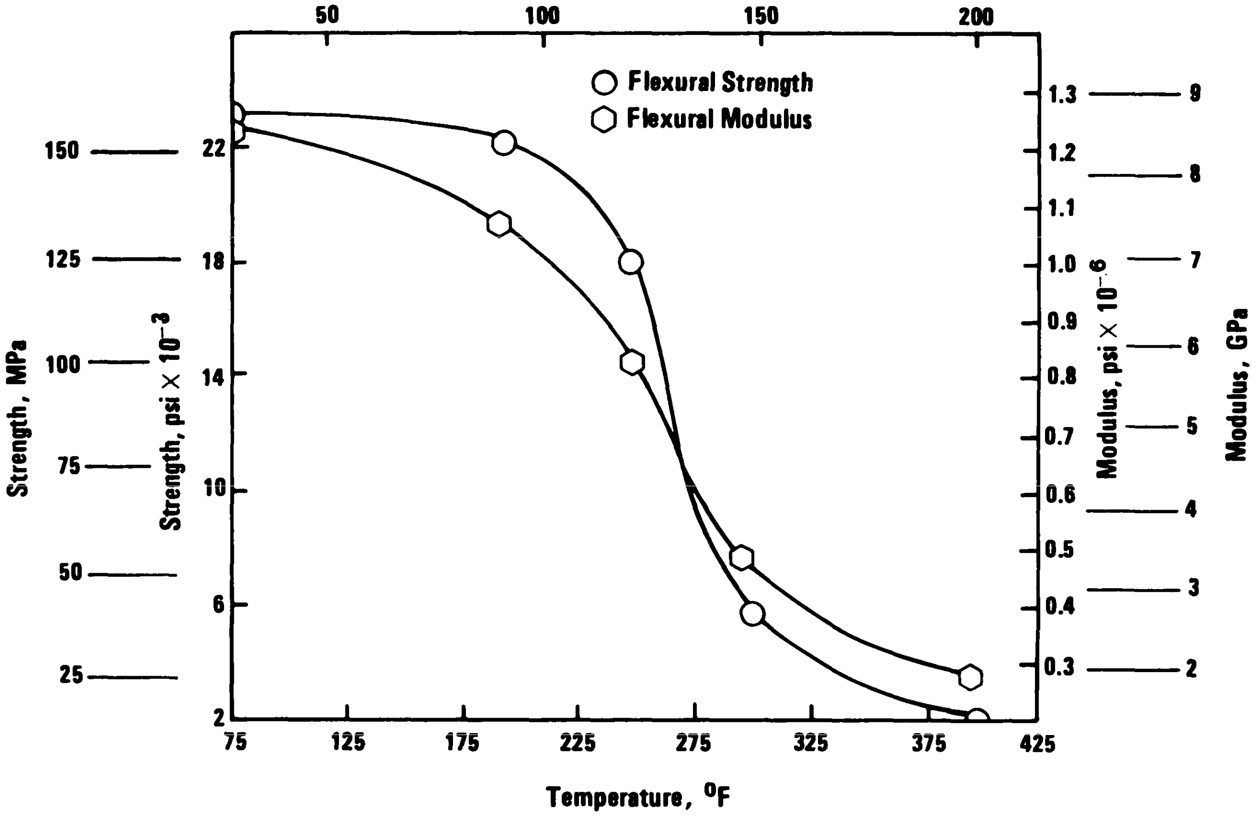


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Figure 6-12. Effect of Temperature on Flexural Strength and Modulus of a Short Fiber Composite With Polyester Resin (Ref. 2)

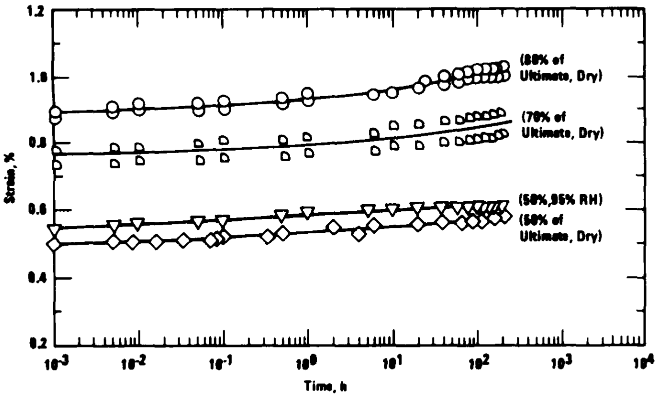

Figure 6-13. Creep for a Vinyl Ester/Fiberglass Composite at 50°C (122°F) and at Several Loads (Ref. 23)

erty values are summarized in Tables 6-13 and 6-14. Table 6-13 lists a range of properties for composites manufactured by the major processing methods. Table 6-14 compares the properties of composites fabricated by matched die molding and includes several reinforcement types with conventional resin systems.

6-2.6 COST CONSIDERATIONS AND PRODUCIBILITY

Production costs can be estimated by combining raw material and manufacturing costs. These estimates are appropriate for initial comparisons and, in many cases, are decisive factors in selecting or eliminating candidate materials and related processes. Precise estimates are more complex and require assistance from custom fabricators, mold designers, and material suppliers. Total costs must account for any finishing operations, scrap, rejects, and test programs for quality assurance and reliability. Overhead charges must be considered and may vary by as much as 200% from one fabricator to another.

Composite fabrication usually is associated with relatively large size components, low quantity runs, long cycle times, and limited automation, each of which

TABLE 6-13. COMPOSITE PROPERTIES FOR VARIOUS FABRICATION PROCESSES

Process[1]	Reinforcement, wt%	Specific Gravity	Tensile Strength		Tensile Modulus		Flexural Strength		Compressive Strength	
			MPa	10^3 psi	GPa	10^6 psi	Mpa	10^3 psi	MPa	10^3 psi
Open Mold										
Spray up	15-40	1.4-1.6	34-124	5-18	5.5-12.4	0.8-1.8	83-193	12-28	103-207	15-30
Lay-up	30-50	1.4-2.1	69-345	10-50	4.1-31.0	0.6-4.5	110-552	16-80	124-345	18-50
Compression Mold										
SMC	15-30	1.6-2.4	55-138	8-20	7-17.2	1-2.5	103-276	15-40	103-207	15-30
BMC	15-35	1.6-2.2	28-69	4-10	7-17.2	48-138	7-20	103-207	15-30	
Preform	25-50	1.4-2.2	103-207	15-30	5.5-13.8	0.8-2.0	138-276	20-40	103-207	15-30
Cold press	20-30	1.5-1.7	83-138	12-20	5.5-11.0	0.8-1.6	138-241	20-35	103-207	15-30
Resin Transfer Molded										
Pressure impregnation	15-40	1.4-1.6	83-138	12-20	5.5-13.7	0.8-2.0	103-207	15-30	103-172	15-25
Filament Winding										
Fiberglass/epoxy	30-80	1.7-2.1	552-1379	80-200	27.6-55.1	4-8	689-1724	100-250	345-552	50-80
Pultrusion										
Rod stock	40-80	1.6-2.0	414-1241	60-180	27.6-41.4	4-6	689-1379	100-200	276-538	40-78
Flat stock	35-40	1.6-1.8	138-207	20-30	12-17	1.8-2.5	172-241	25-35	138-207	20-30
Bag Molding										
Fiberglass/epoxy	60-70	1.8-1.9	379-552	55-80	20.7-24.1	3.0-3.5	517-655	75-95	414-517	60-75
Graphite/epoxy	60-65	1.5-1.6	552-586	80-85	62-69	9-10	621-689	90-100	483-552	70-80
Kelvar 49/epoxy	50-52	1.3-1.4	483	70	29.6	4.3	345	50	172	25
Stamping										
Fiberglass/nylon	20-40	1.0-1.2	97-110	14-16	5.5-6.9	0.8-1.0	124-179	18-26	—	—

[1] Fiberglass/polyester, unless indicated otherwise

TABLE 6-14. PROPERTIES OF REINFORCED PLASTICS MATCHED DIE MOLDED (Ref. 1)

Resin	Polyester				Epoxy			Phenolic		Silicone	Polyimide
Property	Glass Mat & Preform	Chopped Glass[1]	Glass Fabric	Asbestos Mat	Glass Mat & Preform	Glass Fabric	S-Glass Fabric	Glass Fabric	Asbestos Mat	Glass Fabric	Glass Fabric
Specific gravity	1.35-1.50	1.60-2.30	1.60-2.00	1.60-1.90	1.35-1.50	1.60-2.10	1.50-2.00	1.70-2.00	1.60-1.90	1.80-1.90	1.80
Reinforcement, wt%	35-45	20-40	60-70	50-80	35-45	60-70	60-70	65-70	50-80	67-75	75-80
Filler, wt%	0-20	10-40	0-10	0-10	—	—	—	—	—	—	—
Barcol hardness	35-50	35-65	60-80	50-70	35-70	60-80	60-80	60-80	50-70	55-75	40-60
Tensile strength											
MPa	138-172	83-172	276-448	207-345	97-207	276-517	345-621	276-483	276-414	138-276	276-345
10^3 psi	20-25	12-25	40-65	30-50	14-30	40-75	50-90	40-70	40-60	20-40	40-50
Compressive strength											
MPa	103-276	103-276	207-310	207-345	207-262	207-414	276-483	241-345	310-379	124-186	207-241
10^3 psi	15-40	15-40	30-45	30-50	30-38	30-60	40-70	35-50	45-55	18-27	30-35
Flexural strength											
MPa	69-276	69-345	345-552	345-483	138-179	483-689	552-827	276-483	276-379	179-276	179-448
10^3 psi	10-40	10-50	50-80	50-70	20-26	70-100	80-120	40-70	40-55	26-40	26-65
Shear strength											
MPa	14	10-14	8-10	14	17	21-28	21-28	10-17	12	10	17
10^3 psi	2	1.5-2	1.2-1.5	2	2.5	3-4	3-4	1.5-2.5	1.7	1.5	2.5
Impact strength, notched											
J/M	107-534	80-801	267-1601	107-641	427-801	587-1601	587-1601	534-1868	53-320	427	801
ft lb/in.	2-10	1.5-15	5-30	2-12	8-15	11-30	11-30	10-35	1-6	8	15
Heat resistance, continuous											
°C	95-160	120-205	120-175	150-205	95-205	150-230	150-230	175-260	175-315	400	315-370
°F	200-320	250-400	250-350	300-400	200-400	300-450	300-450	350-500	350-600	750	600-700
Relative cost[2] per unit weight	1.2-3	1-4	3-5	—	1.5-4	4-6	18	4	2.4-4.8	10	12

[1] Includes SMC and BMC

[2] Chopped glass at 1.60 sp gr = 1

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strongly influences producibility. Large components suggest design consolidations of smaller assembly units as a means for reducing overall costs, and low quantity runs emphasize the need for low cost tooling. Long cycles and lack of automation may be offset by lower material costs and/or low tooling costs to achieve cost-effectiveness.

6-2.6.1 Raw Material Costs

Calculating raw material costs is complicated by the fact that the reinforcing agent and resin are used in varying amounts, frequently with the addition of fillers, so that each case must be examined individually. The prices of common reinforcements and base resins are listed in Table 6-15 and Table 6-16, respectively. The latter table also includes the prices of two fillers that are used extensively with polyesters.

It is apparent from these price lists why fiberglass and polyester are the major materials for commercial grade products. Fiberglass roving is the least expensive reinforcement and is used in several processes, such as pultrusion, filament winding, spray up, preform molding, centrifugal casting, SMC, and BMC. Woven roving is the cheapest fabric, and it is used effectively for increased strength in combination with mat or roving.

The prices of graphite and aramid fiber have been decreasing as their commercial use has expanded. However, currently, inflationary increases have offset these price reductions. The prices of graphite and aramid relative to other reinforcements has continued to decrease. The high price of boron filament continues despite the development of carbon-core fiber, and its future availability appears uncertain.

The resin prices do not include the total cost of the resin system and may be somewhat higher depending on the curing agents or catalysts that are added. Prices may also decrease with the addition of monomers or reactive diluents.

The use of prepreg materials results in increased raw material costs, which may be offset by a decreased scrap loss. As a general rule, the cost of a reinforcement is almost doubled when it is furnished as a prepreg system. The cost of some prepreg broad goods is given in Table 6-17.

TABLE 6-15. PRICES OF REINFORCEMENTS FOR COMPOSITES

Fiber	$/kg	$/lb
Fiberglass		
E-glass roving	1.46-1.94	0.66-0.88
S-2 roving	4.41-.5.51	2.00-2.50
Woven roving	1.63-2.12	0.74-0.96
Chopped strand mat	1.76-2.20	0.80-1.00
Continuous strand mat	1.63-2.12	0.74-0.96
Graphite		
Celion 3000	77.16	35.00
Magnamite AS	61.73-74.96	28.00-34.00
Magnamite HTS	110.23-165.35	50.00-75.00
Thornel 300	61.73-72.75	28.00-33.00
Thornel P55	44.09	20.00
Aramid		
Kevlar 49	22.0.5-33.07	10.00-15.00
Boron		
4 mil	220.46-440.92	100.00-200.00

[1] January 1981 prices

TABLE 6-16. PRICE OF RESINS FOR COMPOSITES

Resin or Filler	$/kg	$/lb
Polyester		
General purpose	1.23-1.30	0.56-0.59
Isophthalic	1.23-1.28	0.56-0.58
Bisphenol A	2.07-2.36	0.94-1.07
Vinyl Ester		
Corrosion resistant	2.67	1.21
Heat resistant	2.67	1.21
Epoxy		
General Purpose	2.36	1.07
Polyimide		
Solid resin	14.33-165.35	6.50-75.00
Fillers		
Aluminum trihydrate	0.22	0.10
Calcium carbonate	0.11	0.05

[1] July 1980 prices

TABLE 6-17. PRICE OF PREPREG BROAD GOODS[1]

Material	$/kg	$/lb
E-Glass/epoxy	17.64-22.05	8.00-10.00
S-Glass/epoxy	19.84-22,05	9.00-10.00
Graphite/epoxy	108,03-138.89	49.00-63.00
Kevlar 49\epoxy	66.14-77.16	30.00-35.00
Boron/epoxy	440.92	200.00
SMC	0.88-1.10	0.40-0.50

[1] 1981 prices

6-2.6.2 Manufacturing Costs

Tooling costs, labor costs, capital investment, and production rates for several composite fabrication methods are compared in Table 6-18. The comparative ratings are considered to be representative and are subject to a number of variations. For example, the production rate for hand lay-up and spray up can be increased by increasing the number of molds; at the same time, labor costs would be reduced. Environmental factors can affect the total cost. As strict limits are placed on the styrene content or other volatiles permitted in the atmosphere of the plant, pollution control costs must be added to the capital investment. With the open mold processes (spray up and hand lay-up) the cost of installing the necessary equipment can be substantial and can result in significant increases in overhead charges. Such charges are much lower for the closed mold processes because styrene vapor is easier to control under these molding conditions.

The processing methods listed in Table 6-18 can be used to fabricate the same component and are directly competitive. The manufacturing cost depends primarily on the number of parts to be fabricated and the subsequent amortization of mold cost. Such cost comparisons are illustrated in Table 6-19 for a fiberglass polyester part (Ref. 25). It can be seen from Table 6-19 that the most costly mold required for matched die molding produces the least expensive part for production runs above 10,000. Open molds are the cheapest up to approximately 1000 parts. It should be noted that each process does not produce identical parts and that differences exist as to porosity, surface appearance, density, thickness uniformity, part tolerances, and mechanical properties. All of these effects must be considered before a final process selection can be made.

Additional information on product costing may be found in Refs. 2 and 26. Methods for estimating costs of high-performance composite parts fabricated by bag molding techniques are presented in Ref. 3.

TABLE 6-18. COMPARISON OF COST FACTORS FOR SEVERAL PROCESSING METHODS (Ref. 25)

Process	Capital Investment	Tooling		Labor[2]	Material		Production
		cost	Life[1]		cost	Scrap, %	Rate[3]
Hand lay-up	1	1	2-5	15-20	1.2-1.5	10	1
Spray up	3	1	2-5	12	1.2-1.5	25-35	1.2
Cold molding	25-35	4-5	3-10	5	1.2-1.5	25-35	6
Vacuum injection	3-5	5-6	3-10	10	1.5	5	3
Pressure injection	5-10	5-10	3-10	6	1.5	25-35	4
Matched metal die	100	25-35	100-300	1.5	1	5	18-22
Stamping	90-100	20-36	100-300	1	3-4	10	28-35

[1] Thousands of parts
[2] 1 = lowest cost
[3] 1 = lowest rate

TABLE 6-19. PIECE PART COSTS AT VARIOUS PRODUCTION LEVELS FOR SEVERAL PROCESSES (Ref. 25)

Mold Type	Mold cost , $	Mold Life, Parts	Piece[1] Price, $	Total Cost, Includes Mold Amortization, at Various Rates						
				500	1000	6000	10,000	30,000	50,000	100,000
Open	2,000	2,000	16.00	20.00	18.00	18.67	17.00	17.00	17.00	17.00
Cold	9,000	3,000	11.20	29.20	20.00	14.20	14.20	14.20	14.00	14.00
RTM[2]	10,000	3,000	12.00	32.00	22.00	15.33	15.33	15.33	15.33	15.33
RTM-nickel[3]	20,000	100,000	12.00	52.00	34.00	1.5.33	14.00	12.67	12.67	12.67
Matched die	60,000	100,000	8.00	128.00	68.00	18.00	14.00	10.00	9.20	8.60

[1] Excludes tooling; includes materials and labor
[2] Resin transfer molding
[3] Nickel-plated mold

6-3 MANUFACTURING PROCESSES

The major composite manufacturing processes are listed in Table 6-20 together with compatible reinforcement types and the resin systems normally used with each method. The composite processes vary widely as to production capabilities, and each has its own limitations in part size, permissible shapes, production rates, and tooling requirements.

In many cases the component configuration and performance requirements lead to the selection of a reinforcement/resin combination and, hence, dictate which process is most appropriate. In other instances, however, several processes will be directly competitive, and a final process selection will depend on other factors. The essential features of each process are presented to assist the designer in making this decision. Detailed information relative to composite fabrication procedures may be found in Refs. 1, 2, and 27.

6-3.1 OPEN MOLDS (CONTACT MOLDING)

The use of one-piece open molds provides a simple method for the fabrication of reinforced parts. Hand lay-up and spray up are the principal categories; they differ only in the manner in which the reinforcement and resin are deposited on the mold surface. Open molds are also used in automated tape lay-up, a special process for the fabrication of aircraft parts.

Female molds are common, but parts can be formed over a male mold, or “plug”, as well. The part surface in contact with the mold receives a smooth finish; the other surface retains the roughness of the reinforcement. Occasionally, vacuum or pressure is applied to improve the exposed surface of the part. Normal cure, however, is without pressure and at room temperature. The curing rate can be increased by heating or by posturing the gelled part after removal from the mold.

The most common materials are polyester and fiberglass, but epoxy resins are also compatible with the process. Nylon, graphite, and aramid reinforcements have been fabricated in open molds, but only in rare instances. Reinforcements may be mat, woven fabric, chopped strands, roving, or any combination of these. Gel coats (mixtures of resin, pigments, dyes, and thixotropic agents) can be applied to the mold surface prior

TABLE 6-20. MANUFACTURING METHODS FOR COMPOSITES AND REINFORCED PLASTICS

Method	Reinforcements		Resins	Gel Coat	Size	Production Rate	Typical Applications
	Material	Form					
Open Molds							
Hand lay-up	Fiberglass	Mat, roving, fabric	PE, VE	Yes	Large	slow	Boat hulls, prototypes, molds
Spray up	Fiberglass	Chopped fiber	PE, VE, EP	Yes	Large	Slow	Truck cabs, prototypes, tanks
Matched Die Molding							
Sheet molding compounds	Fiberglass	Chopped fiber	PE, VE	No	Small to medium	Fast	Auto grills, hoods
Preform molding	Fiberglass	Chopped fiber, mat, fabric	PE, VE, EP, PH	No	Medium to large	Medium	Housings, truck parts
Cold molding	Fiberglass	Chopped fiber, mat, fabric	PE, VE	Yes	Medium	Medium	Prototypes, low production runs
Stamping	Fiberglass	Chopped fiber and/or roving	PP, NY	No	Medium	Fast	Automotive parts
Resin Transfer Molding (RTM)							
Vacuum impregnation	Fiberglass	Chopped fiber, mat	PE, VE	Yes	Medium to large	Slow	Hoppers, containers, truck cabs, housings
Pressure injection	Fiberglass	Chopped fiber, mat	PE, VE	Yes	Medium to large	Slow	Hoppers, containers, truck cabs, housin,gs
Centrifugal Casting	Fiberglass	Chopped fiber, mat	PE, VE	Yes	Medium to large	Medium	Cylinders, tanks, ducts, large pipe
Filament Winding	Fiberglass, graphite, aramid	Roving	EP, PE, VE, PS	No	Small to large	slow to fast	Pressure vessels, rocket motor cases, tubes, tanks
Pultrusion	Fiberglass, graphite, aramid	Roving, mat, fabric	PE, VE, EP	No	NA	Fast	continuous sections, rods, tubes
Automated Tape Lay-up	Graphite, aramid	Tape	EP	No	Medium to large	Fast	Helicopter blades, aircraft parts
Bag Molding							
Vacuum bag	Fiberglass, graphite, aramid, boron,	Woven fabric, nonwoven fabric	EP, PI, PS	No	Medium to large	Slow	Helicopter blades, sandwich constructions, radomes, aircraft parts. tail fins
Pressure bag							
Autoclave							

PE—polyesler VE—vinl ester EP—epoxy P1—polyimde PP—polyproplene NY—nylon PS—polysulfone
PH—phenolic NA—not applicable

to depositing the resin and reinforcement. In addition to improving the surface finish, gel coats protect the composite from moisture penetration, or "wicking”, and become an integral component of the molding.

Tooling costs are low compared to matched die molding. Mold construction materials include wood, plaster, reinforced plastics, sprayed metal, and rubber. When warranted by production volume, molds are made from more durable materials, such as aluminum, steel, or plated substrates.

There is no apparent limit to the size of components that can be made in open molds, and parts have been fabricated that would be impossible or uneconomical by other methods. Representative examples are boat hulls for pleasure craft, fishing vessels, and mine sweepers, truck cabs, and plastic molds. Despite the rather primitive nature of the process, open molding accounts for approximately 30% of the total reinforced plastics production in the United States.

6-3.1.1 Hand Lay-Up

In hand lay-up, precut patterns of reinforcement, usually mat, are placed in the mold and wetted with catalyzed resin. A brush or roller is used to force the resin into the reinforcement, remove entrapped air, and compact the mix. Successive layers are added to attain the required thickness. Fiber content normally is maintained between 30-50% by weight. Inserts, ribs, reinforcing bars, and localized thickness buildups can be incorporated into the molding. Following cure, the edges are trimmed, and finishing operations are performed as required.

Finished parts tend to hate nonuniform thicknesses and resin distributions. In addition to low production rates and high labor costs, a major disadvantage is a dependency on operator skill to achieve product quality. Production volumes range from a few parts up to 5000 parts.

6-3.1.2 Spray Up

Spray up is an improvement over hand lay-up in that the resin and reinforcement are deposited on the mold simultaneously at controlled rates of fiber to resin. Manually operated spray guns or more advanced equipment are used for this purpose. Reinforcement in the form of roving is fed into the gun, which chops it into predetermined lengths while coating it with catalyzed resin. As with hand lay-up, part thickness is attained by adding the mixture in layers and compacting with hand rollers.

More complex shapes can be molded by spray up than are possible with the hand lay-up of mat or fabric. Fiber contents are controlled between 15-40’% by weight; 25% is considered optimum for processing. Spray up is used frequently in conjunction with hand lay-up.

Manual gun operation has been replaced by numerical or computerized automatic controls to increase production rates and improve product uniformity. A traversing carriage is constructed to control the travel of the spray gun and chopper over the mold area. Resin and fiber are deposited automatically at fixed ratios; compaction is also automatic. Gel coats may be deposited by the same equipment. In a second innovation the spray gun is manipulated by a robot during fiber ‘ resin coverage of the mold surface and compaction of the mix.

The use of rovings, the cheapest reinforcement, represents a cost savings over mat or fabric. Scrap from the cutting of patterns necessary with mat and fabric is eliminated, and scrap from spraying is minimal. As an added advantage, the equipment is portable and can be adapted to field installations.

Depending on the complexity of the part, normal production rates vary from 90-180 kg/h (200-400 lb h). It is not economical, in general, to use spray up unless the production amounts to at least 23 kg/h (50 lb/h). The process is cost-effective for production runs up to approximately 10,000 parts.

6-3.2 MATCHED DIE MOLDING

Matched die molding is the term applied to the compression molding of reinforced plastics and composites. In matched die molding, reinforcements consisting of chopped glass preforms, mats, or broad goods are combined with resin in the mold. Alternatively, precombined materials are fed directly into the mold in sheet form or as shaped charges. The resins are low viscosity liquid systems based on polyester. epoxy, or others. Polyester, again, is most common. The polyesters usually contain fillers to control the flow, provide property advantages, or, as extenders, to reduce the cost. The proportion of resin to reinforcement is variable and depends on the form in which the reinforcement is used. Higher reinforcement loadings are realized with broad goods compared to chopped glass preforms or mats.

6-3.2.1 Preform Molding

Preform molding is a two-stage process in which fiberglass reinforcement is first shaped into a preform closely conforming to the configuration of the components; the preform is placed in the mold, and a measured amount of catalyzed resin is added; mold closing pressure forces the resin into the preform, and the part is consolidated and cured. Two common tnethods for producing the preforms are identified as directed fiber and plenum chamber preforming.

6-3.2.1.1 Directed Fiber Preforms

Directed fiber preforming is a manual operation in which fiberglass roving is chopped and deposited onto a rotating screen that duplicates the shape of the component. A resinous binder or emulsion holds the preform together. Following the required thickness buildup, the preform is oven dried and is ready to be molded. Both small and large preforms are made by this method. Maximum sizes are limited only by the capacity of the molding press. Fibers can be directed to selected areas for added reinforcement or thickness variation, and their lengths are controlled as desired, normally ranging from 13-76 mm (0.5-3 in.). Glass is deposited at an approximate rate of 0.27-0.45 kg/min (0.6-1 lb/min) per strand. Glass waste during preforming is estimated at 5-10%. The rate of preform production normally controls the overall production rate including molding; consequently, production rates are low. The method is limited to low volume runs in the order of 1000 parts.

6-3.2.1.2 Plenum Chamber Preforms

In this mechanized method the fiberglass is chopped and sprayed with binder within an inclosed housing or plenum chamber. The process is illustrated in Fig. 6-14. Equipment variations include a large multicycle unit that is fully automated for continuous operation. The automatic fiber distribution in this method is capable of high production rates, but it limits the part configuration to symmetrical or nearly symmetrical shapes. Existing machines can accommodate preform screens from 0.8-1.5 m (30-60 in.) in diameter. The multicycle version produces at least 120 preforms\h compared to 35/h for a single station machine. The main disadvantages of plenum chamber preforming are that large volume runs are necessary to attain low unit cost and that only a few fabricators have installed this equipment.

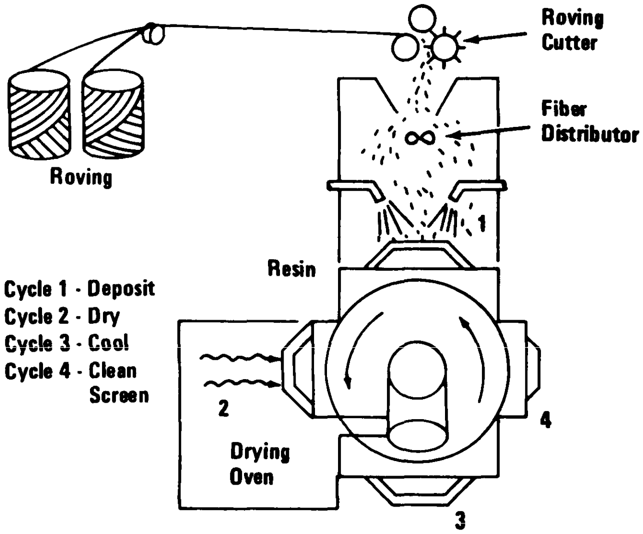

Figure 6-14. Plenum Chamber Preform Machine (Ref. 1)

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6-3.2.2 Mat Molding

Preforms cut from commercial reinforcing mat are used in mat molding. The preform patterns are cut to conform with the component shape, and usually several layers are required to achieve part thickness. Cut sections represent weak points in the finished molding and should not coincide from layer to layer. Additional reinforcements may be necessary to overlap cut sections. Continuous strand mat provides greater strength in finished parts and can be formed into more complex shapes without tearing. It is more costly than the alternative—chopped strand mat.

As in preform molding, resin is added at the mold. Mat molding can be an economical method for low volume production if the part configuration is not too complex or pattern cutting does not result in excessive scrap. Although mainly a fiberglass process, composites with other reinforcements, such as asbestos, have been fabricated by this method.

6-3.2.3 Molding Fabrics

Woven or nonwoven broad goods are preformed and molded in a manner similar to mat molding. These fabrics can be cut or sewn into preform patterns or simply stacked and molded. Although dry preforms may be placed in the mold and resin added, customary practice is to coat the preform with resin just prior to molding or to use prepregs. All the major reinforcement types, i.e., fiberglass, graphite, and aramid, have been molded by this method. The process is applicable to relatively simple shapes, preferably flat or gently contoured, and is confined to small parts since large components are made more economically by bag molding.

6-3.2.4 Cold Molding

Cold molding is a variation of preform molding in which resin and reinforcement are combined at the mold and are cured at low to moderate pressures without the addition of heat. The resin systems are low-viscosity polyesters that are fast curing at room temperature. The exothermic heat of reaction maintains the molds at a constant, slightly elevated temperature, which aids in curing. Molding pressures range from 0.14 to 0.34 MPa (20-50 psi), which enables use of inexpensive plaster or fiberglass molds. The preforms are made by any of the previously described methods, i.e., directed fiber, mat, or fabric. Woven roving or roving are sometimes added for strengthening. Gel coats may be applied to the mold surfaces. Mold release agents may be used to aid in release of the molded part. The method is useful for fabricating prototypes or for small runs of parts that might be produced later by higher volume compression molding methods.

6-3.2.5 Sheet, Bulk, and Thick Molding Compounds (SMC, BMC, and TMC)

SMC, BMC, and TMC are formulations of fiberglass, fillers, and thickened polyester resins that are processed to a dry or slightly tacky condition ready for molding. The formulations considered here are compression molding grades; other formulations at lower glass contents are designed for transfer or injection molding.

SMC can be automatically cut, trimmed, blanked, and stacked into preforms for molding. TMC weighs approximately 39 kg/m^2 (8 lb/ft^2) compared to 4.9-6.1 kg/m^2 (1.0-1.25 lb/ft^2) for SMC so that fewer sheets are required to prepare preforms. BMC is extruded and cut into logs or other bulk forms, which are then shaped into preforms for molding.

Molding pressures range from 3.4-10.3 MPa (500-1500 psi) depending on the fiberglass and filler content in the compound and the depth of draw in the mold. Recent versions of SMC are molded at 1.4-2.1 MPa (200-300 psi). Cure cycles vary with part thickness and are in the order of 2-3 min. Charge weights may be as much as 27-45 kg (60-100 lb), Scrap losses from cutting and deflashing are minor.

SMC molding can be automated, except for the mold loading and unloading phases. The molding of small parts from BMC has been fully automated.

Both SMC and BMC are comparatively inexpensive materials. They may be purchased from material suppliers or prepared in-plant by custom fabricators. SMC and BMC are cost-effective in medium volume runs (6000- 10,000 parts); however, with greater volume and large parts, SMC is probably the most economical process for reinforced plastics.

6-3.2.6 Matched Dies

The construction and cost of a die set and other tooling are the most significant factors in determining the producibility of matched-die-molded parts and must be considered at an early stage of component design. Inexpensive molds of aluminum, fiberglass, plaster, etc., are feasible with some mold types only and then for a limited number of parts. Volume production necessitates use of hardened tool steels to reduce mold abrasion. Closer dimensional control and improved quality are other advantages of steel molds. The high cost of steel tooling, however, may be prohibitive in low volume runs. The alternatives in such cases are cold molding, or open molds, which permit cheaper mold constructions but at some sacrifice in strength and surface properties. SMC, BMC, and preforms require steel molds. Depending on the molded configuration, mat and broad goods can be molded with lower cost tooling in some instances.

Lead time in mold procurement is another consideration. Currently, it may take as long as two years to design and build a steel mold. However, other mold types may be constructed in less than six months. A possible solution is to produce and test prototypes made with a low-cost mold while awaiting permanent tooling.

Matched dies for composites are classified as flash, semipositive, or positive (see par. 5-3.3). Semipositive molds are frequently modified to allow part trimming during molding, to vent deep draw parts, and to facilitate part removal. A hardened shear edge is provided to "pinch off", or trim, the part as shown in Fig. 6-15. The shear edge also serves to retain molding pressure. The flash is made to flow in a vertical direction to prevent thick buildups, which might occur with horizontal flash and prevent full mold closure. Also thick flash is also more difficult to remove. Molds are vented through ejector pins or bottom parting lines of three-piece molds. Part removal must be considered in the design and is accomplished by stripper plates, ejector pins, or air blast. Ejector pins should be located in noncritical areas.

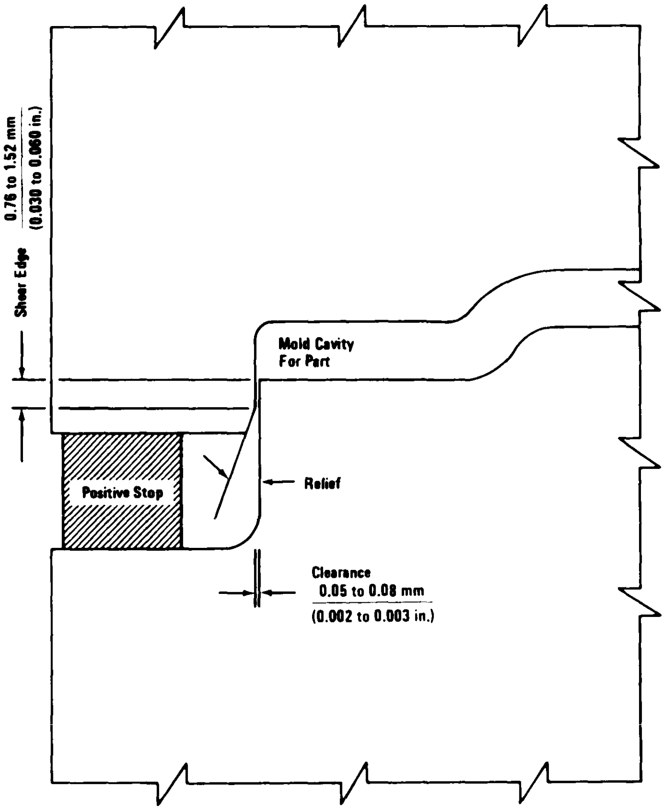

Figure 6-15. Semipositive Mold With Shear Edge (Ref. 20)

Heating of both mold halves is necessary, except in cold molding. With shallow parts the molds may be heated by conduction from heated press platens; however, deeper molds are cored for steam or electrical heating. Pressure requirements vary with material type as well as with the depth of draw. Basic mold features for various materials are summarized in Table 6-21. Further information relating mold constructions to component design is presented in Refs. 1 and 2.

6-3.2.7 Press Requirements

Compression presses, originally built for molding powders, are used for matched die molding also but are being supplanted by machines designed expressly for composites. The newer models provide greater mold areas for a given capacity and handle larger parts with deeper draws. The essential features of compression presses are the following:

1. Press *Capacity.* Production presses range from 90-4500 tonne (100-5000 tons) in clamping pressure (capacity). There are few presses in the 3600-4500 tonne (4000-5000 tons) category, and most of these are captive. However, many 1800-2700 tonne presses (2000-3000 tons) are available, and these can accommodate parts up to 0.77 m^2 (1200 $in.^2$) of SMC or BMC. A 90-tonne (100-ton) press is sufficient for 0.65m^2 (1000 $in.^2$) of mat or preform.
2. *Breakaway Force.* From 20-25% of press capacity is required for mold opening.
3. *Daylight Opening and Stroke.* These determine maximum part depth. The daylight opening must be three times the depth with allowances for mold thickness, ejector mechanisms, and heating platens. The stroke must beat least twice the depth for part removal.
4. *Platen Size.* Platen size is the space between the press strain (tie) rods and is specified as a length from front to rear and the width between the rods, Allowance is needed for bolting the mold to the platens; therefore, maximum mold size is about 300 mm (12 in.) less than either the platen length or width. Platen sizes vary with manufacturers even though capacities may be equal. Typical platen sizes, daylight and stroke, for several presses are listed in Table 6-22.

6-3.3 RESIN TRANSFER MOLDING (RTM)

Resin transfer molding is a closed mold process consisting of the following steps:

1. A dry preform of glass mat, fabric, a combination of mat and fabric, or a chopped strand prepared by a directed fiber method (par. 6-3.2.1.1) is draped over a male mold.
2. The female mold is placed in position.
3. Catalyzed resin is drawn into the preform by vacuum (vacuum injection), or is forced in by pressure alone, or by pressure with vacuum assist. A schematic diagram of vacuum injection is shown in Fig. 6-16.
4. Normally cures are at room temperature, and elevated temperatures are made possible by providing heating elements in the mold.

Polyester and epoxy resins are used in the process and may be formulated with fillers. Resin contents range from 50-60 weight % for mat preform and 35-40 weight % for fabric. Gel coats can be applied to either or both surfaces for smoothness or fiber protection. Strengths are slightly inferior to bag or matched-die-molded parts, but the contents and porosity of voids are negligible.

TABLE 6-21. MATCHED DIE MOLDING PARAMETERS

Material Type	Mold Type	Shear Edge	Mold Heating	Molding Pressure		Molding Temperature		
				MPa	psi	°C	°F	(Resin)*
Broad goods	Flash	No	Platen	1.4-3.4	200-500	120-175 120-190 160-190	250-350 250-375 325-375	(PE) (EP) (PH)
Mat	Flash	No	Platen	1.4-3.4	200-500	120-150	250-300	(PE)
Preform	Flash or semipositive	No Yes	Platen Cored	1.7-10.3	250-1500	75-160 75-160	170-320 170-320	(PE) (EP)
Preform cold molded	Flash or semipositive	No Yes	None None	0.14-0.34	20-50	20-75	70-170	(PE)
SMC	Semipositive	Yes	Cored	1.4-10.3	200-1500	130-175	265-350	(PE)
BMC	Semipositive or positive	Yes	Cored Cored	3.4-10.3	500-1500	130-175	265-350	(PE)

* PE = polyester
EP = epoxy
PH = phenolic

TABLE 6-22. PLATEN SIZES FOR SOME COMPRESSION PRESSES (Ref. 28)

Manufacturer	Capacity Metric Tons	Tons	Platen Size Length X Width m	in.	Maximum Daylight m	in.	Stroke m	in.
Stokes	180	200	0.76 X 0.61	30 X 24	0.97	38	0.41	16
Lawton	“180	200	1.22 x 1,07	48 X 42	1.78	70	1.22	48
Dake	270	300	1.40 X 1.52	55 X 60	1.52	60	0.76	30
Lawton	270	300	1.83 X 1.22	72 X 48	2.03	80	1.52	60
Dake	270	300	1.40 X 1.52	55 X 60	1.52	60	0.76	30
Siempel-Kamp	400	440	1.98 X 1.22	78 X 48	As required		As required	
Dake	450	500	1.63 X 1.78	64 X 70	1.52	60	0.76	30
Lawton	450	500	2.13 X 1.52	84 X 60	2.03	80	1.52	60
Siempel-Kamp	500	550	3.00 X 1.98	118 X 78	As required		As required	

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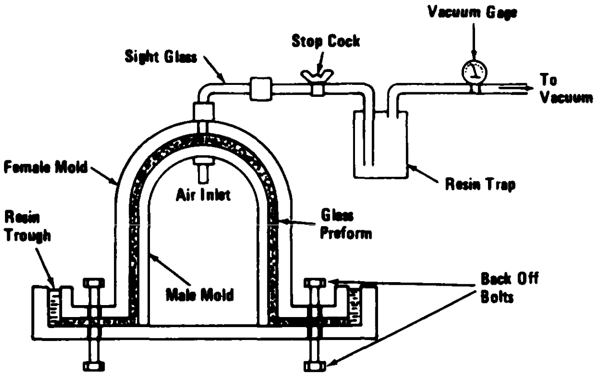

Figure 6-16. Vacuum Injection Molding (Ref. 1)

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RTM is capable of handling large complex parts with close tolerance. Wall thicknesses can be varied, and partitions, core materials, stiffeners, ribs, inserts, and attachments can be incorporated into the component. Precision parts that cannot be fabricated by other composite processes are possible, for example, a helicopter engine cowling defroster with heating elements imbedded in the part.

A major drawback is the long production cycle—2-3 h. There are now over 50 companies with RTM capability; of these approximately 20% are captive. Estimated production for 1981 was 1.3 million kg (2.8 million lb).

Low-cost tooling with RTM limits tool life to about 3000 parts. More durable tooling is not cost-effective compared to matched dies beyond 10,000 parts (see Table 6-19 and Ref. 25). For large, complicated parts at low volumes, there may be no other acceptable process.

6-3.4 CENTRIFUGAL CASTING

Essentially, centrifugal casting is a process for the production of hollow cylindrical shapes although other surfaces of revolution (conical, parabolic, and elliptical) are within the capability of the process. Typical products are pipes, tanks, pressure vessels, and various containers.

In the process, fiberglass mat reinforcement is cut to shape and is placed inside a hollow mold. An alternative method uses roving, in which case the roving is chopped and deposited on the mold surface while the mold is being rotated. In both cases a liquid resin (polyester mostly, epoxy occasionally) is sprayed over the reinforcements. Centrifugal forces distribute the reinforcement and resin uniformly and compact the mixture. Then the rotating mold is either heated from the outside, or hot air is blown in to cure the resin. Glass contents to 50 weight % are attained.

End closures are incorporated into the casting by positioning preforms in the mold before fiber and resin addition, or they may be bonded or bolted to cured cylinders. Split molds are used when external threading is required; inserts are added for internal threading.

Finished products attain uniform thicknesses within relatively close tolerances, and both inner and outer surfaces are smooth. Equipment and tooling are comparatively low in cost, and the process can be automated. The molds are usually made from welded steel sheet. There is no apparent size limitation, and cylinders have been fabricated with lengths exceeding 6.1 m (20 ft) and diameters over 1.5 m (5 ft). As noted, components must be surfaces of revolution without variations in wall thickness.

6-3.5 PULTRUSION

Pultrusion is a continuous process for the manufacture of reinforced plastic products with constant cross sections. The fabrication is accomplished by passing the reinforcements through a resin impregnation bath and then drawing the coated fibers through a heated forming die in which the material is shaped and cured. A variety of processing techniques are used, especially for the curing operation. The feed consists of continuous roving strands, mat, woven roving, fabrics, or combinations of these reinforcements. The mat, woven roving, and fabric are more difficult to process but are required to provide strength in the transverse direction. Roving is the principal longitudinal reinforcement, In a recent process improvement overwind wheels are added to the feed line. These wheels permit hoop or angular windings of rovings to be included in the pultruded structure, which eliminates the need for mat or fabric. Heating the impregnated reinforcements by induction or radio frequency (RF) prior to entry into the forming die has reduced the curing time and led to increased production rates. Speeds in excess of 7.6 m/min (25 ft/min) are now common. Resin contents are controlled at between 40-80 weight %. Fiberglass and polyester are the principal materials in commercial applications, but other material combinations can be pultruded as well. Graphite fibers and hybrids of graphite and fiberglass, both with epoxy resin, have been pultruded as structural sections for use in aerospace applications. The graphite function in these composites is to increase the longitudinal modulus of elasticity.

Pultruded products may be purchased as off-the-shelf items or fabricated to specification. Typical shapes include flat sheet stock, rods, tubes, hollow box beams, angles, channels, I-beams, H-beams, and other structural profiles. Continuous sheeting has been fabricated in widths up to 1.4 m (56 in.) and thicknesses from 1.65 mm (0.065 in.) to 12.7 mm (0.50 in.). Typical beams have flanges or webs up to 0.3 m (12 in.) and thicknesses to 12.7 mm (0.50 in.) (Ref. 2).

6-3.6 FILAMENT WINDING

Filament-wound components are fabricated by winding resin-impregnated reinforcements over a mandrel in predetermined patterns, curing the composite, and then removing the mandrel. The reinforcements used are continuous strands or rovings. Although fiberglass is the principal reinforcement, graphite and aramid filaments are used when greater rigidity is needed. The resins are polyester, vinyl ester, or epoxy. In "wet winding" the reinforcement is coated with resin during winding; "dry winding" uses prepreg roving. Elevated cures without pressure are normal, but occasionally vacuum or autoclave pressure is applied.

A typical winding machine consists of a mandrel drive head, a tail stock for mandrel support, and a traversing feed carriage. Mandrel rotation and traverse speed are synchronized to control the winding angle and pattern. Machines range from simple lathe-like equipment to computer controlled units with automatic operation.

The basic winding patterns are hoop (circumferential), polar (longitudinal), and helical as shown in Fig. 6-17. Hoop windings approach 90 deg in relation to the mandrel axis. Polar winds are at low angles as determined by the length of the mandrel and rarely are less than 15 deg. Helical windings are intermediate to hoop and polar and provide reinforcement in both hoop and longitudinal directions; the proportion of each depends on the helical angle. Structures may consist entirely of (1) helical layers, (2) hoop layers combined with polar

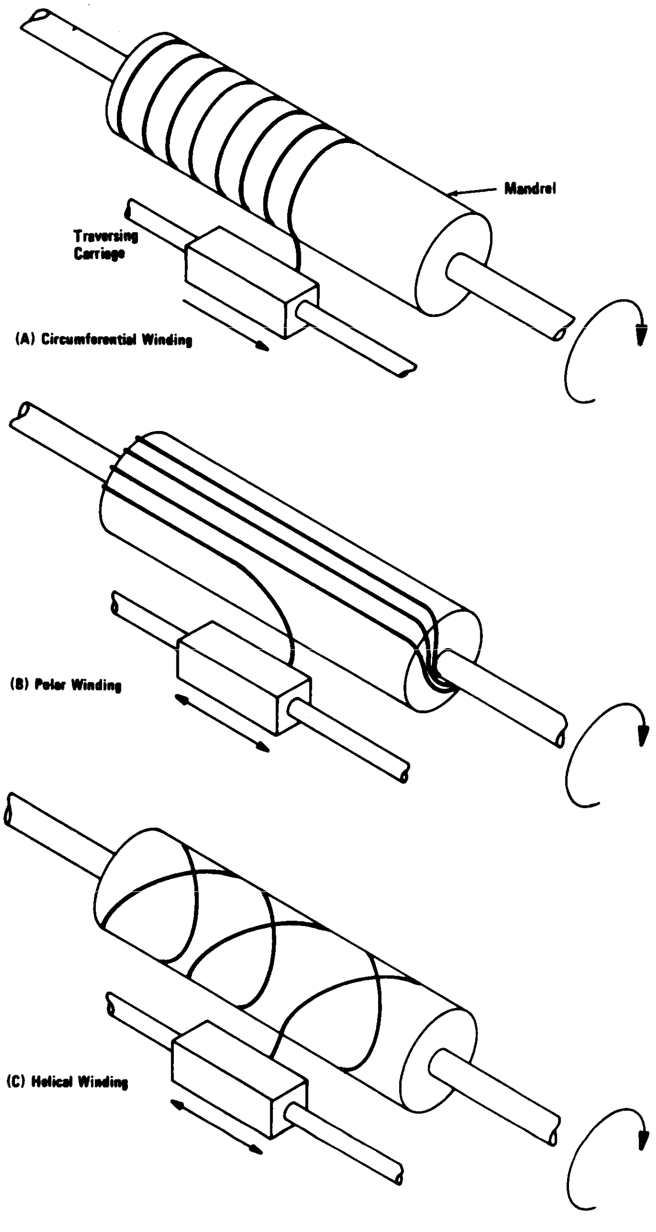

Figure 6-17. Winding Patterns

layers, or (3) helical layers combined with hoop layers. The winding angles and layers are adjusted to meet specific loading conditions, such as internal pressure, external pressure, shear, or torque. Stresses can be calculated as described for angle-ply laminates (par. 6-2.5. 1).

Variations in the process permit the winding of various structural parts. Normal winding is restricted to surfaces of revolution, but other shapes are possible within limits. As an example, a helicopter rotor blade is fabricated by winding over an inflatable mandrel and then curing in a closed mold under internal pressure. Components may be cylindrical and vary from a few millimeters to more than 3.7 m (12 ft) in diameter. Spherical, conical, and geodesic shapes are within winding capability. End closures in pressure vessels or rocket motor cases can be integral parts of the windings. Also filament (hoop) winding is used to reinforce thermoplastic pipe and metal pressure vessels.

Mandrel construction and cost are important considerations in determining component producibility. For open-end structures, cored or solid mandrels of steel or aluminum are adequate and inexpensive. For closed ends, however, the mandrels are more complex and costly. The designs of such mandrels include segmented collapsible metal, low-melting alloys, eutectic salts, soluble plasters, breakout plastics, sand combined with polyvinyl alcohol, and inflatable elastomers. Spherical vessels can be wound over metal liners that remain bonded to the composite.

Commercial and high-performance (aerospace) winding practices differ in several respects. Commercial winding is with E-glass polyester at high production rates. Speeds in the order of 90-120 m/min (300-400 ft/min), equivalent to 910 kg/h (2000 lb) of composite, are attained. Costs, consequently, are relatively low.

High-performance winding is conducted at much slower speeds, i.e., from 10-30 m/min (30-100 ft/min), to control the winding parameters, such as winding angle, width of the reinforcement band, and filament spacing. S-glass, graphite, and aramid filaments with epoxy are the principal materials to meet more exacting strength-to-weight and stiffness requirements. Total costs, therefore, may be 10-20 times greater than those for commercial grades. It should also be noted that only a few manufacturers have the capability for precision winding in contrast to numerous commercial winders (Refs. 1, 2, and 29).

6-3.7 BAG MOLDING PROCESSES

Bag molding is the principal method for the fabrication of high-performance “aerospace grade” composites. Commercial grade products also can be bag molded although this practice is less frequent. Variations in bag molding are vacuum bag, pressure bag, and autoclave molding; these differ mainly in the way pressure is applied during the cure cycle.

Preparation for molding is essentially the same for each method. Optimum quality and reliability can be obtained only with prepregs. Woven and nonwoven broad goods or tapes are used, individual plies are cut to size and stacked on the mold as illustrated in Fig. 6-18, and the bag is placed over a completed lay-up and sealed. Heat and pressure are applied to consolidate and cure the plies. Trapped air and any residual volatiles from the prepregs must be removed to attain sound structures. Some resin flow is necessary for elimination of volatiles. Either vertical or edge bleed out is used to absorb any excess resin. A sacrificial ply may be added to the lay-up to protect the surface for subsequent bonding, and a caul plate serves to improve the surface in contact with the bag. The rates of heating and pressurization are carefully controlled to obtain maximum consolidation and optimum properties. Cure temperatures generally coincide with the maximum service temperature of the resin system. Epoxy systems qualified for 120°C (250°F) and 175°C (350°F) service are cured at those temperatures, polyamides are cured up to 315°C (600°F), and temperatures of at least 315°C (600°F) are needed to soften the thermoplastic polysulfone. Pressure bag and autoclave molding conditions of 1.38 MPa (200 psi) pressures and 175°C (350°F) temperatures are routine with standard equipment. Custom-built autoc-latesare necessary to cure the high-melting polyamides and to consolidate the polysulfones.

The vacuum bag method is capable of accommodating larger components than the other two methods, but it does not produce optimum properties in all cases. A pressure bag is preferable for components with deep contours, and autoclave molding is size limited but is the best choice for the higher pressure curing cycles.

Various materials have been suggested for mold constructions. For example, hardened tool steels and steel molds with ceramic inserts yield optimum properties and have thermal expansions compatible with the high-performance composites being molded. Unfortunately, they are the most expensive tools and are justified only when a sufficient number of parts is to be fabricated. Aluminum and wrought or cast metals are less costly choices; however, they are less durable, and their thermal expansions are excessive for graphite composites. Also they are limited to temperatures of 175°C (350°F). Sprayed or electroformed mold shells backed by heat-conductive plastics or alloys are other possibilities. The thermal expansions of several composites and tooling materials are listed in Table 6-23.

Bag molding in the aerospace industry is an extremely expensive operation. The manual lay-up and preparation of prepreg for bagging, in particular, is a costly step and typically accounts for 50 to 90% of the total labor costs in component production. Fortunately, automated equipment has been developed to reduce

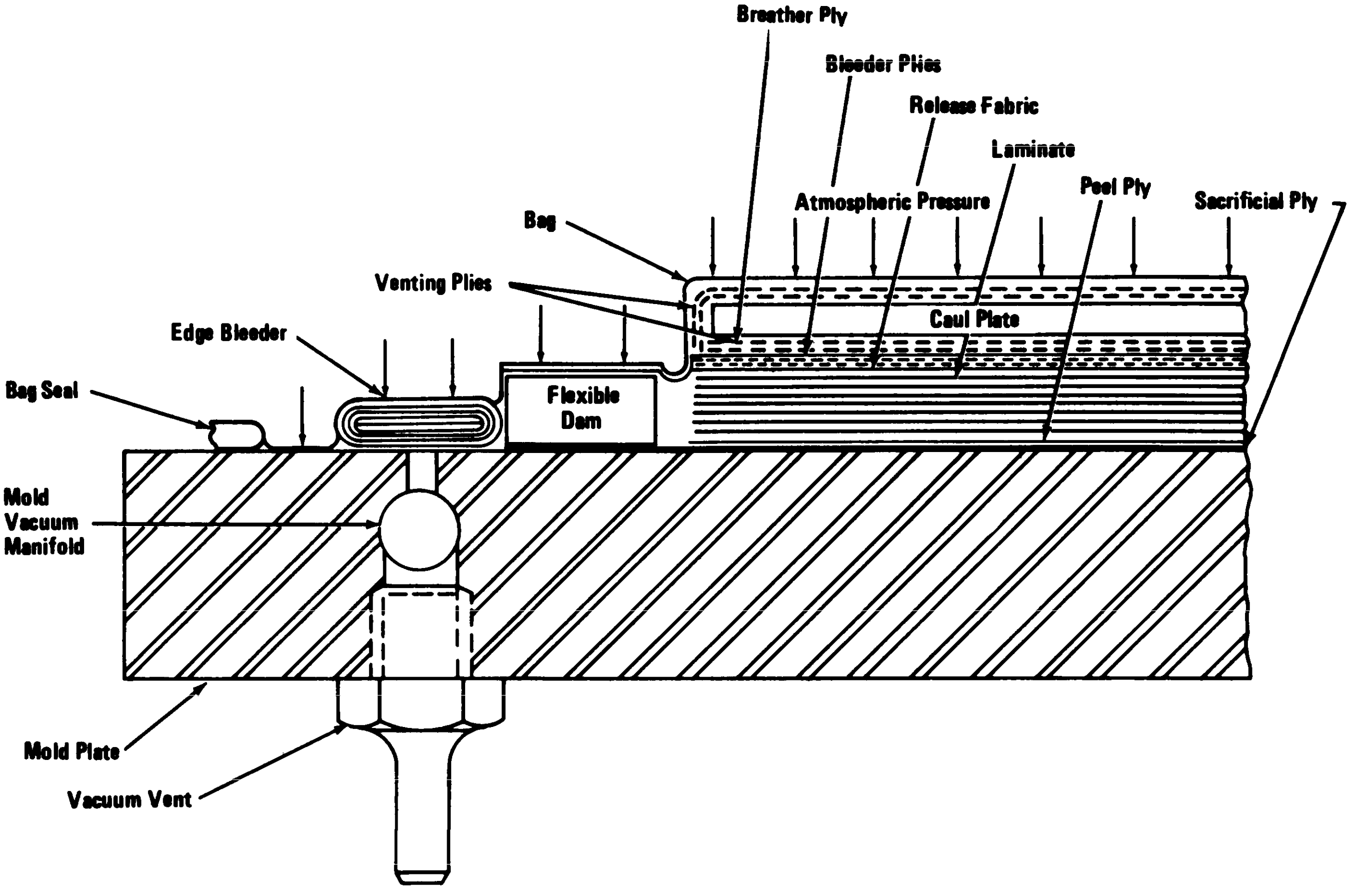

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Figure 6-18. Vacuum Bag Molding With Vertical Bleedout (Ref. 29)

TABLE 6-23. LINEAR THERMAL EXPANSION OF UNIDIRECTIONAL COMPOSITES COMPARED TO TOOLING MATERIALS (Ref. 29)

Material	% Expansion from 24° to 204°C (75°F to 400°F)
Composites	
Aramid	0.016-0.033
Graphite	0.016-0.033
Boron	0.081-0.162
Fiberglass	0.12-0.16
Tooling	
Slip cast ceramic	0.015
Tool steel	0.20
Electroformed iron	0.21
Electroformed nickel	0.23
Semi-steel	0.24
Thermally cycled plaster	0.25
High-temperature epoxy	0.35
Aluminum	0.42

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these costs. Existing automated lay-up machines or wide good dispensers are incorporated into systems that can convert prepreg into fully laid up parts. The system includes prepreg trimming, robotic or flip table stacking units, devices for placing the lay-up on molds with complex curvature, TV cameras for lay-up inspection, and modules for forming flat, multi-ply lay-ups in substructure components (Ref. 3). These machines are supplanting earlier numerical control tape-laying machines, which lacked trimming and stacking capability. Future plans envisage completely automated processes.

Bag molding, even with these innovations, does not offer many opportunities at present for the production of Army components. It is anticipated, however, that continued developments in aerospace manufacturing wil1 lead to commercial adaptations for the fabrication of strong, lightweight structures.

6-3.8 STRUCTURAL SANDWICH PANELS

Structural sandwich panels are combinations of relatively thick, low-density cores with thin composite facings. The principal cores for structural applications are honeycomb configurations fabricated from aluminum strips, fiberglass/phenolic, and Nomex (a Du Pent polyimide fiber) with phenolic or epoxy. Of these aluminum honeycomb is used most frequently. A description of various core materials and their properties is contained in MIL-HDBK 23A (Ref. 30).

Sandwich panels are manufactured by bag molding processes, in which one of two methods is *used* to bond the composite facings to the honeycomb core. In the two-stage process, cured facings are bonded to the core; the other method is a single-stage, or cocuring, process, and the facings are cured and bonded to the core in one operation.

The two-stage bonding is completed by first forming the composite facing by any of the three bagging processes; the cured facing and an adhesive film (normally epoxy based) are placed over each surface of the core; the lay-up is bagged and autoclave molded to make a bond.

The less expensive cocuring method uses "adhesive-type" prepregs that are formulated to restrain resin flow during cure and to achieve a uniform filet between the facings and the cells of the honeycomb. The lay-up is bagged and again cured in an autoclave. Somewhat lower strengths are attained with adhesive prepregs compared to the normal prepreg grades.

In both methods autoclave pressure is limited to 0.34 MPa (50 psi), and temperatures are maintained at lower levels (175°C (350°F) maximum) to prevent damage to the core.

Honeycomb cores have received little attention in commercial molding. Commercial sandwich panels generally use rigid foams as the core material. The foams are used to provide thermal insulation, to stabilize a structure, or for flotation in boat hulls. In these applications foam-in-place techniques are used, or the facings are adhesively bonded to foam slabs.

6-3.9 STAMPING THERMOPLASTIC SHEET

Thermoplastic stamping is a process in which preheated reinforced sheets are formed under moderate pressure in matched metal dies. It can be described as compression molding of a thermoplastic in which melt flow occurs. The method is essentially the same as the process described in par. 5-3.8.2. The differences are that larger parts are formed and that the sheet contains continuous fibers.

The feedstock is blanked into shapes suitable for forming and usually covers from 50 to 90% of the projected mold area. The blanks are heated in infrared ovens to temperatures approximately 25°C above the melting point. A controlled heating cycle is essential to prevent temperature gradients throughout the thickness and to avoid surface degradations.

Both mechanical and hydraulic presses are used for stamping. Mechanical presses close more rapidly, but the pressure decreases as the part cools and shrinks. Also melt flow may continue after the platens cease movement, in which case nonuniform thicknesses result. Conversely, hydraulic presses maintain a constant pressure during the cooling cycle. Conventional, positive-type dies are used with tight vertical shear edge clearances of about 0.05 mm (0.002 in.) to retain the material in the mold. Molds may require cooling.

Cycle times are faster in stamping than in any other of the reinforced plastic processes. Some stamping cycles are even faster than injection molding. (Comparisons of cycle times for various processes are shown in Fig. 6-19.) Although the press operation is fully automatic, it is still necessary to transfer blanks manually from the oven to the die. This obvious weakness detracts from the fast cycle operation.

Representative applications are automotive oil pans, tractor housings, shroud bases for rotary lawn mowers, and guitar cases.

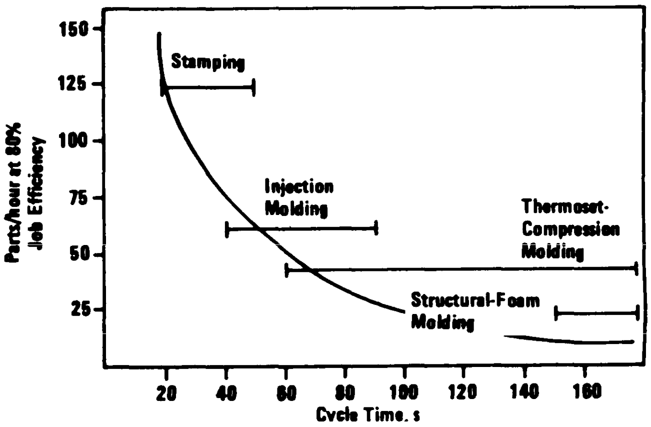

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Figure 6-19. Cycle Times for Several Processes (Ref. 31)

6-3.10 MACHINING

Machining operations, such as sawing, routing, turning, reaming, grinding, and sanding, can be performed with reinforced plastics and composites. Tool designs, feed rates, and machine speeds vary for each reinforcement, so that it is necessary to obtain machinery recommendations from the fiber manufacturers. Boron fibers, which are hard, and the brittle graphite fibers require special treatment. A summary of the machining characteristics for these reinforcements is presented in Table 6-24.

General observations relative to composite machining are the following:

1. Optimum results are obtained with shearing actions and sharp tools.

TABLE 6-24. MACHINING SUMMARY FOR BORON AND GRAPHITE COMPOSITES (Ref. 8)

Composite Type	Boron/Epoxy			Graphite/Epoxy			Boron/Epoxy (with interleaf)[1]		
Operation	Tool Reqd	Limitations	Nominal Finish	Tool Reqd	Limitations	Nominal Finish	Tool Reqd	Limitations	Nominal Finish
Drilling	Diamond core drill	0.05 mm (0.002 in.) tolerance, requires flood coolant and backup	2.5-5.1 micrometer (100 to 200 μin.)	Diamond core drill	Easily delaminates, requires flood coolant and backup	Equivalent to fiberglass holes	Diamond core drill	±0.05 mm (0.002 in.) tolerance, requires flood coolant and clamp-up	2.5-5.1 micrometer (100-200 μin.)
Reaming	Diamond reamer	0.5 mm (0.002 in.) tolerance	2.5-5.1 micrometer (100 to 200 μin.)	Diamond reamer	None	Good	Diamond-plated reamer	±0.05 mm (0.002 in.) tolerance	2.5-5.1 micrometer (100-200 μin.)
Countersinking	Diamond tools	None	Good	Diamond countersink	None	Good	Diamond tools	None	Good
Routing	Diamond-slotted tools	None	Good	Diamond-slotted tools	None	Good	Diamond router	Unsuccessful when cut touches metal	Good
Milling	Diamond cup wheel	Not suited to internal pockets	2.5 micrometer (100 μin.)	Diamond cup wheel		2.5 micrometer (100 μin.)	Diamond cup wheel	Not suited to internal pockets	2.5 micrometer (100 μin.)

[1] Titanium or stainless steel

2. Heat generation is damaging, and cooling is required in most cases.

3. Outside composite layers require special attention. Fibers in these layers should be restrained by external backing.

4. In drilling, consideration should be given to chip removal. Fluted twist drills may be required to bring chips to the surface, and a strong vacuum assists in removing chips from the work area.

5. Excessive pressure exerted by the tool can lead to fiber crushing or delamination.

6. Thin laminates, i.e., 2.5 mm (0.1 in.) or less, are especially vulnerable to damage.

Several of the less conventional machining methods have been applied successfully. Rotary ultrasonic drilling works well with boron/epoxy. High-pressure water jet (par. 4-2.2.2. 1) and laser profiling are applicable to all composite types. These three methods, however, are more costly than conventional machinery and may be cost-effective only with the high-performance composites (Refs. 3 and 8).

6-3.11 JOINING METHODS

The fiber-reinforced composites are joined to themselves or to other materials by mechanical fasteners or adhesive bonding. In some cases a combination of both methods is used to insure reliability or to meet localized stress conditions. The decision whether to use mechanical fastening or adhesive bonding requires careful consideration of all variables and should be made at an early stage in the design. The variables influencing the selection and the subsequent design configuration include the structural performance requirements, relation of the joint to the assembly, materials to be joined, environmental conditions, fabrication procedures, and cost. It is emphasized that design criteria acceptable to commercial grade materials may be inadequate for more critical high-performance components.

The advantages and disadvantages of each method are summarized in genera] terms:

1. *Mechanical Fasteners-Advantages:*
   a. No surface preparations *or* cleaning required
   b. Not as adversely affected by thermal cycling or high humidity as are bonded joints
   c. Inspection of joints is simplified.
   d. Permit disassembly and access holes.
2. *Mechanical Fasteners—Disadvantages:*
   a. Machined holes, which weaken the structure, may be required.
   b. They lead to stress concentrations, which can induce failure.
   c. They are not usually as strong as bonded joints unless heavy fasteners are used.
   d. They may add weight to the joint.
   e. They may corrode.
3. *Adhesive Bonding-Advantages:*
   a. They distribute loads over a larger area and eliminate stress risers.
   b. They do not require machining in the joint area, which can weaken the joined members.
   c. Weight additions are minimum.
   d, They may be installed without access to inside areas.
4. *Adhesive Bonding-Disadvantages:*
   a. They require surface preparation and extensive cleaning.
   b. They are subject to degradation] from temperature and humidity cycling.
   c. They are difficult to inspect for unbonded areas and voids.
   d. They do not allow disassembly without destruction of the joint.

The basic joint configurations shown in Fig. 5-10 for the plastic materials are also applicable to the composites. Additional design concepts for bonded, bolted, and bonded/bolted joints are shown in Refs. 12 and 32.

6-3.11.1 Mechanical Fasteners

Self-tapping screws have been used successfully with reinforced plastics where high strength is not required. However, better use of self-tapping screws is in conjunction with an adhesive bond. The screws serve to hold the surfaces together while the adhesive cures; the screws also contribute additional strength to the joint.

Rivets in various styles, sizes, and metals can produce effective connections. Backup washers are recommended for distributing the stresses over a greater area.

Satisfactory connections can be made with standard bolts, nuts, and washers through either drilled or molded-in holes. When the connection is to be permanent, a tight joint can be made by applying a polyester or epoxy adhesive before inserting the bolt. For removable bolts threaded metal inserts should be used. The inserts may be bonded in place or, when possible, molded in place.

Shims or other metal inserts maybe embedded in the composite to reinforce the connection. Examples are the metallic inclosure bosses for motor cases and pressure vessels and the complex joints for attaching helicopter rotor blades to the hub.

6-3.11.2 Adhesive Bonding

The bonding of fiberglass-reinforced materials in noncritical applications is relatively simple. Epoxy-. polyester-, or polyurethane-based adhesives are used. All contaminants and release agents are removed from the composite surfaces by a solvent wash followed by sanding. Metal adherends may require primer coats. After the adhesive is applied, the joint is clamped and held under pressure until curing is completed. Although some adhesives cure at ambient temperatures, elevated temperature cures produce superior bonds. Joints should be designed to avoid excessive peel stresses. Adhesive joints are strongest in tension or compression and somewhat weaker in tensile or compressive shear.

The bonding of graphite, aramid, or boron high-performance composites is more complex and requires a detailed analysis in designing the joint based on a knowledge of the mechanical properties of the adhesive and adherends. These aspects are considered in Refs. 12 and 32.

Adhesive types for the high-performance composites are based on epoxy, epoxy-novolac, nylon-epoxy, epoxy-phenolic, and vinyl-phenolic resins. In normal use the adhesives are in the form of films, i.e., an adhesive with a scrim cloth carrier. Surface preparation and cleaning procedures are essential steps in the operation. The use of peel plies to protect the surface has been noted previously (par. 6-3.7). Fixtures are constructed so that the pressure over the entire bonding area is uniform. Normal practice is to subject the parts to autoclave bagging pressures and to cure at elevated temperatures. A major example of this procedure is the construction of sandwich panels by the two-step process (par. 6-3.8).

6-4 TESTING, INSPECTION, AND QUALITY CONTROL

A comprehensive testing program to evaluate component performance is an essential feature of a design and is required [o demonstrate producibility. In all but the simplest cases prototype testing is indicated if a complete evaluation is to be achieved. Testing is conducted under various loading and environmental conditions as dictated by performance requirements. Test results are used to prepare performance specifications, which define inspection and quality assurance procedures to be followed during production.

6-4.1 TESTING

Testing uses existing or standardized procedures; however, it may be necessary at times to improvise methods for specific components under specific conditions. Destructive testing includes tests of the component in bending, tension, compression, impact, internal pressurization, cyclic (fatigue), vibration, sustained (creep), torque, or combined loading conditions. Tests are also conducted under environmental conditions of temperature variation, humidity, moisture or chemical exposure, or after cycling through exposure extremes. Alternatively, specimens maybe cut from a component and tested by standardized procedures; electrical and chemical resistance tests may also be run in this manner. Accelerated testing is recommended to determine the effects of weathering and other environmental exposures. In short, the test program must insure that all performance requirements are satisfied and that no unforeseen failures will occur.

Testing is also carried out to anticipate the effects of fabrication variables and the defects that may occur in processing.

A list of major defects to be found in filamentary composites, short fiber composites, and sandwich constructions includes the following:

1. *Unbend.* separation of a secondary adhesive bond or of a sandwich facing from the core
2. *Delamination.* separation of plies within a laminate
3. *Damaged fibers.* broken filaments, knots, or splicing in rovings or fabric yarns
4. Fiber *misalignment.* disorientation of fabrics or filaments; deviation from predetermined lay-up or filament winding patterns; washout of fibers from excessive resin flow
5. *Variation in resin fraction.* resin-rich or resin-starved areas; excessive variability over the surface of a laminate brought about by variations in prepreg resin content or improper resin bleed out during bag molding cure; variations due to flow conditions in short fiber moldings
6. *Variation in thickness.* normally associated with variation in resin content for laminates; inherent in open mold processes
7. *Variation in density.* associated with resin variations, voids, and porosity
8. *Voids.* entrapment of air or other volatiles present in the resin system; may be on a macro or micro level, localized or uniformly distributed
9. *Porosity.* numerous open or closed macroscopic or microscopic bubbles
10. *Contamination.* inclusion of foreign matter
11. *Moisture pickup. excess* moisture not normal for the resin or reinforcement
12. *Warpage.* uneven shrinkage due to uneven mold temperatures or fiber orientation caused by long flow paths in a mold
13. *Sink marks.* nonuniform shrinkage during molding due to uneven temperatures in mold halves or insufficient pressure
14. *Flow lines.* local waviness or surface due to fiber orientation or low mold temperatures
15. *Washout.* abnormal tearing or fiber displacement during molding caused by poor preforming or a high-viscosity resin.

The extent to which these defects may be tolerated, the frequency of occurrence that is permissible, and their effects on properties must be ascertained. Acceptance criteria will depend on analysis of the defects, and it should be remembered that insistence on removal of all defects may result in excessive cost increases. Only those defects that materially affect performance are considered nonacceptable.

6-4.2 INSPECTION

Component inspection may be a simple procedure consisting of dimensional and tolerance measurements, weighing, density determination, cure determination by Barcol hardness or tapping, and a visual examination for defects. More complex inspection methods use various nondestructive testing (NDT) techniques. NDT methods, in general, are expensive and may add as much as 20’% to the cost of the component; therefore, their use is warranted only *in* critical applications. Furthermore, only a few fabricators have the equipment to make these inspections. The NDT methods applicable to composites are summarized in Refs. 3 and 12. The defects that can be detected by each process are listed in .Table 6-25.

6-4.3 QUALITY CONTROL

The control of the processing during production runs is a function left to the manufacturer, and it is inadvisable for the Government buyer to specify process conditions. Should he do so, he is obligated to accept the entire production output whether or not it meets all requirements. To avoid this situation, the purchase specification should include provisions that consider the significant t process variables. These provisions are derived from tests performed during prototype manufacture and evaluation. As an additional precaution, it can be specified that the basic raw materials (resin, reinforcement, prepregs) comply with military or other specifications. There is an increasing tendency to depend upon specifications prepared by the Society of Automotive Engineers, Inc., and designated as Aerospace Materials Specifications (AMS). In many cases these specifications and military specifications are nearly identical. Typical AMS specifications related to composites are shown in Table 6-26.

6-5 DESIGN OF COMPONENTS FOR PRODUCIBILITY

Composite producibility is measured on the basis of performance and cost effectiveness and can be demonstrated only with a close coordination of the design with the fabrication process. A systematic approach to the design is an essential feature and consists of the basic phases summarized in the following:

1. Establishment of design requirements based on the design concept

TABLE 6-25. DEFECTS DETECTED BY VARIOUS NDT METHODS (Ref. 12)

Defect, Discontinuity, or Variable	X-ray Radiography	Neutron Radiography	Gamma Radiation	Ultrasonic	Sonic Vibration	Microwave Transmission	Infrared Scanning	Heat Sensitive Agents	Liquid Penetrants	Acoustic Emission
Unbond	x			x	x		x			x
Delamination	x[1]			x	x	X	X		x	x
Undercure				x	x	x		x		
Fiber misalignment	x	x	x							
Damaged filaments	x								x	x
Resin variation		x								
Thickness variation	x		x	x	x	x				
Density variation	x		x	x	x					
Voids	x		x	x	x	x	x		x	x
Porosity	x		x	x	x	x			x	x
Fracture	x		x	x	x				x	x
Contamination	x		x	x						
Moisture	x	x								

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[1] If oriented parallel to X-ray beam

TABLE 6-26. TYPICAL AMS SPECIFICATIONS RELATING TO COMPOSITES

AMS No.	Partial Title
3616	Resin, Polyimide, Laminating, and Molding
3671	Plastic Molding Compound, Novalac Epoxy, Short Glass Fiber Reinforced
3687	Adhesive Film for Sandwich Panels
3823B	Fabric, Glass Cloth Style 7781
3828	Glass Roving, Epoxy Resin Preimpregnated
3832A	Glass Roving, Type S-Glass, Epoxy Impregnated
3865A	Filaments, Boron-Tungsten Substrate
3867 thru 3867/3	Boron Tape, Epoxy Impregnated
3894B, 3894/1 thru 3894/9	Graphite Fiber, Tape and Sheet, Epoxy Impregnated
3899	Graphite Fiber, Tape and Sheet, Polysulfone Impregnated
3906 thru 3906/7	Glass, Nonwoven Fiber, Tape and Sheet, Epoxy Resin Impregnated

2. Development of a preliminary product design

3. Selection of candidate materials and the related fabrication methods

4. Fabrication and testing of production prototypes

5. Finalization of the design and selection of material and process.

The material selection process is the critical element in design. The composite selected determines which processes are applicable; the process, in turn, imposes restrictions on a design. Material comparisons are not limited to composites. The molding compounds, especially the glass-filled materials, and other structural materials must be considered as well.

Prototype testing provides the means for a realistic evaluation of a component. Process defects and variations due to processing can be tested to ascertain their effects on performance. These tests form the basis for acceptance standards and quality control measures.

Prototype testing attains greatest significance when the product is fabricated in production-type tooling and equipment. A careful selection of candidate materials and processes is essential if excessive tooling and fabrication costs are to be avoided at this stage of a design.

Composite structures may require redesign to comply with the limitations associated with a particular process. These design changes may be minimized by adherence to conventional practices normally adopted by custom fabricators, Typical of such practices are the quality of surface finishes, tolerances, minimum wall thicknesses, corner radii, and others.

Consultation with material suppliers, fabricators, and material specialists is a necessary step in the design process and should be initiated at an early stage. Information critical to material and process selection maybe obtained from these sources and may be unavailable elsewhere.

6-5.1 SELECTION OF MATERIALS AND FABRICATION PROCESSES

The initial step in selecting materials and processes is to enumerate all component requirements including the principal dimensions. A generalized list of such requirements is shown in Table 6-27.

Configuration parameters often are sufficient to determine the appropriate process or at least to limit the possible choices. The applicability of matched die molding, open molds (hand lay-up or spray up), centrifugal casting, filament winding, or pultrusion is immediately established by the configuration itself and is further limited by the size of the component. The maximum size of matched-die-molded parts depends on the press capacity and platen dimensions as noted in par. 6-3.2.7. The largest parts are fabricated by open mold techniques, The minimum size capabilities of open or matched die molding depend on the complexity of the part and the strength requirements. Often small, complex parts are best produced by injection or compression molding of glass-filled molding compounds.

Strength and rigidity are the primary factors that determine the type of reinforcement, fiber geometry, and fiber volume fraction. The reinforcement choice places further restrictions on potential fabrication methods. For structural components with critical strength requirements, methods applicable to the high-performance composite, i.e., bag molding, must be considered.

Improved impact resistance, a frequent performance criterion, may be imparted to a composite by the use of flexible resin types. With the brittle graphite fibers protective plies of another reinforcement type may be necesssary.

Nonstructural and environmental requirements generally are functions of the resin system. Although only a few generic resins are used with composites, numer-

TABLE 6-27. DESIGN REQUIREMENTS RELATED TO MATERIALS AND PROCESSES

Requirement	Effect
Configuration	
Shape	Limits applicable processes
Size	Limits applicable processes
Thickness	Limits process, effects reinforcement
Weight	Strength weight of reinforcement
Structural	
Strength	Reinforcement type and form
Rigidity	Reinforcement type and form
Cyclic loads (fatigue)	Resin and reinforcement
Dynamic loads	Resin and reinforcement
Sustained loads (creep)	Resin
Nonstructural	
Thermal	Resin mostly
Electrical	Resin system
Environmental	
Service temperature	Resin system
Humidity	Resin mostly, reinforcement form
Weathering	Resin system
Chemical	Determines resin
Production and Costs	
Quantity	Determines process and tooling
Rate (parts/day)	Helps determine process
Lead time	May determine process and tooling

ous variations are available, which permit selections for high-temperature service and for improved chemical and electrical properties.

As discussed in par. 6-2.6, the crucial factor in the final selection of a process is the overall component cost, which depends upon the number of parts to be produced.

Selection of the most cost-effective method may require a reevaluation of the design to upgrade material performance. For example, if hand lay-up is most economical, thicker walls, ribs, stiffeners, or woven fabrics may be incorporated into the design to improve strength and stiffness properties.

6-5.2 PROCESS DESIGN GUIDES

Design features applicable to several fabrication processes are listed in Table 6-28. Compliance with these limitations aids in increasing the producibility of a component and in preventing additional tool costs or design changes.

6-5.3 DESIGNING WITH HIGH-PERFORMANCE COMPOSITES

The initial incentive in manufacturing parts from high-performance composites was to obtain weight savings and reliability; cost-effectiveness was a lesser concern. Composite parts were substituted for metals with only minor design changes. Consequently, the manufacturing costs for composite parts exceeded the costs of their metallic counterparts in numerous cases. The current design philosophy differs from the earlier approach, and major efforts are directed to cost reductions. Part of the original weight savings has been sacrificed to achieve this end. At the same time, weight trade-offs have resulted in increased structural reliability. In effect, the appeal of composites is now based on simplified and cheaper fabrication methods with equivalent or slightly superior performance compared to other alternatives. As this trend continues, bag molding and related processes will become efficient techniques and will be feasible for fields of application other than aerospace.

A number of steps may be taken to improve the producibility of composites, some of which are documented in Ref. 3. The principal measures include the use of less costly material versions, design simplifications, more efficient tooling, automated lay-up equipment for reduced labor, and improvements in quality control and inspection.

Significant cost savings have been accomplished by using cheaper grades of graphite and Kevlar/epoxy rather than boron epoxy or the more epcnsive higher modulus graphite fibers. Equivalent strength, stiffness, and reliability can be obtained with the cheaper materials by adding a few extra plies to the lay-ups or by design improvements. Greater reliance on standardized prepreg systems with less stringent specifications is a recommended procedure. Such systems can be optimized for ease of handling during lay-up and are advantageous to the prepreg supplier because materials can be reproduced more consistently.

Hybrids offer an opportunity for further cost reductions and should be considered in all strength- or stiffness-critical applications. Hybrids also reduce the quantity of material required for a part and provide a balance of properties not available in single materials.

The form of the prepreg, i.e., narrow tape, wide tape, woven fabric, nonwoven fabric, must be optimized for each lay-up, and final selection must be made on the basis of minimum scrap, maximum coverage per dol -

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TABLE 6-28. DESIGN LIMITS FOR VARIOUS FABRICATION PROCESSES (Ref. 33)

	Matched Die Molding			Hand Lay-Up or Spray Up	Cold Molding	Stamping Thermoplastic Sheet
	SMC	BMC	Preforms			
Minimum inside radius, mm (in.)	1.6(1/16)	1.6 (1/16)	3.2 (1/8)	6.4 (1/4)	6.4 (1/4)	3.2 (1/8)
Molded holes	Yes[1]	Yes[1]	Yes[1]	Large	No	Yes[1]
Trim in mold	Yes	Yes	Yes	No	Yes	Yes
Core pull and slides	Yes	Yes	No	No	No	No
Undercuts	Yes	Yes	No	Yes	No	No
Minimum recommended draft, deg						
(a)[2]	1-3	1-3	1-3	0	2	1-3
(b)[3]	3	3	3	0	3	3
Minimum practical thickness, mm (in.)	1.27 (0.05)	1.52 (0.06)	0.76 (0.03)	1.52 (0.06)	2.03 (0.08)	1.27 (0.05)
Maximum practical thickness, mm (in.)	25.4 (1)	25.4 (1)	6.4(1/4)	No limit	12.7 (1/2)	12.7 (1/2)
Normal thickness variation, ± mm (in.)	0.13 (0.005)	0.13 (0.005)	0.20 (0.008	0.51 (0.020)	0.25 (0.010)	Not available
Maximum thickness buildup	As required	As required	2 to 1	As required	2 to 1	3 to 1
Corrugated sections	Yes	Yes	Yes	Yes	Yes	Yes
Metal inserts	Yes	Yes	No	Yes	No	No
Bosses	Yes	Yes	Yes	Yes	No	Yes
Ribs	As required	Yes	No	Yes	No	Yes
Molded in labels	Yes	Yes	Yes	Yes	Yes	Yes
Raised numbers	Yes	Yes	Yes	Yes	Yes	Yes
Mold surfaces reproduced	2	2	2	1	2	2

[1] Parallel to ram action only
[2] To depth of 152 mm (6 in.)
[3] To depth greater than 152 mm (6 in.)

lar, and ease of lay-up. The use of multi-ply and filament-wound prepregs maybe of advantage here. In all cases drawings should clearly indicate the ply sequence, orientation, and trim lines for each lay-up.

Automatic lay-up can reduce costs substantially and insure product uniformity. However, it is not adaptable to all component configurations, and in addition, the equipment is not widely available. As an alternative, improved methods of hand lay-up or partially automated lay-up should be considered in preliminary designs. Whenever possible, tooling should serve a dual purpose, for example, ply trimming fixtures used as bonding fixtures.

Co-curing methods should be investigated for all sandwich constructions and other bonding operations. In general, the manufacture of sandwich panels with expandable honeycomb cores is an expensive operation, and other methods of stiffening should be considered. Pultruded channels, hat sections, or box beams can be produced cheaply and make efficient stiffeners when bonded or mechanically fastened to a structure.

As a general conclusion, the producibility of the high-performance composites can be increased only by an approach in which design, manufacturing, and quality control are integrated at all levels including the following:

1. Elimination of design features that are difficult or expensive to manufacture
2. Means for inspecting the structure are provided in the design
3. Reduced tooling costs by using combination fixtures and simpler tools
4. Coordination between process and quality control to establish realistic specifications, allowable defects, and reworking of rejects.

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CHAPTER 7

PRODUCIBILITY CONSIDERATIONS FOR MECHANICAL ASSEMBLIES

Automation of the assembly operation can be difficult unless the product designer takes producibility into consideration. This chapter introduces the general considerations relating to automated assembly. Design considerations relating to the total assembly are considered first with emphasis on design simplifications, human and mechanical constraints, and the assembly sequence. Next the producibility considerations for the individual components of an assembly are considered. Included here are factors that ease assembly along with approaches for feeding, orienting, and loading components. The subsequent paragraphs cover fastening and joining, including mechanical, fasteners, mechanical connections, and a variety of heat-type joining methods, such as soldering, brazing, and welding. Par. 7-5 contains basic rules for producibility in assembly with rules for product design and the design of components. Finally, short paragraphs are included on nontraditional assembly techniques, which introduce industrial robots and comment on inspection and testing.

7-1 GENERAL CONSIDERATIONS

To exploit manual or machine assembly to the fullest extent, the product to be assembled must be inherently suited to and designed for the method. It is quite safe to say that what is difficult for the human assembler to do is probably also difficult for an automatic assembly machine. Refs. 1 and 2 are recommended reading to understand the interface between human movements and equipment design. The design of the product, its component parts, and the means used to fasten it together exert a powerful influence on determining the ease of assembly.

7-1.1 AUTOMATIC MACHINE ASSEMBLY

With the current trend to greater use of automatic machinery for assembly, the product designer must change his thinking to suit the actions of the machine. There will no longer be a human operator to make decisions. The perfect machine, the human being, will be replaced. The human hand can move in a wide range of combined motions; it has sense of touch, and it is controlled by all the senses. Product designers, when designing to suit automatic mechanical assembly, will be dependent upon mechanical functions; all of which are designed to perform a set cycle of events. Any decisions the machine may have to make must be anticipated and built in. This requires rethinking by the product designer to eliminate as much machine decision making as possible.

7-1.2 CONSIDERATIONS FOR ASSEMBLY BY MACHINE

The majority of current products are not designed for assembly by machine. This new technique raises a whole range of problems. Obviously, the function and reliability must never suffer, but designing for mechanical assembly may well dictate different materials. Also the product may be designed to be thrown away and not repaired. This has been an accepted principle for some electrical gear and for some types of alarm clocks, for example. Conversely, the product may, for economic reasons, be designed for disassembly and repair during its life cycle. In either case the designer must consider this eventuality in the initial product design. For a more detailed discussion of mechanical assembly see Ref. 3.

7-1.3 DESIGNING FOR ASSEMBLY

The real problem lies in the techniques of design for mechanical assembly. The rules and guidelines can be given, but real knowledge of their use comes from applying them in practice. It is not difficult to design components for manufacture on automatic machines and presses. These are common tools for all industries, and what applies in the manufacture of one product also applies in the manufacture of others. In assembly work, however, different shapes, materials, tolerances, and sizes have to be considered. Parts that tangle or become damaged and contaminated require special consideration on the assembly machine. Apart from designing for producibility in manufacture, designing for easy orientation, selection, and feeding makes the problem quite different. With the advent of standard assembly machines, the product designer must have known parameters available to him to guide his design. He can design to suit the equipment in his production shop, as he does for the manufacture of component parts. In the initial stages until full experience has been gained, the best way for the product designer to learn is by working with the machine tool designer on a project. In most engineering projects compromise is necessary; the same is true in product design for automatic assembly. The product designer has to meet the requirements of function, reliability, appearance, normal production techniques, and a dictated price. To add to this existing burden may seem unreasonable, but to achieve maximum producibility, the designer must also consider the limitations of assembly techniques, automatic or manual.

Experience indicates that it is difficult to make large savings in cost merely by the introduction of mechanized assembly. Where large savings are claimed, examination shows that often the savings are really due to changes in the design of the product to facilitate the introduction of the new process. Undoubtedly, the greatest cost savings are to be made by careful consideration of the design of the product and its individual component parts. Generally, when a product is designed, consideration is given to the ease of manufacture of its individual parts and to the function and appearance of the final product. For obvious reasons it must be possible to assemble the product; however, little thought is given to those aspects of design that will facilitate assembly of the parts, and great reliance often is placed on the assembly operators. A trained operator is able to make logical decisions and assemble the most complicated parts based on those decisions. One of the first steps in the introduction of mechanization in the assembly process is to reconsider the design of the product so that mechanical, rather than human, logic is applicable.

7-1.4 MAJOR FACTORS IN DESIGNING FOR ASSEMBLY

The use of automatic or manual assembly methods will probably be dependent on the availability of equipment, the complexity of design, and economics. Regardless of this decision, when designing for producibility in the assembly process, the designer must consider three interrelated areas: the total assembly as a unit, the individual components, and the method of fastening or joining the components.

7-2 PRODUCIBILITY CONSIDERATIONS IN THE TOTAL ASSEMBLY

Designing for assembly should always consider three basic items: (1) design simplification as a means of reducing the complexity of the assembly, (2) human factors and mechanical constraints of the assembly, and (3) the sequence of assembly regardless of the volume. In design for high-volume assembly, consideration must be given to progressive assembly. Additional factors, such as the division of labor and transfer of units, must also be considered.

7-2.1 DESIGN SIMPLIFICATION

The most obvious way in which the assembly process can be facilitated by the product designer is to reduce the number-of different parts to a minimum. An example of this is given in Fig. 7-1. Here the original design consisted of 13 parts and required many difficult operations to assemble. The new design reduced this to two parts requiring only one simple assembly operation. Clearly, great savings in production cost were brought about by the redesign of the product. Further examples of product simplification for mechanized assembly are given in Figs. 7-2 through 7-6.

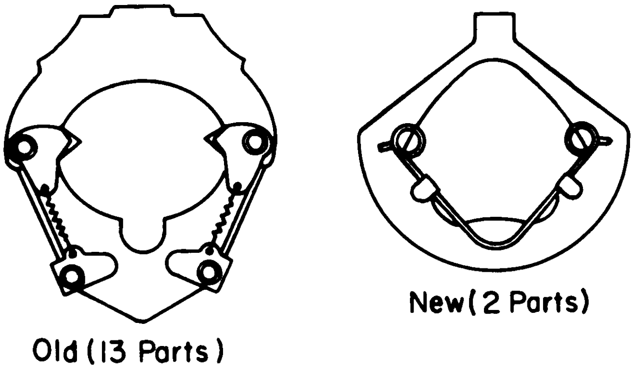

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Figure 7-1. Reduction of Parts to Save Assembly Costs (Ref. 3)

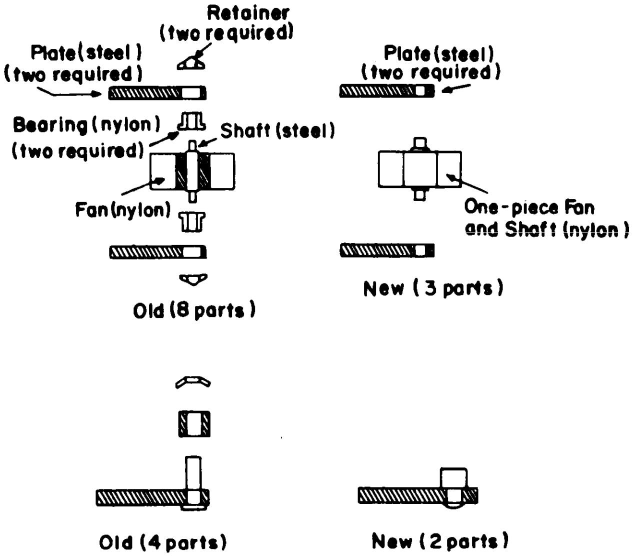

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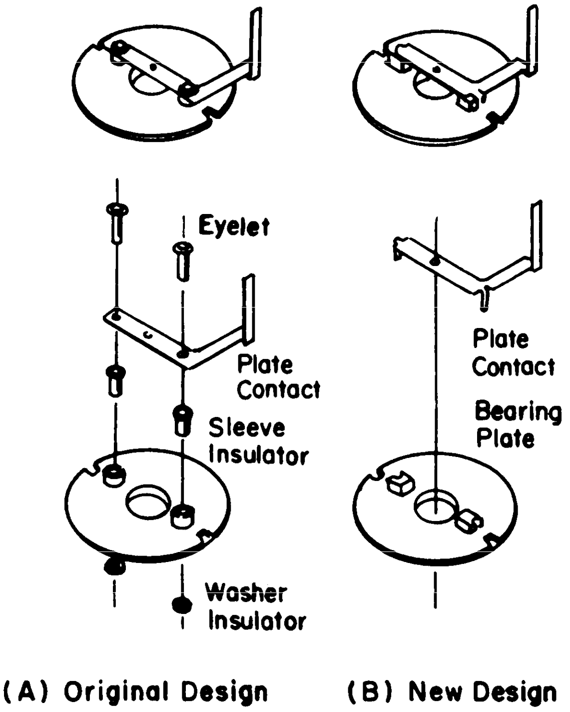
Figure 7-2. Further Examples of Product Simplification (Ref. 3)

7-2.1.1 Simplification by Manufacturing Process

It is sometimes possible to simplify a product by preparing it as a net shape using one of the new processes that enable a group of complex contacting parts to be produced as a single entity. These parts can sometimes replace complete subassemblies and hence elilminate many assembly operations. Powder metallurgy, warm and hot forging, and squeeze casting are examples of processes that may help in this respect.

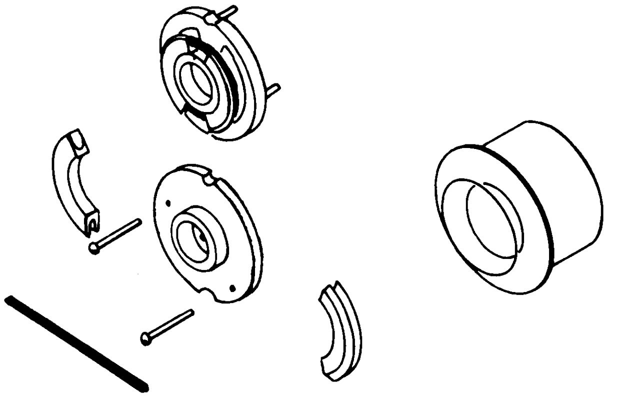
7-2.1.2 Simplification in the Assembly Process

One or more important factors may arise during the redesign of a product. For instance it might be sug-



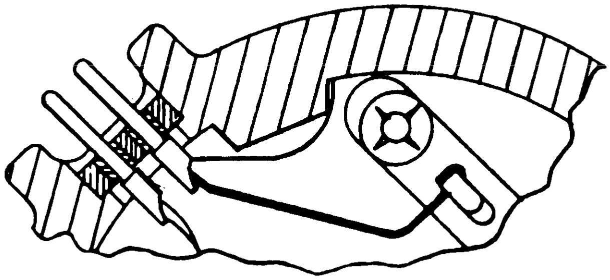
(A) Original Design **(B) New Design**

Figure 7-3. Eight-Piece Assembly Redesogmed to Two-Piece Assembly

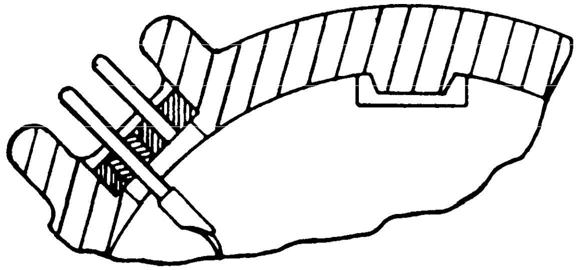


(A) Original Design **(B) New Design**

Figure 7-4. Six-Piece Assembly Redesigned to One-Piece Assembly

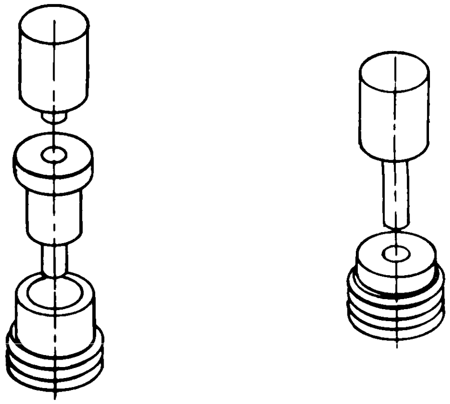


(A) Original Design
Jumper Wire from Receptacle to Ground Clip



(B) New Design
Receptacle Grounded to Housing

Figure 7-5. Ground Clip, Fastener and Grounding Lead Replaced by Pin Grounded to Housing



(A) Original Design
Actuator Pin Inserts Into Two-Piece Terminal Assembly

(B) New Design
Actuator Pin Passes Through One-Piece Insulated Connector Sleeve

Figure 7-6. Three-Piece Assembly Redesigned to Two-Piece Assembly gested in a particular situation that a screw, nut, and washer be replaced by a rivet or, alternatively, that the parts be joined by welding or by use of adhesives. The suggestion would eliminate at least two assembly operations but would result in a product that would be more difficult to repair. This illustrates a common trend in which the introduction of mechanization may result in a cheaper product but one that is quite uneconomical to maintain.

7-2.1.3 Guidelines for Simplification

There are no rigorous guidelines for product simplification across all product lines. There are only two checklist questions that can be used universally to achieve design simplicity:

1. Is this component necessary? Each component of an assembly should be examined to determine whether it can be eliminated and its function built into an existing component. Components should be examined jointly and individually.
2. Can these components be combined? In this situation the designer is seeking net shape manufacturing processes that can be used to manufacture, as an integral component, a series of mating or contacting components that do not move independently of each other.

7-2.2 HUMAN FACTORS AND MECHANICAL CONSTRAINTS

The net result of human or mechanical constraints is similar in almost all cases, but it may be easier for the product designer to consider them separate]}.

7-2.2.1 Human Factors

The human operator has a lot of dexterity and judgmental capabilities; however, the human is limited in arm span, grasp, and weight lifting and holding capabilities. For example, a single operator cannot perform an assembly operation requiring a 3.7-m (12-ft) arm span or three hands. Assemblies requiring more than one operator are difficult to develop and coordinate and should be avoided.

There are texts on human factors that list the types of things that people cannot do, the types of things that are difficult for them to do, and guidelines for avoiding both, e.g., Refs. 1 and 2. Considerations of human factors may conflict with the desire to reduce the number of components in an assembly. In case of such a conflict, the human factors should take precedence.

7-2.2.2 Mechanical Assembly Constraints

Mechanical devices may not have the physical restrictions of human operators, but the cost and space requirements of these devices should be considered in product design. The limitations on the span of the operation and on the weight of components that must be lifted are not as rigorous as the limitations for human operators, but such limitations must reconsidered just as they are in the structural design of other devices.

7-2.2.2.1 Mechanical Decision Making

Lack of logical decision making capability in machines must also be considered. When a man is instructed to insert a shaft into a bearing, he has the ability to feel that shaft into that bearing. .4 simple machine doing the same thing lacks the ability to adjust the location based on feel and, therefore, must have the parts precisely located and oriented. Proper fixturing is the key here. Just as in machining operations, assembly operations need accurate locations and flat surfaces for fixturing. Typically, the forces for assembly are normally rather low; however, occasionally the use of mechanical presses must be involved in which forces can become higher. Pm-haps the addition of an external boss with machined flats and precision holes for location can be used for both assembly and machining operations. Motor blocks, with their machined flats for seals, and gear cases, with precision holes for gear shaft mounting, are good examples of these methods.

7-2.2.2.2 Assembly Forces

Once the main part or body is accurately in place on the assembly machine, the individual part loading can be considered. Is the body strong enough to withstand assembly tooling forces? Be sure to consider any pressing, sizing, or machining opreations performed tried on the assembly machine. High production rates may increase these forces.

7-2.2.2.3 Assembly Motions

The next logical step is loading motions. Can the parts be placed in the main body with simple, short, straight-line motions? If not, can clearances be provided to assist the tool motions? Avoid combined rotary and straight-line motion if possible because these usually will require two or more stations. Also compound motions us usually require a separate special motion or even a separate machine. The assembly of turbine vanes is a good example of a compound assembly motion.

7-2.2.2.4 Assembly Tooling

In addition to loading motions, tooling clearances require some thought. Think in terms of disassembly. If you do not have room to glasp or push the part out of position, you may have difficulty loading it into that position. 11 precision alignments are required, locating points for the tooling will be requiled in addition to (clearances.

7-2.2.2.5 Product Design as an Assembly Aid

In all cases, chamfers, leads, and guide surfaces will enhance the assembly. Rivets are a good example of this. Because of hot forming and different vendors, the rivet chamfer may vary. Therefore, adding a chamfer on the mating part will enhance producibility of the assembly. On stamped parts the direction of punching may be important. As previously noted in par. 4-2.2.1.2, only the upper portion of a punched hole is cleanly sheared; the lower portion is torn out and is normally 10% oversize. Further, the punch will tend to deform the metal in a slight dome and pull any resulting burr in the direction of the punch. Any or all of these conditions could be detrimental to an automatic assembly. Also the relationship of groups of holes for mating parts is critical to assembly since the relationship of one group of holes to another can provide the primary alignment for proper functioning. Such groups should be dimensioned and located from a common location. This common location should be consistent within the assembly fixture.

7-2.3 ASSEMBLY SEQUENCE

There are two major factors the product designer should consider in regard to the sequence of assembly operations. One impacts the ease or efficiency of the assembly tasks; the other impacts the in-process inspection and repair of assemblies.

7-2.3.1 Efficient Assembly Sequences

In either manual or automatic assembly, position changes of the unit being assembled are wasted motions and are, therefore, detrimental to producibility. Assembly of small parts is difficult from any direction other than from directly above. Manual assembly of large parts can be performed on the sides, but assembly within or under the part is difficult. Therefore, assembly from directions other than directly above is a major factor to be considered in design.

7-2.3.1.1 Assembly Method

The aim of the designer should be to allow for assembly in sandwich or layer fashion, i.e., each part is placed on top of the previous one. The greatest advantage is that gravity can be used to assist in the feeding and placing of the parts. It is also desirable to have workheads and feeding devices above the assembly station where they will be accessible if a fault is caused by the feeding of a defective part. Assembly from above may also help to solve the problem of keeping parts in their correct positions during the machine index period when acceleration forces in the horizontal plane tend to displace them. In this case, with proper product design for self-locating parts, gravitational force should be sufficient to hold the part until it is fastened or secured. If assembly from above is not possible, it is probably wise to divide the assembly into subassemblies. For example, an exploded view of a power plug is shown in Fig. 7-7. In the mechanized assembly of this product, it would be relatively difficult to position and drive the two cord grip screws from below. The remainder of the assembly (apart from the main holding screw) can be conveniently built into the base from above. In this example the two screws, the cord grip, and the plug base could be treated as a subassembly dealt with prior to use of the main assembly machine.

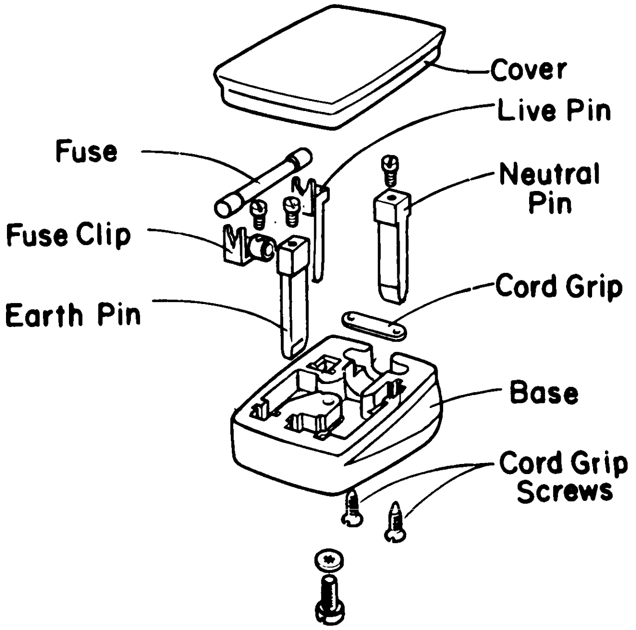


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Figure 7-7. Assembly of Three-Pin Power Plug (Ref. 3)

7-2.3.1.2 Assembly Process

It is always necessary in mechanized assembly to have a base part on which the assembly can be built. This base part must have features that make it suitable for quick and accurate location on the work carrier. Fig. 7-8(A) shows a base part for which it would be difficult to design a suitable work carrier. In this case if a force were applied at X, the part would rotate unless adequate clamping were provided. One method of insuring that a base part is stable is to arrange it so that its center of gravity is contained within flat, horizontal surfaces. For example, a small ledge machined into the part will allow a simple and efficient work carrier to be designed as shown in Fig. 7-8(B). Location of the base part in the horizontal plane is often achieved by dowel pins mounted in the work carrier. To simplify assembling the base part onto the work carrier, the dowel pins can be tapered to provide guidance as in the example shown in Fig. 7-9.

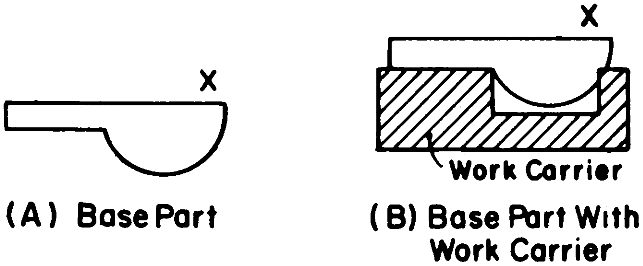

Figure 7-8. Design of Base Part for Mounting on Work Carrier

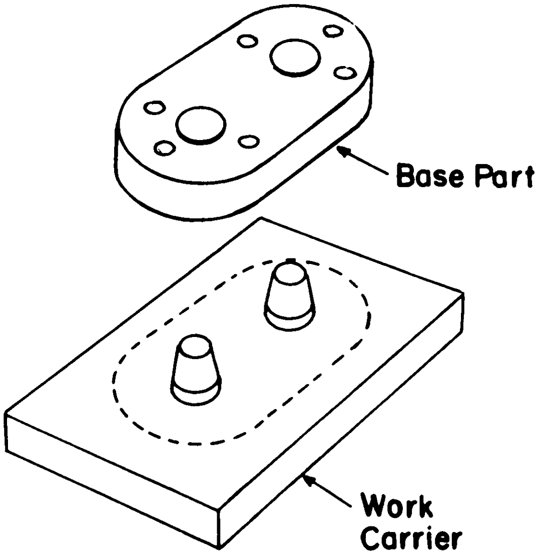

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Figure 7-9. The Use of Tapered Pegs to Facilitate Assembly (Ref. 3)

7-2.3.2 Assembly Sequence for In-Process Inspection and Repair

Excessive disassembly and resulting damaged component costs can be avoided if test and inspection of the partially assembled unit is performed early in the assembly process. The objective is to have a working assembly unit prior to the assembly of covers and cases. Therefore, the product designer should, wherever possible, segregate the working components from the cover. It should be possible to test important components before they are hidden from view and inaccessible.

7-2.4 DESIGN CONSIDERATIONS FOR HIGH-VOLUME ASSEMBLY

With a few exceptions, high-volume assembly means progressive assembly, in which assembly operations are divided among several work stations. Also progressive assembly can be found in low-volume operations. Progressive assembly does, however, place additional constraints on the product designer. Two obvious factors must be considered: (1) dividing the work of the assembly and (2) transferring the in-process unit from one assembly station to the next.

7-2.4.1 Work Division

Assume an operator has time to place two awkwardly shaped components into the assembly build. At the next work station a riveting operation is performed on one of the components with the possibility of dislodging the other. There are three alternatives:

1. Clamp the part which is likely to be dislodged while riveting takes place.
2. Use two operators. The first operator placcs one component, and at the next station riveting takes place. The second operator then places component number two, which is riveted at the following station.
3. Design the product so that both parts can be held and riveted at the same time.

The last alternative is of course the ideal, but it may not be possible. This example shows to some degree the depth of thinking necessary for product design and the need for sound knowledge of assembly line balancing techniques.

7-2.4.2 Assembly Line Balancing

The sequence in which parts can be assembled can be determined by logic, but more often a graphical approach is better, and it should show all alternatives. One such graphical approach is a precedence diagram. The sample in Fig. 7-10 shows the steps in getting dressed. This is a simplistic example to aid the understanding of a precedence diagram. Most assembly operations are more restrictive since the first loading operation is usually a single choice--a main casting or stamping.

However, in this simplistic example there are several alternatives for the first operation. Any of the events in column I may occur first; there is no required precedence. But the events in column II require that those events in column 1, with a connecting arrow, precede them in order of accomplishment. For example, you cannot put on your pants until after you have put on your shorts. Likewise, in column III you cannot put on your coat until after you have put on your shirt and undershirt. This is a precedence diagram-it describes only what events must precede other events. Do not be misled into believing that you must put your hat on before you put on your tie. All this chart says about the sequence of putting on your hat is that it must be preceded by putting on your undershirt. Everything else can be put on after you put on your hat, only the undershirt must precede it. This chart is not an ordering of succeeding events; it is only an ordering of preceding events.

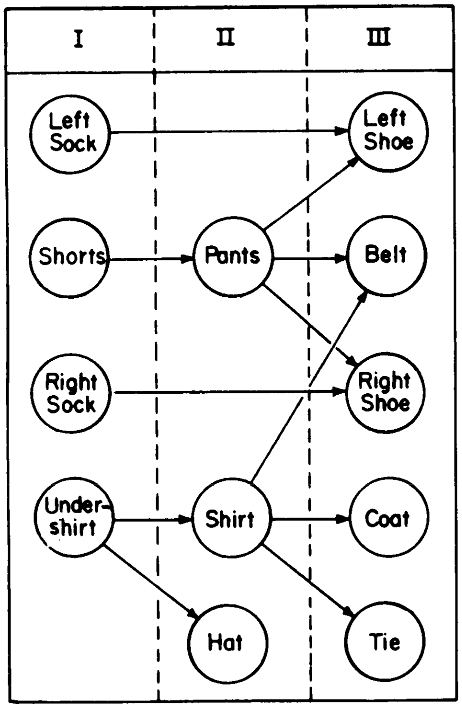

Figure 7-10. Precedence Diagram of How to Get Dressed

During the design phase, a precedence diagram may be helpful in designing the product for maximum flexibility during the assembly process. This flexibility provides the assembly machine configuration for means of optimizing his machine configuration for placement of operators, minimum floor space, accessibility for maintenance and operation, and the feeding and unloading positions of parts. The precedence diagram can also prevent designing something which cannot be assembled or which can be assembled but only with great difficulty.

7-2.5 DESIGN GUIDANCE FOR THE TOTAL ASSEMBLY

A set of helpful hints follows to assist the designer in achieving maximum producibility in mechanical assemblies from the standpoint of the total assembly.

7-2.5.1 Datum Surface

The product should be so designed that it has a datum surface or datum point on which to build the assembly. This provides a known vertical height for the automatic placing of components. As each component is placed in position. new location points are established. Close control of tolerances may be necssary to insure that when many parts are fitted together, the buildup of' maximum or minimum limits is within the capacity of the automatic workheads,

7-2.5.2 Location Points

The product should have location points for assembly to provide a known horizontal position for the automatic placing of components. If no salient features of the component can be used, tooling holes or projections on the component may be necessary. Datum and location points are commonly used in metal removing machinery. Therefore, it is reasonable to expect this practice to apply on assembly machinery. The words “vertical” and “horizontal” for positioning the components should be considered only as an explanation. The majority of products are assembled one part on top of another, but datum and location points are just as important where this is not the case. It is essential that as each component is placed into the assembly build, it is held in such a way that it cannot move out of position. The ideal is to have it held in position by surrounding parts, and this is most readily achieved if the assembly build is of the layer type, i.e., vertical build.

7-2.5.3 Vertical Build Assembly

Design the product so that one component can be placed on top of another. It is difficult to feed parts into the assembly from the side. For example, if a component is designed to be assembled into a vertically built assembly after the part above it and the part below it are in place, it must be fed into the assembly from the side. The alternative to this side feeding process is to attach the component previously to either the part above it or the part below it to faciliate automatic assembly.

7-2.5.4 Single Assembly Orientation

Never turn the assembly oven if it can be avoided. At best, a mechanial or manual work station will be needed to perform the operation. Complications can arise from working from a new datum and location, and the work carrier becomes more complcx. The most important reason is that, if the previously placed components have not been fastened together, turning the assembly over may cause them to move out of position. Even so, experience has shown that it is far better to turn the part assembly over than to assemble components from below. Feeding components from underneath complicates the workhead, esecially if accessibility is to be maintained for tool chainging and for clearing of jams.

7-2.5.5 Accessibility of Important Components

Any component whose position cannot be seen or readily checked by a mechanical probe after the assembly is complete must be checked during assembly prior to the positioning of other parts, or it must suffer the cost of remote sensing. Remote sensing can be accomplished through the use of X-ray or components containing low level radiation. Remote sensing can add extra workheads to the machine. On electrical equipment manufactured in large quantities—such as that found in automobiles, telephones, and domestic appliances—simple components are used. Small paper bushings are often used for insulation. These are difficult for an operator to handle and almost impossible for a machine. Insulated screws or rivets could be used instead, as shown in Fig. 7-11. An electrical continuity check will show whether or not the assembly is correct, This would be a very complex build if small insulated bushings had to be positioned between the screws and contact blades during the assembly.

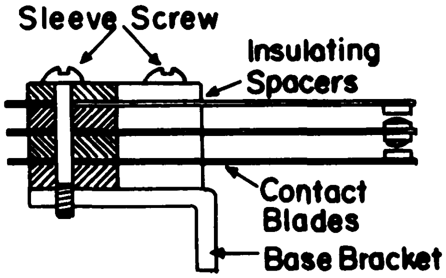

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Figure 7-11. Relay Stack Assembly Using Mylar Polyester Clad Screws (Ref. 3)

7-2.5.6 Standardize

The component parts in any one assembly or, better still, any one product should be standardized. Often component parts are difficult to differentiate, especially on small electrical assemblies. For example, rivets should be standardized to the same length, diameter, and material. Washers and screws are other possible candidates for commonality. It is very easy for the assembly machine to become jammed because the wrong parts have been introduced.

This difficulty can be overcome by coloring the components and painting the hopper feeder the same color, or by using some distinguished feature, such as type of rivet head. However, these are moves to be considered only when tooling an existing product for mechanized assembling. A little thought on new products can generally eliminate these expensive additions to storage, ordering, and administration.

Eliminate as many components as possible from the assembly. Examine the parts carefully in light of the production processes described in other chapters of this handbook to determine what parts can be combined. Finally, examine all parts to determine their essentiality to the intended design function.

7-3 PRODUCIBILITY CONSIDERATIONS FOR INDIVDUAL COMPONENTS OF AN ASSEMBLY

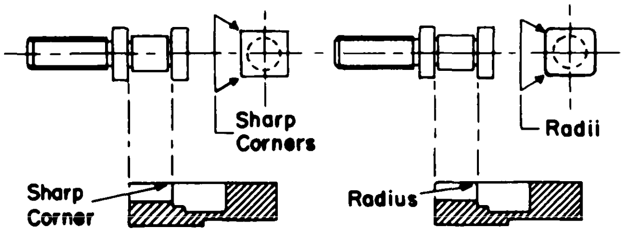
Previous paragraphs in this chapter have addressed the producibility considerations of the total assembly. The primary concern in this paragraph is to improve producibility in the assembly of an end item by considering the individual components. There are many things the designer can do to the individual components that will enhance producibility of the assembly. The problem is simplified if these are categorized under their two major objectives, i.e., (1) ease of assembly of parts and (2) feeding, orienting, and loading parts,

7-3.1 EASE OF ASSEMBLY

The designer can contribute greatly to the producibility of a mechanical assembly through the design of special features of components to facilitate their assembly. The approach should be to design all components so that they will fall together and can be oriented with either side up—i.e., no preferred orientation. The basic rule should be to design the components for easy manual assembly. It naturally follows that if the product is easy to assemble by hand, it is probably easy to assemble by automation.

7-3.1.1 Elimination of Sharp Corners

To ease assembly, it is always good practice, as demonstrated in Fig. 7-12, to allow generous chamfers and to eliminate sharp corners that can cause parts to cross lock. Human operators often resort to selective assembly when parts do not fit; if necessary, they discard a part and pick up another. This cannot happen on machine assembly.



(A) Accurate Positioning Needed For Assembly
(B) Ports Foil Together Easily

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Figure 7-12. Generous Radii and Chamfers Help Assembly (Ref. 3)

Good examples of the need for chamfers are screw point forms. The point form of a screw is the feature that dictates more than any other whether it can be located in true relationship to the mating thread ready for driving. If one attempts to drive a screw automatically into a tapped hole that is not easily accessible (for example, at the bottom of a counterbored hole), it is often impossible to control the screw point so that it positively centers in the tapped hole. Under these conditions it is necessary that the form of the screw point is such that the screw centers itself. This example is particularly difficult, but self-centering screws should be used at all times if possible. In the examples of screw point forms shown in Fig. 7-13, the cone and oval points tend to be self-centering. Evaluation of the various types of thread point follows:

1. *Rolled Thread Point.* Very poor in locating hole—will not center without outside diameter positive control
2. *Header Point.* Only slightly better and then only if guaranteed to be forged square and clean
3. *Chamfer Point.* Fair in locating hole since the chamfer angle is larger than the header angle
4. *Dog Point.* Fair in locating hole
5. *Cone Point.* Very good in locating hole
6. *Oval Point.* Very good in locating hole.

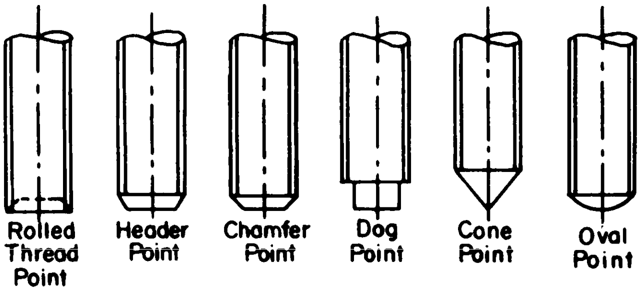

Figure 7-13. Types of Thread Point Commonly Encountered in Assembly Operations

The approach used with screws applies equally well to all components, i.e., if the parts will fall together, it is impossible to do better.

Fig. 7-14 shows the line of approach that should be adopted if possible; let the parts fall naturally into place.

7-3.1.2 Self-Guiding Assemblies

Apart from eliminating sharp corners on screws and pins, great improvements often can be made by the introduction of guides and tapers that directly facilitate assembly. An example of this is given in Fig. 7-15. Sharp corners are removed so the part to be assembled is guided into its correct position during assembly.

7-3.1.3 Component Design to Facilitate Assembly

The designer's primary objective is to create a design that satisfies the performance characteristics of the product. Of secondary concern are the producibility aspects of the components in that design. All too often the concern stops there without considering the assembly aspects of the finished part. Frequently, it is assumed that if the components can be assembled in the prototype shop, the item is adequately designed for producibility. A second look at the design would reveal that some basic redesign with the proper guides, chamfers, etc., would ease the assembly operations and maximize the producibility of the item. This "second look" can be doubly rewarding because it facilitates assembly and provides the added benefit of assuring that the design will be properly assembled into a functioning end item with a minimum of rework and rejects, which maximizes the producibility aspects. This second look at the design can also provide the necessary design features to permit the use of common parts, ease of feeding, orienting, and loading parts in the assembly process.

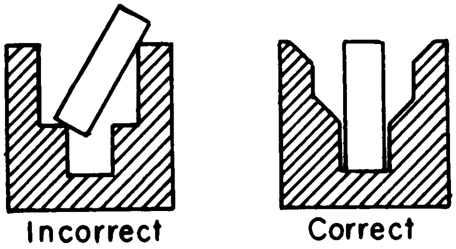

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Figure 7-14. Remove Sharp Corners so That Parts Will Fall Naturally into Place (Ref. 3)

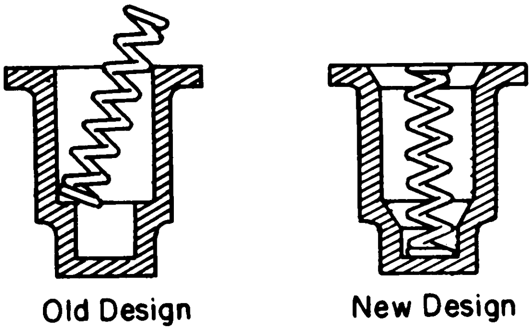

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Figure 7-15. Redesign of Product for Ease of Assembly (Ref. 3)

7-3.2 FEEDING, ORIENTING, AND LOADING

The necessity for feeding components so that they can be separated, oriented, fed, and placed by an automatic device is another basic reason for designers to take a “second look” at their designs. In assembly this is referred to as rethinking the component design. Most problems of feeding, orienting, and loading originate in the design of the component.

7-3.2.1 Component Design to Facilitate Feeding

The product designer must first consider the various ways components are delivered to the assembly stations.

7-3.2.1.1 Fabrication at Assembly

For example, one can supply strip material to the machine, form the part, and immediately place it into the assembly build. This eliminates all the problems of handling the component in a bulk form, i.e., taking a random heap of components and marshaling the components into a single file, orienting them for individual selection, then placing them into the assembly build. The alternatives for consideration by the designer are as follows:

1. Make the component on the machine.
2. Load the component ‘into a magazine or buy components preloaded in magazines or rolls.
3. Deliver components in a random bulk to the machine.

Knowing which method can or cannot be used depends on cooperation between the machine tool designer and the product designer. Normally, making the component on the machine usually involves only press work. Because of slight interference, irregularities, or eccentricity of mating parts, fine metal chips, powder, or shavings, known as swarf, can be created. Swarf is a thing to avoid on the assembly machine since it tends to create considerable difficulties by contamination of the machine and product being assembled. (Also see par. 7-4.2.5 on force fitting.) Fig. 7-16 shows a simple washer being made and passed straight to the assembly build.

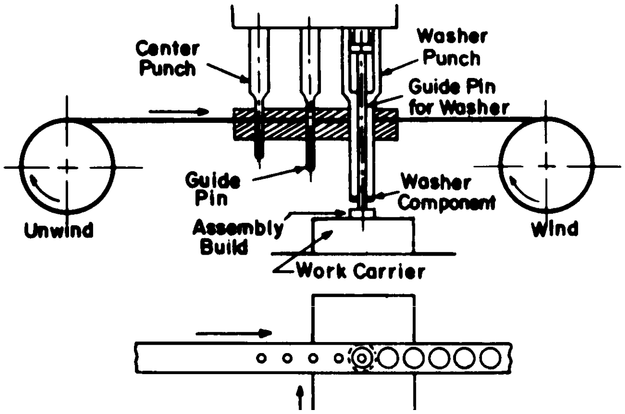

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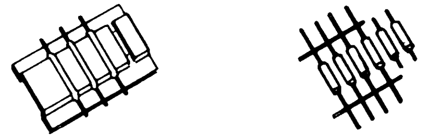
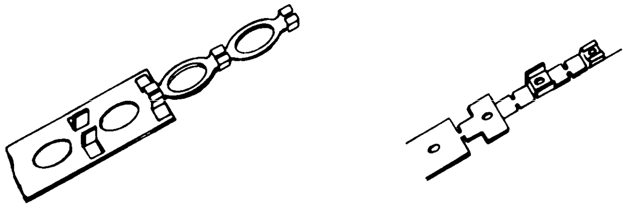
Figure 7-16. A Simple Washer Being Made and Passed Straight into the Assembly Build (Ref. 3)

7-3.2.1.2 Prepackaged Components

The technique of loading the component into a magazine, as demonstrated by Fig. 7-17, is used frequently by the electronics industry for components that are difficult to handle by other means. Another example of magazine supply is a stapling tool in which the staples are supplied stuck together ready for placing into the tool. Ballrace outer rings and even complete ballraces can be purchased in cardboard tubes ready for mounting on the assembly machine. There are other uses for the magazine, such as for sorting out faults prior to presenting the part to the machine and using the magazine as an inspection device.



(A) Reed Switches Carried In Plastics Carrier **(B) Semiconductors Carried on Wire Strips**



(C) Terminals Joined Together **(D) Press Part With Captive Nut**

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Figure 7-17. Magazine Loaded Components (Ref. 3)

7-3.2.1.3 Bulk Delivery of Components

Delivering components in a random bulk to the machine is the most common method presently used. The necessity for feeding components so that they can be separated, oriented, fed, and placed by an automatic device is the basic reason for rethinking component design. The major considerations in this rethinking process are component configuration, manufacturing tolerances, and component quality because these are the major factors that influence bulk delivery methods.

7-3.2.1.4 Feeding Methods

Parts arriving at the assembly machine are usually delivered in bulk and are typically placed in a hopper and then tracked to a loading station. Whether the hopper is vibratory, rotary, or oscillatory, it relies on gravity and/or friction to move parts past gating or orienting features to allow only parts in the proper orientation to pass to the next orienting feature and ultimately out of the bowl into a track. Typically, nonvibratory feeders are limited in the number of orientations they can perform. Some of the feeding problems are listed:

1. First is the number of orientations required. In many cases, unoriented parts are returned to the bottom of the bowl. The odds of a part going out of the bowl on its first try decrease with the number of orientations required. The way to increase the odds is to reduce the number of orientations by part symmetry.

2. Hard to sense features, such as off-center holes or cavities, are another problem, and sometimes they may require extra tooling outside the bowl to sense and orient. The obvious solution to this dilemma is to change dimensions, to add an external feature, or possibly to change the center of gravity of the part.

3. Tangling is another common problem. A protrusion on the part can enter an opening in another part. Here again, the solution is obvious—eliminate the protrusion, close the opening, or both. The compression-type coil spring is the most common part that has this problem. Close coiling the ends, increasing wire diameter, and increasing the pitch all help alleviate the condition.

4. Nesting, such as paper cups, can also be a problem. Here the solution can be either to keep them from engaging by changing diameters to keep them from sticking by increasing the angle of the taper or by adding ribs.

5. Shingling, or overlapping parts in the feed mechanism, is sometimes a problem. It may be possible to feed parts in this attitude, but it usually complicates the escaping of the overlapped parts from the end of the track. Increasing the thickness of the surfaces contacting adjacent parts as shown in Fig. 7-18 or providing a different tracking surface may solve this problem.

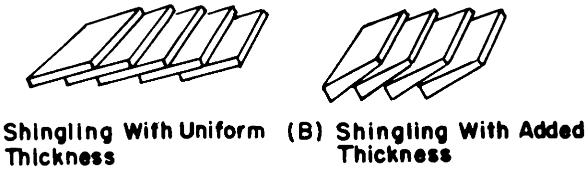
(A) Shingling With Uniform Thickness (B) Shingling With Added Thickness

Figure 7-18. Overlapping Parts Feed

6. In in-line feeders or in any place where the top of the part is confined, jamming may occur. This is true of extremely thin parts and of parts with tapered edges. Solutions are obvious once the problem is defined: keep the parts from climbing and jamming by making the common contacting surface large and vertical or increase the angle of the contacting surface to the point where parts will not climb.

7. Another part configuration that can lead to poor hopper efficiency and can severely limit feed rates is instability caused by the tracking surface and center of gravity. If the part is unstable in the sense that its center of gravity is high relative to its tracking surface dimension, the part will fall over. Related to this is having the part land wrong side up when it is returned to the bowl. The design change here maybe moving the center of gravity or increasing the tracking surface.

8. Soft or rubber parts cause still another problem. They may tangle in the hopper, but more serious, the bowl driving forces may distort the part to the point that orienting in the bowl is impossible. Distortion of parts caused by stacking and handling can create serious problems. Plastic, rubber, and thin metal parts are susceptible to these adversities. Additionally, parting line flash from molded parts can be easily overlooked since it does not appear on the drawings. This is analogous to burrs and cutoff tabs in stampings. The designer of feeding mechanisms should keep in mind that the part drawings may show a perfectly clean part, but the actual part from the manufacturing process may have these minor imperfections that can cause feeding difficulty unless they receive adequate consideration early in the process.

9. The sensitivity of the part to moisture, static electricity, and residual magnetism are usually not apparent until too late.

10. Sometimes certain surfaces are sacred and must be protected for subsequent operations. “Ibis problem may preclude using automatic feeding methods.

11. New dies and molds, including multiple cavities, can also create problems in building and running the assembly machine. After the dies and molds hate been run for a time, problems of excess flash and sharpness disappear.

12. Incompletely molded and broken parts add to the problem of poor efficiency.

13. Foreign material will usually decrease hopper efficiency. This includes not only material from machine environment but also contamination of the parts from previous processes.

Once you have paid for an orientation, why discard it? One method of retention is to use trays or magazines to transport parts and to feed the assembly machine loading stations. Another is to feed directly into the next assembly station or through a queueing device into the next machine. Direct in-line feeders are commonly used for this purpose.

7-3.2.2 Orienting Methods

There are two types of easily oriented component configurations. The ideal is the completely symmetrical part, which, by its very nature, is always in an oriented condition. Examples, illustrated in Fig. 7-19, are a sphere (e.g., a ball bearing), cube, and cylinder.

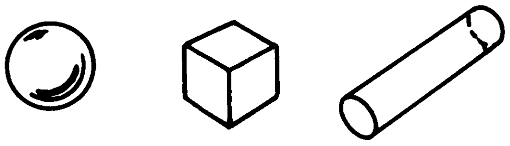

Figure 7-19. Symmetrical Parts

The second type is a component with marked polar properties, either of shape or weight. If it is the shape that creates the difference, some mechanical means of orientation is usually possible. The greater the difference, the easier orientation becomes. If the difference is weight, the location of the center of gravity to one end of the component produces a natural tendency to feed and be oriented in one direction. Quite often both shape and weight apply on such components as those illustrated in Fig. 7-20. From the foregoing we have two simple rules:

1. Components should be symmetrical if possible.
2. Components should have distinct polar properties by geometry and/or weight if they are not symmetrical.

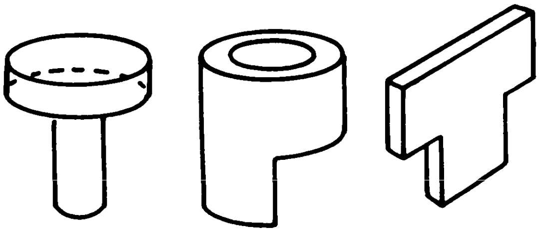

Figure 7-20. Nonsymmetrical Parts

All orienting systems, when bulk feeders are used, must be based upon the natural resting aspect of the component. If components already exist, it is simple to find this property. For example, if 100 component parts of a given type are tossed into the air to fall on a flat table, the majority will normally come to rest in a particular orientation. All orienting systems should start with this; otherwise one will be working against nature.

As an example, consider the shapes in Fig. 7-19. It is obvious that these would all come to rest in the same aspect. If, however, the cylindrical object had a length equal to its diameter, it might fall on the flat face of the part. If the object became a disc, it would certainly fall on a flat face.

For the parts in Fig. 7-20 other than the tee part, it would not be possible to predict the natural resting aspect. The tee part would fall on one of its flat faces, but if it had a length equal to its width, it would also become unpredictable.

Having found the natural resting aspect of the part, the next objective is to devise a system so the items not in their natural resting aspect can be so positioned. The three techniques used are described.

7-3.2.2.1 Statistical Technique

The statistical technique, so called because of its reliance on the statistical probability that parts will arrive properly oriented, is usually performed on tracks in a vibratory bowl feeder. This technique uses the silhouette or profile of the part to determine correct orientation. The parts flow past a shaped opening on the track. If incorrectly oriented, they fall through and return to the feeder bowl as shown in Fig. 7-21. The system has limitations in that it depends on component shape and center of gravity, i.e., parts must be markedly asymmetrical. Some form of mechanical filter is used for this operation.

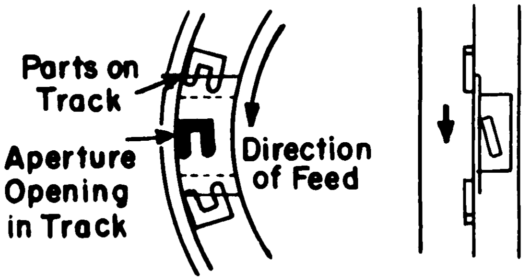

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Figure 7-21. The Silhouette or Profile Method of Part Orientation (Ref. 3)

A variation of this profile technique, called the air jet variation, is used when the asymmetrical features of the part are vertical to the feed track as shown in Fig. 7-22. In this situation the parts are fed through an inclosed track past improperly oriented profile openings in the

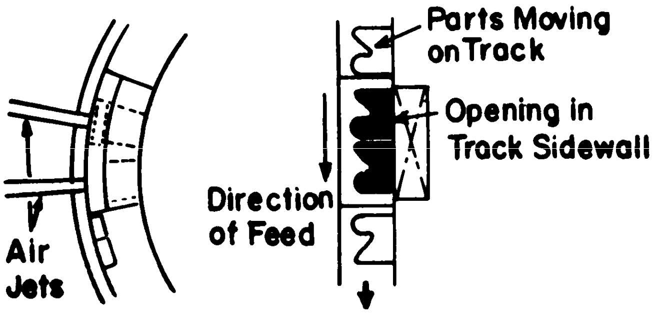

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Figure 7-22. Air Jet Variation (Ref. 3)

track sidewall. Air jets on the opposite side of the track blow improperly oriented parts through the profile opening. Frequently, dual openings are used to provide a second filter to capture improperly oriented parts that might pass the first profile opening.

7-3.2.2.2 Polarizing Technique

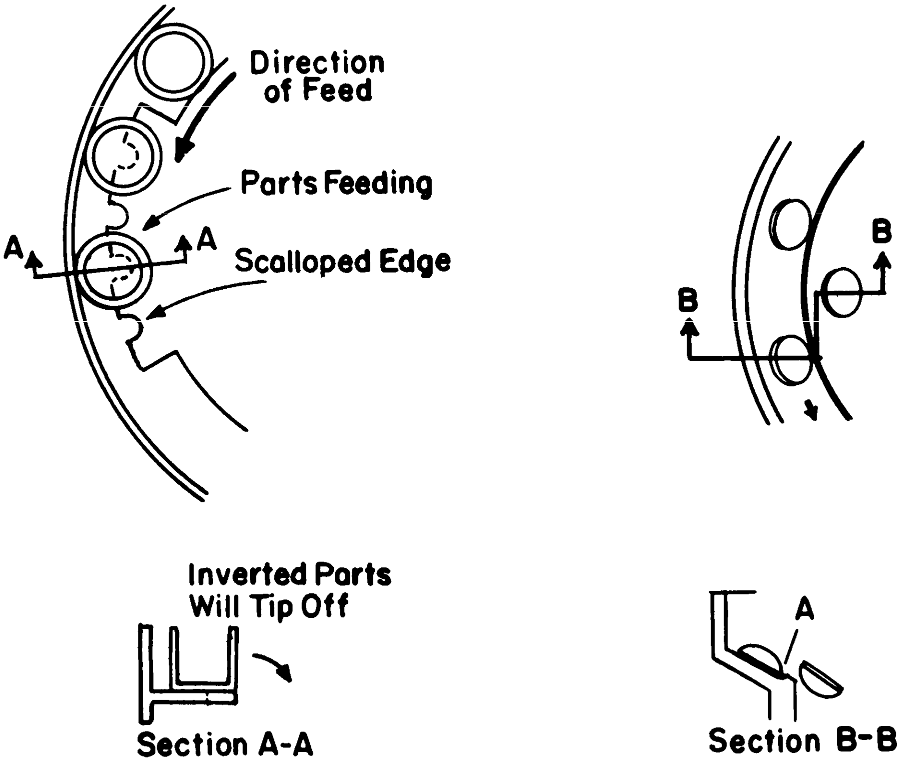
This system is very similar to the statistical technique. The difference is that with the statistical technique, shape is the principal means of selecting correctly and incorrectly oriented parts while the polarizing technique is used where both shape and weight differences occur. Mechanical filters are used in the vibratory bowl feeder in this technique also. In Fig. 7-23 typical examples of the polarizing technique are shown. In Fig. 7-23(A) the base of the track carrying cupped parts is scalloped. The parts are needed open end and any inverted parts engage with the scallops, overbalance, and return to the bowl. In Fig. 7-23(B) the small ledge A prevents correctly oriented parts from falling back into the bowl.

7-3.2.2.3 Other Techniques

The generally ideal components, those which are symmetrical or have marked polar properties of shape and weight, have been considered. It is components that fall between these ideals that cause the greatest difficulty with orientation. The complex range of probable shapes in an assembly precludes any scientific formula to guide the product designer. It is therefore necessary to use simple examples.

A cube is a perfect part for orientation provided all the faces are symmetrical about their center. A cube has six faces, and each face has four edges, any of which could be the base and leading edge. In all there can be 24 alternative leading edges. The orienting probability of a cube is 1/24 because the alternative number of possibilities is 24. To find the correct position of an offset blind hole in one face of the cube, one must select one of 24 possibilities. There is no great difference in weight to affect the natural resting aspect of the part. In Fig. 7-24 if the hole had been on the centerline on one face of the cube, the orienting probability would be 1/6, or one face of six possible faces. On an average one part in six would be in its correct position. No holes at all or holes on all faces returns the component to a perfect symmetrical condition, i.e., where any face or any edge is acceptable and the orienting probability would be one.

A solid or hollow sphere is a perfect part; it is always oriented properly. If it is modified only slightly, it



(A) Cupped Parts

(B) Dished Parts

Figure 7-23. Examples of Polarizing Technique

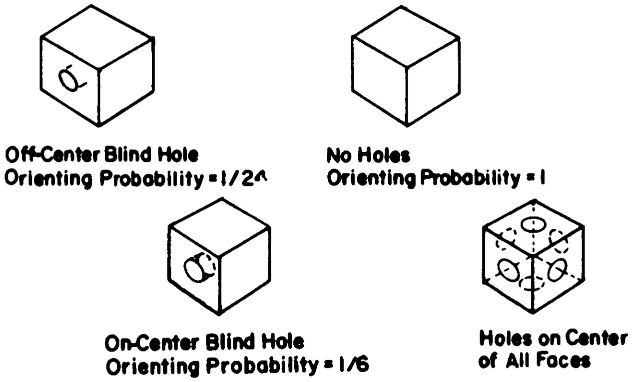


Figure 7-24. Cube Shaped Component

becomes difficult to orient. In Fig. 7-25 a sphere is modified into a bead by a central hole through it. Assume it is desired to detect the hole so another part can be assembled to the sphere. If the hole is large enough to form effectively a pair of flats, there is a good chance of orienting because a marked polar difference in shape and weight has been created. The center of gravity has been altered in one plane so that the natural resting aspect would tend to allow the part to be resting on one of the two flat portions. If the hole were so small that the sphere had no short axis, orientation would be difficult without sophisticated, costly equipment. These two examples produce a third rule, i.e., component should have the least possible number of important directions.

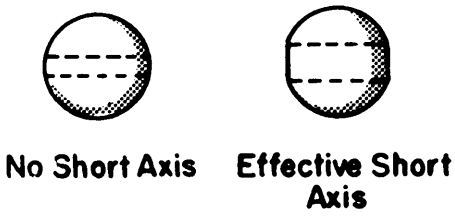


Figure 7-25. A Modified Sphere

7-3.2.2.4 Design to Minimize Orientation Problems

There are numerous everyday examples of near symmetrical, simple parts that, due to minor differences, cause considerable problems with orientation. Consider a round pin as shown in Fig. 7-26. Many dowel pins are spherical at one end and have a chamfer at the other, i.e., no marked polar difference to assist in easy orientation. Why could it not be either chamfered or spherical at both ends? Functionally it does not matter, and the only object of the spherical end is appearance. To have a spherical format both ends may be too costly, but these are the sorts of questions the product engineer must ask himself. If in doubt, he can discuss his problem with the machine designer who will be faced eventually with the task of handling the part automatically.

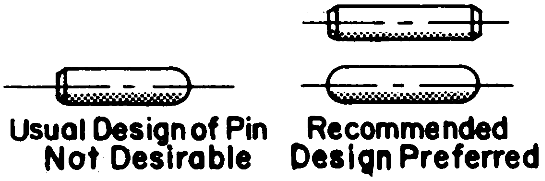


Figure 7-26. Dowel Pin Designs

Consider the orientation of washers or discs. Often the part has a slight radius on one edge that has to be in a given plane, but this radius is often not sufficiently pronounced to orient the part. When the radius is enlarged or replaced by a sufficiently rigid chamfer, a small lip will retain the washer in one position but will allow it to fall back into the bowl in the other position. Fig. 7-27 illustrates this. On pressed washers or discs the radius is fairly constant, and at times parts would be fed the wrong way. If the radius is made smaller than the lip shown in Fig. 7-27, the part will pass as a correctly oriented one.

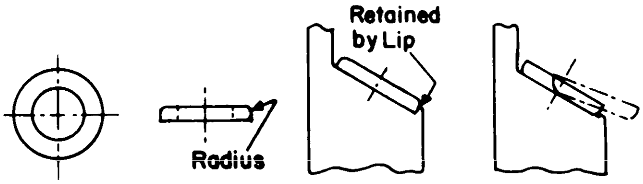


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Figure 7-27. Washer or Disc Components (Ref. 3)

7-3.2.2.5 Components That Tangle

Components that can tangle and are difficult to separate are a hazard. This applies as much to a manual line as to an automatic assembly machine and generates another rule, i.e., avoid the use of components that can tangle with one another.

The most notorious component in this respect is the open coil compression spring shown in Fig. 7-28. To avoid entanglement in feeding devices, it may even be necessary to couple a spring winding machine to the assembly machine. This would produce, one at a time, the springs needed for each assembly at each cycle of the machine.

There are two areas of difficulty here that the product designer should investigate. One concerns secondary treatment to the component—heat treatment or a further operation, which cannot be performed economically on the assembly machine. The other concerns the spring characteristics. Spring winders are affected by the material used, and a slight difference in the compo-

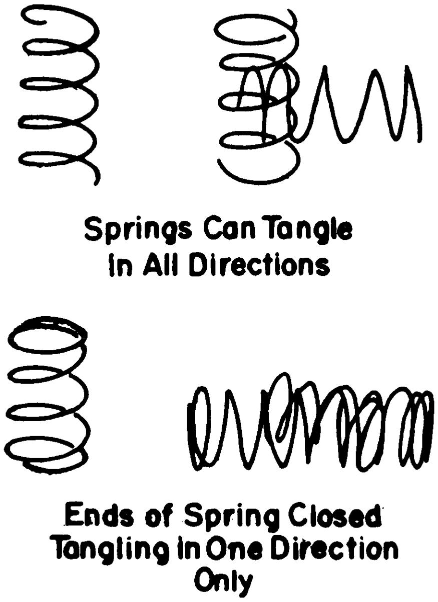

Figure 7-28. Open Coil Compression Spring

sition or diameter of the wire can alter the spring rating. These variants must be taken into account when designing the product. Too stringent a rating may require excessive inspection of stock, which results in very low production rates and thereby precludes the use of a spring winder adjacent to the assembly machine.

Slight modifications to many components can eliminate tangling problems. The open spring lock washer, shown in Fig. 7-29(A), will tangle, but the closed type (Fig. 7-29(B)) will do so only under pressure. Modification does not affect function. A straight, continuous slot invites trouble, but it can be avoided by a simple modification to the design, as illustrated by Fig. 7-30. Nesting is a hazard with open-ended components. The original parts shown in Fig. 7-3l(A) were bound to nest. Four internal ribs, as shown Fig. 7-3l(B), are an effective remedy. Another common mistake is found on small pressed parts with lugs and slots. The slots are often larger than the lugs, as shown in Fig. 7-32(A), and parts get locked together. As in Fig. 7-32(B) the designer should make a point to specify slots smaller than the lugs on a component to prevent the parts locking together.


(A) Open Type **(B) Closed Type**

Figure 7-29. Open Spring Lock Washer

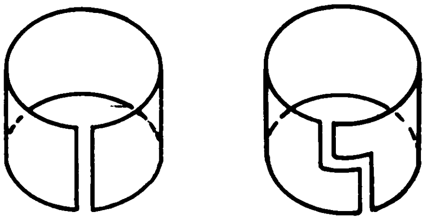

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Figure 7-30. Straight Continuous Slot (Ref. 3)

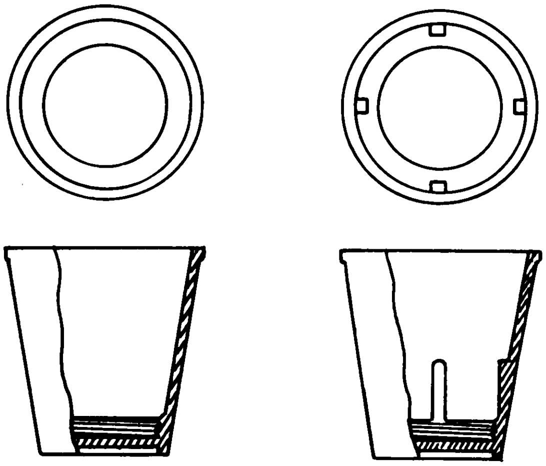
(A) Original Part **(B) Part With Ribs**

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Figure 7-31. Open-Ended Component (Ref. 3)

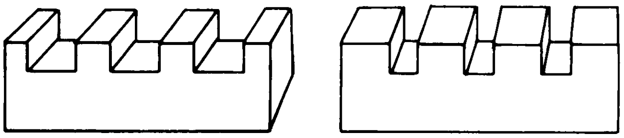
(A) Slots Wider Than Lugs **(B) Lugs Wider Than Slots**

Figure 7-32. Parts With Lugs and Slots

7-3.2.2.6 Critical Assembly Dimensions

Consistency in the dimensions used to feed, orient, and locate the component is essential. With manual assembly certain dimensions are not important. Operators can make adjustments, and the components are not mechanically handled in hopper feeders, along chutes, and into slides where jams can occur through inconsistency of manufacture. The assembly machine, on the other hand, is accurate and has dimensional limits on its work carriers, workheads, hoppers, and chutes. It is also inflexible and cannot learn to cope with components outside these limits. The designer must consider the tolerances that the assembly machine can accommodate, and the shop producing the component must not exceed them, or the assembly machine will fail. Of course, the added cost of improving component quality and consistency may not be worthwhile under certain circumstances. This again is where complete cooperation is essential among product design, machine design, and the production shop floor.

7-3.2.2.7 Tolerances and the Assembly Process

With regard to the connection between tolerances and the ability to feed, consider the case of a screw. (Also see par. 7-4.1.) The majority of screws with a head diameter appreciably larger than the shank diameter can be fed, but in the case of a screw with a head only slightly larger than the shank, difficulties can arise. Fig. 7-33 shows the results of an experiment to find minimum length to head diameter ratio of a pin for successful feeding. Below a ratio of 2.5:1 orientation becomes uncertain.

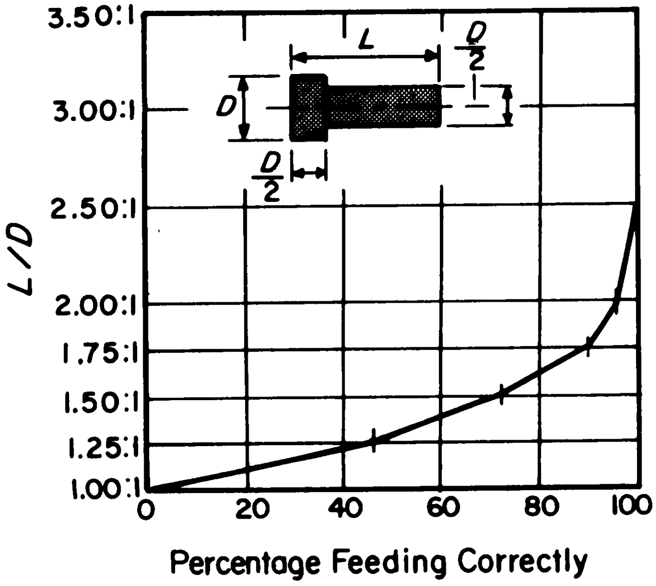

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Figure 7-33. Feeding Rate of Pins With Varying Lengths to Diameters (Ref. 3)

Certain manufacturers of electrical equipment sometimes use a 6BA screw cut from standard stock brass bar of nominal 3.18 mm (0.125 in.) diameter. This screw has a head diameter of 3.18 mm (0.125 in.) and a shank diameter of 2.77 mm (0.109 in.). This leaves a shoulder under the head of only 0.20 mm (0.008 in.). To feed the screws successfully, the carrying mechanism has to be made very accurately and the quality of the screw very carefully controlled. The product designer must control these two items:

1. The head must be concentric with the shank.
2. There must be an absolute minimum or no radius at all under the head.

It would be most difficult to orient a headed part with such a small diameter other than between rails as shown in Fig. 7-34(A). For most screws it is necessary to transport them finally through a tube into the screwdriving workhead as in Fig. 7-34(B). Occasionally it is necessary to feed through both rails and tube as illustrated in Fig. 7-34(C). A well-finished screwdriver slot is essential. Other quality characteristics apply in addition to the length to head diameter ratio. For example, excessive saw burr in the screwdriving slot must be avoided; otherwise the screw will jam in the tube. The overall length must, in all cases of transport through a tube, be greater than the screw head diameter to prevent jamming.

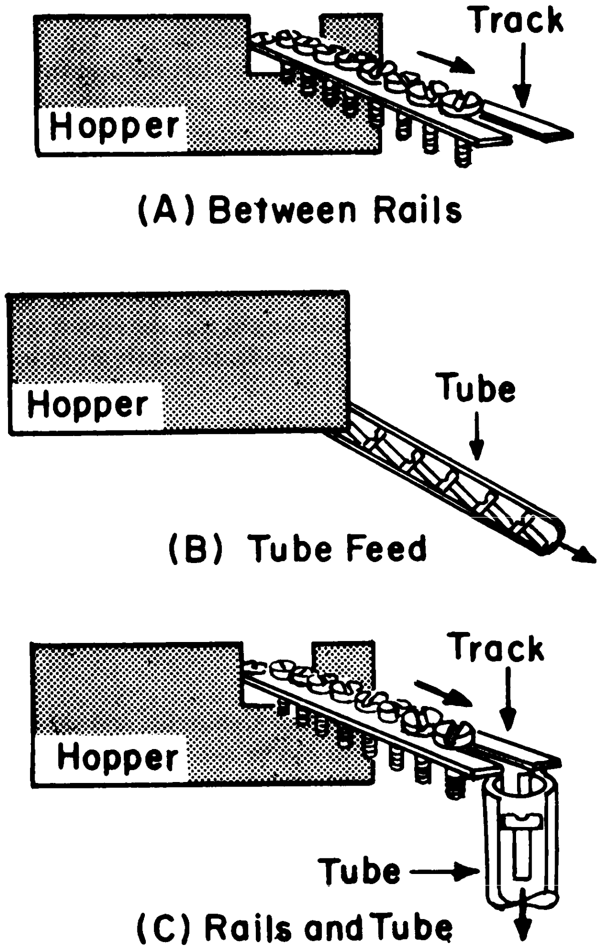

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Figure 7-34. Three Modes of Transfer for Headed Fasteners (Ref. 3)

The points that follow are those the product designer must consider in screw component design and, when necessary, provide for on the component drawing. As a guide to product designers, the following ratios of length to head diameter may be of assistance:

1. Danhead screws: L = 1.1 *H*
2. Round, countersunk, and raised countersunk head screws: L = 1.25 *H*
3. Hexagon head screws: L = 1.25F

where

L = minimum nominal length under the screw head
H = head diameter
F = hexagon head across corners.

Component tolerances also affect the buildup of an assembly. Fig. 7-35 shows a buildup of plates and washers riveted together. In Fig. 7-35(A) the assembly will be loose because all components are made to a minus tolerance. If pulled tight, the rivet shank may bend and cause stress in the parts being assembled. At the other extreme, shown in Fig. 7-35(B), where the parts are all made to plus tolerance, the rivet maybe too tight, and considerable strain may be placed on the rivet setting head. Rivets which are too loose or too tight will cause the rivet setting machine to become overloaded and stall. As shown in Fig. 7-35(C), some form of makeup washer may be necessary to bring the overall tolerance to within limit if it is not possible to maintain a consistency in the dimensions of the components used. Fig. 7-36 indicates the cost increases one may encounter when tightening tolerances in riveted assemblies.

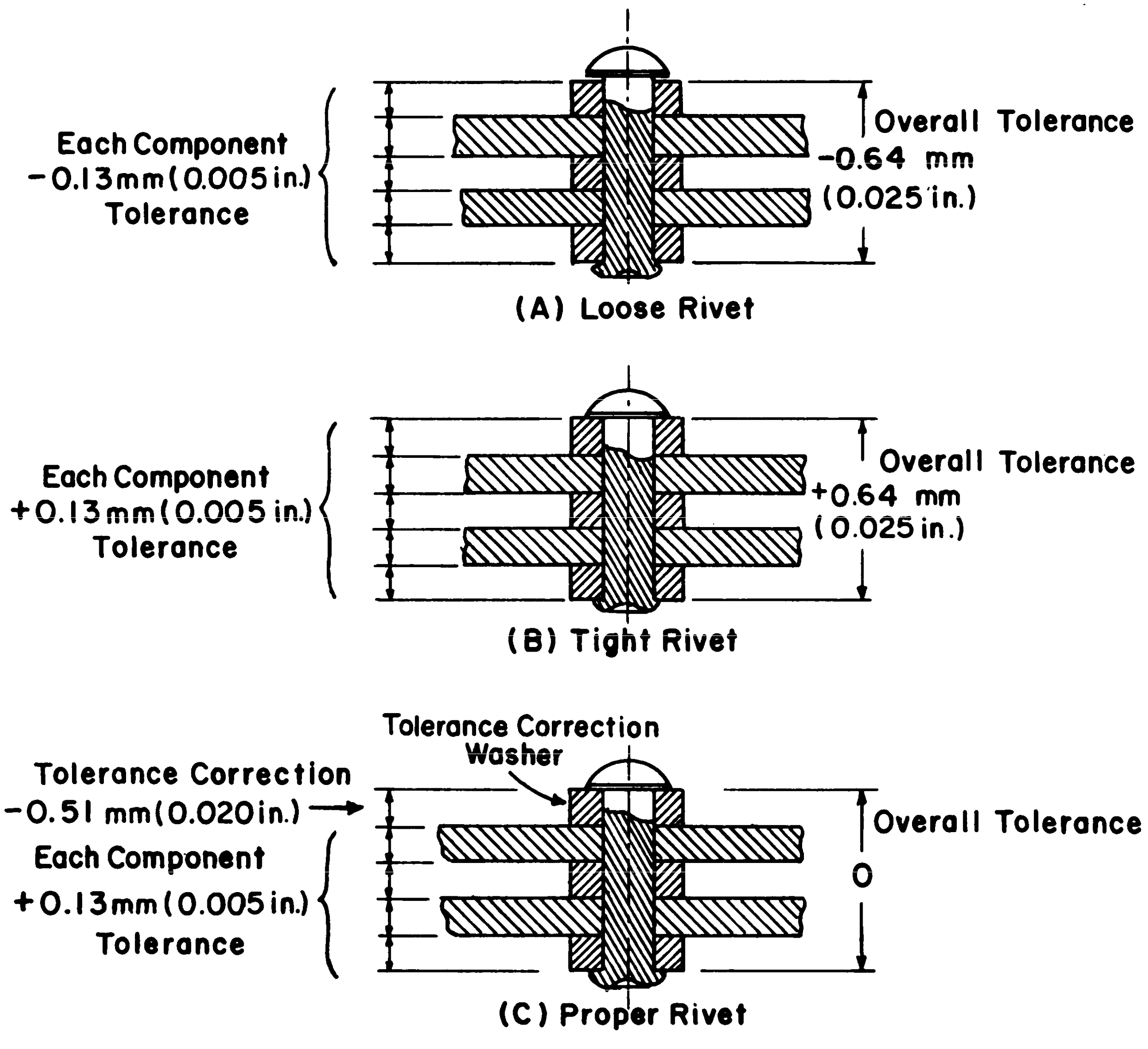
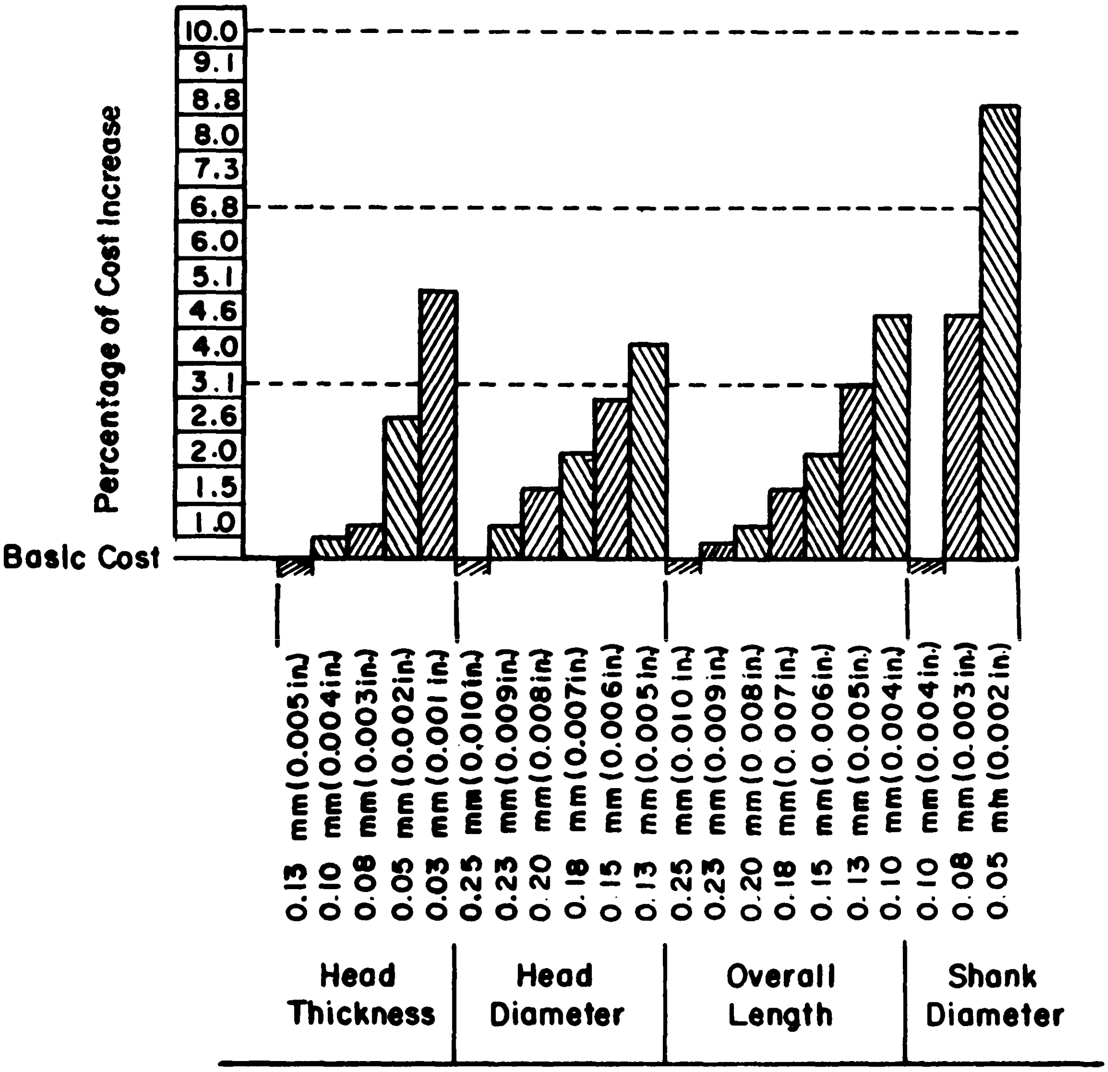


Figure 7-35. Examples of the Effect of Accumulative Tolerances



NOTE: The smallest tolerances given represent the recommended practical minimum limits. Basic cost is unit cost at time of study, and the cost increase is compared to that basic cost.

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Figure 7-36. Cost Increase of Closer Tolerances on Rivets (Length = 7.11 mm (0.280 in,)) (Ref. 3)

7-3.2.3 Loading Methods

The most efficient type of loading station is one at which the part can be dropped into the assembly over a pilot pin from either open tracks or a tube and then followed down with tooling to insure part placement, This free-fall, self-locating loading method is most efficient because of its simplicity, This loading method will also provide very high efficiency. For loading in this manner pilot holes are required in the part as is a location feature in the mating part. The short, straight-line motion is also an asset in. obtaining high station efficiency.

Unfortunately, not all parts can be loaded into the assembly build using a self-locating, free-fall method. Some parts will require that they be grasped, lifted, and moved into the assembly build. There are three possible methods for grasping parts to load them into the assembly build:

1. Mechanical clamping
2. Vacuum
3. Magnetic forces.

Mechanical clamping requires the mechanical actuation of a clamp. This is usually accomplished with a pneumatic device and, therefore, involves the use of timed signals, solenoid valves, and complex tool motions, all of which tend to decrease efficiency of assembly. However, parts can be designed to minimize the decrease in efficiency by providing good clamping surfaces, pilot holes and pins for assembly alignment, generous chamfers for easy entry, and short, easily controlled loading motions. The best test for each of these attributes is to put yourself in the place of the loading device. If you hate difficulty loading the part, the machine will too.

Vacuum loading should be considered if mechanically clamping the part is impractical. To use the vacuum method, the designer must provide large, flat, smooth surfaces on the component to facilitate pickup. and he should add locating features if possible. Thin disks, for instance, could have raised circular ridges on which to locate or flat or raised lips, which may provide an external feature for radial alignment.

Magnetic forces are occasionally used, but most assembly machine manufacturers avoid this method because holding forces decrease rapidly with small amounts of dirt and oil on the contacting surfaces. Obviously, the attraction of ferrous metal chips and grit rapidly degrades performance. Also residual magnetism is usually strictly forbidden in the final assembly.

In general, the rules for loading are

1. Provide good grasping surfaces for the part length and weight, or provide locating surfaces or holes to guide the part into position.
2. Keep loading strokes as straight and as short as possible.
3. Keep external features for radial location in mind for use if needed.
4. Avoid vacuum if possible; if not, keep surfaces large and flat. For flat disks provide locating feature, such as a circular ridge.

7-4 FASTENING AND JOINING

There are three principal ways in which component parts can be joined to the final assembly build, i.e., threaded fastenters, pressure, and heat.

7-4.1 THREADED FASTENERS

In component design screws are considered based on their ability to align within a tapped hole. Nuts are more difficult to feed and assemble automatically than screws. If it is intended to feed and drive a nut onto a screw, the problem is holding the nut square while starting the thread (danger of cross threading). Removing the first thread to give some seating helps, but this is not absolutely reliable. The machine designer can help by arranging the feeding and driving of the nut onto the screw in two operations-a very light pressure at one station to give the nut an initial start followed by final tightening at the next station. If it is possible, it is always better to feed the nut into the assembly build first and then drive the screw into it. The examples of screw points shown in Fig. 7-13 should be considered.

7-4.2 FASTENING BY PRESSURE

Pressure fastening is one of the better methods for automatic assembly. The more common pressure fastening methods include riveting, swaging, staking, crimping, and force fitting.

Certain pressure fastening methods need specific times for metal flow. This may require an in-line transfer where the first station will not allow time for completion of an operation, and the work is transferred, and the operation completed at the next station. This may be necessary on certain pressure fastening systems and will be dictated by production output.

For example, for a production rate of 900 assemblies/h (4.5 s each) assume all parts placing operations plus transfer can be performed in this time, but a swaging operation takes 6 s to complete. There are two alternatives: Use two work stations; partly swage at one and finish swage at the next (indexing machine). Fig. 7-37 shows swaging accomplished over two stations to achieve overall cycle time. Use two indexing machines at a production rate of, say, between 7 and 9s. Fig. 7-38 shows swaging accomplished using two machines to achieve overall cycle time.

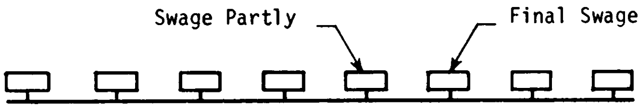

Figure 7-37. Fixed Indexing Cycle of Equal Pitches

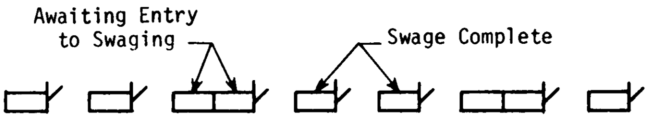

Figure 7-38. Free Transfer Cycle

The first method can be used provided this two-step forming is free from work hardening to an extent likely to affect such a procedure. Swaging, spin riveting, and vibratory riveting are the most likely operations to require step-wise forming. Normally, with manual assembly two operators would be used for this work, each taking alternative assemblies and completing the operation. This can be done automatically provided the transfer line for automatic assembly is of the free transfer type or is individual operator paced.

7-4.2.1 Riveting

Perhaps the least desirable of the pressure fastening methods is riveting because a separate component (the rivet) is required. By eliminating the rivet, obvious savings can be obtained in material and component consistency. An example of a riveted assembly is shown in Fig. 7-35. For more detail on the riveting process, including sizes, standards, and efficiencies, see Ref. 4.

7-4.2.2 Swaging

Swaging is a method of shaping material, reducing the diameter of a tubular part, and pressure bonding it to a smaller tube, rod, or to other parts inside the tube. The process is performed by a machine that causes the work to be struck a number of successive blows by hammers contoured to match the surface of the part.

7-4.2.3 Staking

Staking is a process used to lock two pieces of material together by upsetting the two materials at one or more points along a common contact line. As an example, a threaded plug screwed into a tapped hole can be locked into place by centerpunching along the joint line, as shown in Fig. 7-39, after the plug is threaded into place.

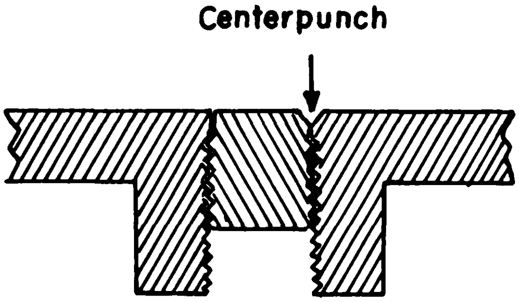

Figure 7-39. Staking

7-4.2.4 Crimping

Crimping is a process used to join two pieces of material by crimping or folding their edges together. It is most commonly used in the tin can industry for assembling ends on cans.

7-4.2.5 Force Fitting

Force fits, or interference fits, are generally used on cylindrical parts and depend on closely controlled dimensions for the outer diameter of the inside part and the inner diameter of the outside part. These dimensions are designed so that the inside and the outside parts have diameters that overlap each other slightly and result in an interference fit. This type of pressure fastening is obviously expensive due to the precision machining required on the matching surfaces and the hazards of creating swarf (see par. 7-3.2.1.1), However, sometimes the efficiency of the resulting assembly process offsets the cost of the precision machining. The element of critical concern to the designer is the amount of pressure required to press the two parts together. There must be assurance that the parts and the assembly build can withstand the pressure. Table 7-1 provides some information relative to the pressure factors encountered in press fitting steel parts of different diameters with an interference fit range of from 0.025 mm (0.001 in.) to 0.038 mm (0.0015 in.). For further discussion and information see Ref. 4.

TABLE 7-1. PRESS FIT LOADS

Part Diameter		Total Load to Press to 25.4 mm (1.0 in.) Depth	
mm	(in.)	tonne	tons
102	(4.0)	1.25	(1.38)
76	(3.0)	1.27	(1.40)
51	(2.0)	1.31	(1.44)
25	(1.0)	1.36	(1.50)

7-4.3 FASTENING BY HEAT

These processes will result in metallurgical bonds that are considered permanent and are generally not disassembled except for repair. Specific processes included under this category are welding, brazing, and soldering. Soldering requires the application of heat to the parts to be joined and the addition of a nonferrous filler metal with a melting point less than that of the base metal but never more than 425°C (800°F). Brazing also requires the application of heat to the parts to be joined and the addition of a nonferrous filler metal with a melting point less than that of the base metal; however, the melting point is more than 425°C (800°F). Welding requires sufficient application of heat to cause the surfaces being joined to become molten; while molten, they are joined together and allowed to cool. The use of filler metal and pressure in the welding process is optional.

7-4.3.1 Soldering

Heat is applied to a solder joint with a soldering iron, an oxyacetylene torch, electric induction or resistance elements, or a stream of hot neutral gas. The parts being joined should be free of oxides, dirt, and oil. When the joint surfaces are hot enough to meet the solder and permit a capillary flow of the material throughout, the joint will result in a good bond after cooling. Solder filler metal can be obtained in many forms including bar, wire, pig, slab, ingot, ribbon, powder, and foil. It is also available in many compositions for different applications as shown in Table 7-2.

Ultrasonic fluxless soldering is a more recently introduced method of soldering. This process makes use of high-frequency vibrations to permit the solder to penetrate surface oxides and films. Metals that can be soldered by this method include aluminum, copper, brass, silver, magnesium, germanium, and silicon.

TABLE 7-2. PROPERTIES AND APPLICATIONS OF SOLDER

Composition, %				Melting Temperature		Applications
Tin	Lead	Antimony	Silver	°C	°F	
70	30	—	—	192.2	378	Coating metals
60	40	—	—	190.0	374	General purpose solder
50	50	—	—	216.1	421	Most used general purpose
40	60	·	—	237.8	460	Joining lead pipes and radiator cores
30	70	—	—	255.0	491	For torch and machine soldering
20	80	·	—	277.2	531	Filler metal
20	79	1	—	269.4	517	For machine soldering and metal coating; not for use on galvanized iron
1	97.5		1.5	308.9	588	For copper, brass, and similar metals with torch heating
5	95			312.2	594	Coating and joining metals

7-4.3.2 Brazing

Brazing requires heating the part to a suitable temperature above 425°C (800°F) and using a nonferrous fillermetal with a melting point below that of the base metals. The filler metal is distributed by capillary action between the closely fitted surfaces of the joint. The methods used to obtain the necessary temperatures are described in succeeding paragraphs. The properties of the brazing filler metals are most important and must meet the following criteria:

1. It must be able to wet effectively the base metals at the operating temperatures to insure good total contact and a good joint.
2. The melting temperature and flowing action must be suitable for good distribution and good capillary action.
3. The chemical characteristics must be suitable and must create no undesirable interaction with the base metals.
4. The mechanical characteristics must also be suitable, i.e., must have sufficient strength, etc.

Brazing filler metal properties and applications are given in Table 7-3. For additional information and more detail properties see Ref. 4.

In brazing, care must be taken to avoid various types of deterioration of the base metals, such as hydrogen, sulphur, or phosphorus embrittlement, and stress cracking. Parts should be designed so that they will be self-positioning during brazing to ease assembly and cut down on rejects from misalignment. Also when possible, assemblies should be designed so that gravity flow will aid capillary action during the brazing operation.

When metals with different coefficients of expansion are being joined, the clearance between the parts should be considered at brazing temperature since it may differ at room temperature. Finally, proper fluxes must be used to neutralize effectively or render harmless any undesirable products of the brazing in order to promote a good bond. The principal types of brazing are torch, dip, furnace, resistance, and induction.

7-4.3.2.1 Torch Brazing

In torch brazing the heat required by the process is furnished by a gas torch. The work is cleaned, prepared, fluxed, and heated by a hand-held torch until the temperature is deemed correct. Then, filler metal is fed in, melted, and absorbed by capillary action, with any excess forming a fillet, The process can be mechanized, however, by propositioning the filler metal and having stationary flames provide a heating zone with the work moving through it. Some advantages to this process are

1. Simple to set up
2. No points of stress concentration
3. Lead time short
4. Generally no special production tooling required
5. Good, strong joints can be produced
6. Method adaptable to many metals and shapes
7. Finished assembly is relatively stress free.

Some disadvantages of torch brazing are

1. Clearances must be accurate for good capillary action. (This requires more precise machining and tighter tolerances.)
2. Fairly high operator skill is required to make satisfactory joints.
3. Production speed is slow.
4. The atmosphere in which torch brazing is done cannot be readily controlled.
5. Disassembly is quite difficult.

TABLE 7-3. BRAZING FILLER METAL PROPERTIES

AWS-ASTM Classification[1]	Composition,[2] %						Melting Temperature		Standard Form	Application
	Ag	Cu	Zn	Al	Ni	Other	°C	°F		
BAlSi-1	—	—	—	95	—	Si, 5	629	1165	Wire and rod	Joining aluminum including the cast alloys. Suitable for furnace, dip, and torch brazing. Requires joint clearances from 0.0152 mm (0.0006 in.) to 0.635 mm (0.025 in.). Lap-type joints only.
BAlSi-2	—	—	—	92.5	—	Si, 7.5	613	1135	Sheet	
BAlSi-3	—	4	—	86	—	Si, 10	585	1085	Wire, rod, and sheet	
BAlSi-4	—	—	—	88	—	Si, 12	582	1080	Wire, rod, and sheet	
BCuP-1	—	95	—	—	—	P, 5	899	1650	Strip	Joining copper and copper alloys with some use on silver, tungsten, and molybdenum. Suitable for all brazing processes. Use lap- and butt-type joints with clearances from 0.025 mm (0.001 in.) to 0.13 mm (0.005 in.).
BCuP-2	—	93	—	—	—	P, 7	807	1485	Wire, rod, and powder	
BCuP-3	5.5	88.5	—	—	—	P, 6	804	1480	Wire, rod, and powder	
BCuP-4	5.5	87.5	—	—	—	P, 7	721	1330	Wire, rod, and powder	
BCuP-5	15	80	—	—	—	P, 5	816	1500	Wire, rod, and powder	
BAg-1	45	15	16	—	—	Cd, 24	618	1145	Strip, wire, and powder	For joining all metals except aluminum, magnesium, titanium, and metals with melting points below 760°C (1400°F). Applicable to all brazing processes. Works best with lap joints; however, it can also be used with butt joints. Joint clearance should be from 0.05 mm (0.002 in.) to 0.13 mm (0.005 in.).
BAg-2	35	26	21	—	—	Cd, 18	702	1295	Strip, wire, and powder	
BAg-3	50	15.5	15.5	—	3	Cd, 16	688	1270	Strip, wire, and powder	
BAg-4	40	30	28	—	2	—	779	1435	Strip, wire, and powder	
BAg-11	75	22	3	—	—	—	788	1450	Strip, wire, and powder	

[1] Alloy designations are jointly classified by American Welding Society (AWS) and American Society for Testing Materials (ASTM) and contain chemical symbols preceded by a "B" for brazing filler metal.

[2] Chemical abbreviations used are Ag, silver; Cu, copper; Zn, zinc; Al, aluminum; Ni, nickel; Si, silicon; P, phosphorus; and Cd, cadmium.

7-4.3.2.2 Furnace Brazing

In this process the parts are heated to the proper temperature in a furnace. The heat maybe furnished by flames or by electrical coils, and there mayor may not be a special atmosphere. The brazing filler metal is usually preplaced. Work can either be batch loaded or continuously fed through by means of conveyor belts, etc. As in other types of brazing, the temperature and clearances between the parts must be closely controlled. some advantages of furnace brazing are

1. Very good joints can be made.
2. The finished assembly is free of stresses; there are no points of stress concentration.
3. The method is easily adaptable to an economical, high-output operation.
4. A relatively low skill level is required for product ion.
.5. Generally, it is used for steel parts, but the process is also effective with other metals and with dissimilar metals.

Some disadvantages are

1. Tolerance in parts must be quite close; this requires expensive machining before brazing.
2. Clearance problems result from joining parts made of metals with different expansion coefficients.

7-4.3.2.3 Induction Brazing

In induction brazing, the heat required is generated by inducing eddy currents with a high-frequency alternating field in an induction coil closely coupled to the workplaces. There is no actual current flow between the induction coil or coils and the workplaces. Normally, smaller induction coils are air-cooled, but the larger installations use water cooling. Inasmuch as the eddy currents and, consequently, the heating can be limited to the surfaces of the pieces, it is possible to heat rapidly only the section holding the brazing filler metal. Thus the bond is rapidly completed without heating the entire assembly. Also the heat input per unit time can be faster than that required for the other methods. The brazing filler metal is generally prefluxed in the form of washers, rings, powders, or coatings on the base metals. Controlled atmospheres can also be used with induction brazing. This method is adaptable to to various metals, sizes, and shapes. Some advantages of induction brazing are

1. Good joints can be achieved.
2. There are no points of stress concentration; finished assemblies are relatively stress free.
3. The method is very fast, which allows high output.
4. Heating can be concentrated at the surfaces being joined with little heat loss.
5. Once the timing cycle is adjusted correctly, very uniform results are achieved.

Some disadvantages are

1. Disassembly is difficult.
2. Coupling distances between coils and work must be kept small.
3. A thick wall being joined to a thin one creates the danger of overheating the joint.
4. Part design must allow preplacement of metal.

7-4.3.2.4 Dip Brazing

The heat required for this operation is obtained by dipping the workpiece in a molten bath. The molten bath can consist of a salt bath (essentially the flux) or of molten filler metal. In a flux bath the filler metal is preplaced prior to dipping. In a metal bath there is generally a cover of molten flux on the surface of the metal bath, and the parts being immersed must first go through the flux. Some advantages are

1. Easily controllable bath temperature
2. No stress concentration; stress-free joints
3. Skill level required fairly low
4. Process lead time short.

Some disadvantages are

1. Process is generally limited to smaller parts.
2. In some cases considerable cleaning is required after brazing.
3. Large baths of molten material are a safety hazard.
4. Preheating is almost always required to avoid thermal shock.

7-4.3.2.5 Resistance Brazing

The heat required for this method is obtained by passing a current through the pieces being joined. Most of the heat is generated by the resistance at the contact electrodes from which it is then conducted to the workpieces. The same equipment used for resistance welding can be used (with slight modifications) for resistance brazing. The voltage range is from 5 to 25 volts, and the current range is 50 to several thousand amperes, depending on the size of the workpiece. The brazing filler metal is generally preplaced. Some advantages are

1. Pressure exerted to keep electrodes in good contact tends to squeeze out filler metal; this produces a good bond.
2. Preplaced filler metal reduces time required for the operation.

Some disadvantages are

1. Disassembly is difficult.
2. Electrodes require frequent cleaning.
3. Joints must be accessible from both sides to apply pressure.
4. Process is generally limited to small parts since uniform heating is difficult to maintain.
5. Current flow timing is at the operator's discretion, and this leads to uncertain process repeatability.

7-4.3.3 Welding

Numerous welding processes are in use by industry today, The capabilities of the processes overlap in some areas; usually, one will have a specific advantage over another in a particular application. In some cases only one welding process can do the job; in others, two or more processes could do the job although one wil1 probably do it best.

Selecting the optimum method requires analysis of the design, the joint requirements, metals to be joined, configuration of parts, production quantity involved, producing rates desired, and equipment available. Table 7-4 is a guide containing information to assist in making the selection. More comprehensive guides to recommended practices are published in most welding handbooks. Ref. 5 is one such handbook. The principal welding processes are discussed in the paragraphs that follow.

7-4.3.3.1 Arc Welding

Arc welding is a versatile and widely used welding process wherein the heat of an electric arc is used to bring metals to a molten state. Almost all arc welding now employs a shielded arc to protect weld metal from impurities and embrittlements. The method is fast and suitable for automatic production methods. Six principal arc welding processes are described briefly in the succeeding paragraphs.

1. Coated *Electrode Are Welding.* A coated electrode is a metallic core wire of a specified chemical analysis covered with a formulated coating. The coating forms an atmospheric protection about the arc, aids the metal transfer, alters the chemical composition of the metal deposited, and forms a protective slag over the weld deposit. Most ferrous metals and some nonferrous metals, such as aluminum alloys, bronzes, and high nickel alloys (such as Inconel and Monel), can be welded with prescribed electrodes. Welding electrodes are classified by the American Welding Society (AWS) and the American Society for Testing and Materials (ASTM) on the basis of the composition of the metal deposit, tensile strength, type of welding current, and welding position of the electrode. Welding electrodes in each class may have been developed by different elect rode manufacturers. Coated electrodes also are found in various sizes depending on the diameter (1.1908 mm to 9.52 mm (0.01688 in. 100.375 in.)) of the core wire. Selection of the proper electrode depends on the type and thickness of the material to be welded, the physical requirements of weld deposits, the response of the weld metal to heat treatment, the position in which the weldment is to be made, and the configuration of the materials in all thicknesses except extremely thin sheet stock.

2. *Inert Gas Metal Arc Ccmsumable Electrode Welding.* The inert gas metal arc consumable electrode welding process employs small diameter wire and high current density. This results in a relatively high rate of metal deposit. Specially designed welding equipment is required to perform the various functions of this method of welding, which can be either partially or fully automated. The selection of the filler wire is dependent upon the material to be welded and the mechanical properties of the weld metal deposit. The inert gas metal arc consumable electrode process can be used to weld carbon and stainless steels, and specific alloys of aluminum, copper, nickel, and titanium. It is especially applicable to heavy materials or where relatively rapid travel speeds are required on thin sections of material. Fig. 7-40 is a schematic diagram of equipment used for this type of welding.

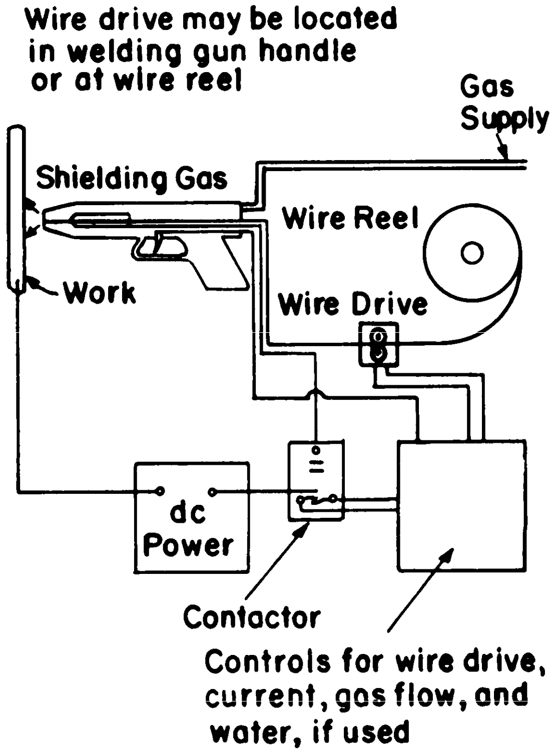

Figure 7-40. Schematic Diagram of Equipment for Inert Gas Metal Arc Consumable Electrode Welding

3. *Inert Gas Tungsten Arc* Weldlng. This process is an electric arc welding method in which coalescence is produced by heating with an electric arc between a metallic tungsten electrodc and the work. (See Fig. 7-4 1.) Tungsten electrodes are used because they hate a higher melting point and arc not attacked (consumed) when contained within an inert protective atmosphere, such as helium or argon gas. Filler wife may be added manually. pt> of filler wire used depends on the material to be welded and on the mechanical require-

TABLE 7-4. RECOMMENDED WELDING PROCESSES

		Shielded Metal Arc[1]	Submerged Arc	Atomic Hydrogen	Inert Gas—Tungsten Arc	Inert Gas—Metal Arc	Flash Welding	Spot Welding	Seam Welding[2]	Gas Welding	Brazing Furnace	Brazing Torch	Thermit
Based on Welded Materials													
Low carbon, mild steel types		R	R	S	S	S	R	R	R	R	R	S	S
Medium carbon steel types		R	R	S	S	S	R	R	S	R	R	S	S
Wrought alloy engineering steels		R	R	S	S	S	R	R	NR	S	S	NR	S
High alloy stainless steels, austenitic types		R	R	R	R	R	R	R	R	S	S	S	NR
Stainless steels, ferritic and martensitic types		R	S	S	S	S	S	S	S	S	S	S	NR
High temperature alloys		R	S	S	S	S	S	S	R	S	NR	NR	NR
Cast iron, gray iron		S	NR	NR	S	NR	NR	NA	NA	R	NR	R	S
Aluminum and aluminum alloys		S	NR	S	R	R	S	R	S	S	R	R	NA
Nickel and nickel alloys		R	S	S	R	R	S	R	S	S	S	R	NR
Copper and copper alloys		NR	NR	NR	R	R	S	S	NR	S	S	R	NR
Magnesium and magnesium alloys		NA	NA	NR	R	S	NR	S	NR	NR	NR	NR	NA
Silver		NR	NR	R	R	S	S	NR	NR	R	S	R	NR
Gold, platinum, iridium		NR	NR	R	R	S	S	S	NR	R	S	R	NR
Titanium and titanium alloys		NA	NA	NA	R	NR	S	S	NR	NA	NR	S	NA
Uranium, molybdenum, vanadium, zirconium, tungsten		NA	NA	NR	R	NR	S	S	S	NR	NR	NR	NR
Based on Joint Design													
Butt joint	Light section[3]	S	S	R	R	NR	NR	NA	NA	R	NR	S	NA
	Heavy section[4]	R	R	S	S	R	R	NA	NA	S	NR	S	R
Lap joint	Light section	R	S	S	R	NR	NR	R	R	R	R	R	NA
	Heavy section	R	R	S	S	R	R	R	R	S	R	R	NA
Fillet joint	Light section	R	S	S	R	NR	NR	NA	NA	R	R	R	NA
	Heavy section	R	R	R	S	R	R	NA	NA	S	R	R	NA
Edge joint	Light section	NR	NR	R	R	NR	NR	NA	R	R	NA	S	NA
	Heavy section	R	S	S	S	S	S	NA	R	S	NA	S	NA
Overlav welding													

Notes: 1 — Shielded metal arc (coated electrode)
2 — Gas welding (oxyacetylene)
3 — Light section—0.13 to 3.18 mm (0.005 to 0.125 in.)
4 — Heavy section—3. 18 mm (0.125 in.) and over.

Key:
R—recommended; S—satisfactory; NR—not recommended; NA—not applicable

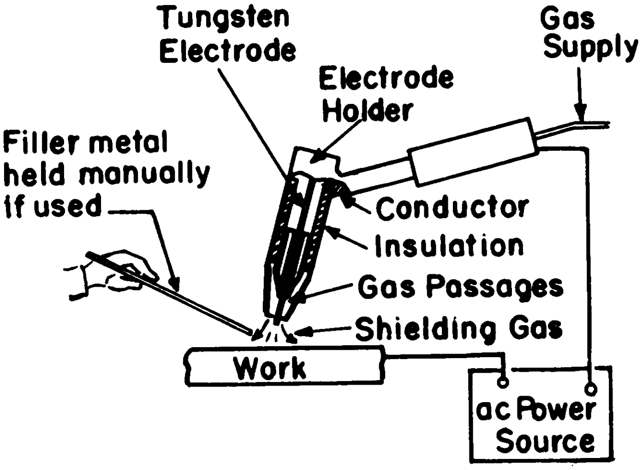

Figure 7-41. Schematic Diagram of Equipment For Inert Gas Tungsten Arc Welding

ments of the weld deposit. The tungsten arc welding process is applicable to materials such as carbon steels, stainless steels, aluminum alloys and is frequently recommended for welding dissimilar metals.

4. *Submerged Arc Welding.* Submerged arc welding is an arc welding process that produces coalescence by heating with an electric arc or arcs between a bare wire electrode or electrodes and the work. The welding is shielded by a blanket of granular, fusible material on the work. The granular material is referred to as a flux although it does not perform the functions usually ascribed to a flux. Filler wire is fed continuously by the welding equipment to maintain a constant voltage at a predetermined welding current and voltage. A hopper feeds the flux by gravity ahead of the arc. The diameter of the filler wire ranges from 0.64 mm to 9.52 mm (0.025 in. to 0.375 in.), and the type of wire depends on the material to be welded and the mechanical properties required. The composition of the flux differs depending on the material to be welded, the filler wire used, and the application. Submerged arc welding is best suited to relatively heavy weld deposits. Most carbon, low alloy, and stainless steels can be readily welded with the submerged arc process. Nonferrous alloys, such as nickel, Monel, Inconel, copper-nickel, and copper-silicon, can also be successfully welded with this process.

5. *Atomic Hydrogen Welding.* ‘I-he atomic hydrogen process has been largely displaced by gas-shielded and plasma-torch arc welding, but it is still used in some manual operations for which heat input must be closely controlled. In the atomic hydrogen process an arc is formed between two metallic electrodes in a stream of hydrogen gas. Molecular hydrogen is formed by dissociation of the hydrogen molecules passing through the ac arc. When this stream of atomic hydrogen strikes the workpiece, cooling permits molecules to be formed, which releases the heat stored during the dissociation that occurred in the arc. The heat generated can be applied to the base metal or to filler metals that may be added. The hydrogen arc cools the electrodes and acts as a shield over the workpiece. The atomic hydrogen is a powerful reducing agent, will remove any oxides that may be present, and keeps others from forming. On the other hand, hydrogen can cause a number of metallurgical problems, so a metallurgist should be consulted before using this process. The atomic hydrogen welding process is applicable to carbon and alloy steels, aluminum, and nickel alloys, such as Monel and Inconel.

6. *Plasma Arc Welding.* Plasma arc welding is one of the largest fusion welding techniques. It uses a high velocity plasma stream consisting of inert gas ionized in an electric arc. Materials up to 6.35 mm (0.25 in.) thick can be welded in one pass. Advantages offered over gas tungsten arc welding are that its arc is more stable, square butt joints can be welded, it is faster, and welds can be produced without filler material. Fig. 7-42 is a schematic diagram of a plasma arc gun.

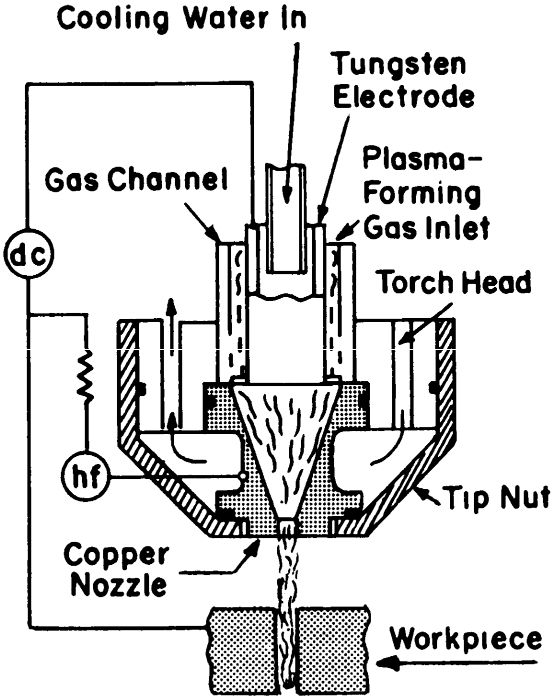

Figure 7-42. Schematic Diagram of a Plasma Arc Gun

7-4.3.3.2 Resistance Welding

Resistance welding, one of the principal welding methods, employs electrical energy to generate heat for melting. It is adaptable to very high production rates, produces a highly uniform weld, and requires less skillful operators for specialized applications. To take advantage of these features of resistance welding, however, the large power, air pressure, and water requirements for cooling must be considered. The process may require a substantial expenditure of money for capital equipment.

7-4.3.3.3 Gas Welding

This method provides heat by burning a mixture of oxygen and gas, usually acetylene. It is not suitable for high production rates except on light-gage metals or alloys with low melting points. It is adaptable to low production rates and quantities and requires little capital equipment but requires skilled welders.

7-4.3.3.4 Thermit Welding

In the thermit welding process brat is generated by a reaction involving finely dividied aluminum and iron oxide. The method is not suitable for high production. It is gentrally used to fabricate large weldments or to repair castings. It is used to make electrical cable connections and fine wire joints.

7-4.3.3.5 Electron Beam Welding

Electron beam melding is the process in which the kinetic energy of an electron beam, which has impacted the workpiece in a finely focused, high intensity stream of electrons, produces the required heat. In most machines the workplaces must be contained in a vacuum atmosphere, but recently nonvacuum electron beam welding techniques have been developed. Since heat is localized, narrow welds, which practically eliminate distortion, can be made. Changes in mechanical properties are minor because the low energy input does little to change the microstructure. Welds can be made on material ranging up to 19.05 mm (0.75 in.) thick, and speeds can range from 0.3 m/min to 7.6m/min (10 in./min to 300 in./min) for thin material, Steel, stainless steel, high-temperature and refractory alloys, and alloys of titanium, aluminum, and copper can be welded with this technique. Fig. 7-43 is a schematic diagram of an electron beam gun.

7-4.3.3.6 Ultrasonic Welding

Ultrasonic welding applies ultrasonic energy to produce a metallurgical bond between joined or clamped workpieces. There is no fusion of the weld metal since the weld temperature only approaches 3.5% of the absolute melting temperature of the metal. This solid-state process produces a minimum of oxides other impurities and is used chiefly for aluminum.

7-4.3.3.7 Summary

In summary, all of the welding techniques present one common problem to the designer, i.e., the quality of the welds is dependent on the correct application of production techniques. In some processes operator skill is more important than in others. However, in many welding operation on military equipment, specifications require certification that the operators can consistently produce welds that meet the applicable specifications. This requirement and the one for exceptionally close quality control and inspection procedures are elements that the designer should consider in his design.

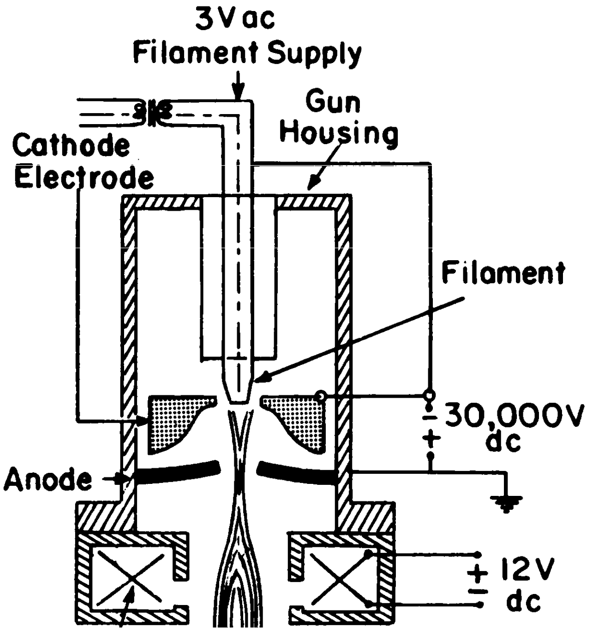

Figure 7-43. Schematic Diagram of Typical Electron Beam Gun

7-4.3.3.8 Design Considerations

1. Heavy structural parts being assembled by welding should be welded from the center out toward the edges to let the stresses work out to an edge to avoid or minimize locking stresses into the work.

2. Welded joints must be accessible to the welder to minimize welding time and maximize quality.

3. Joints must be clean to avoid contamination, porosity, and cracking.

4. Very heavy material, in excess of 25 mm (1 in.), and very light material, less than 0.912 mm (0.036 in.), will require special welding procedures.

5. The most producible welds are achieved by using steel with a carbon range of 0.13 to 0.20%, manganese 0.4 to 0.6%, silicon 0.1% maximum, sulphur 0.035% maximum, and phosphorus 0.035% maximum. Higher alloy steels will require special treatment, such as preheating to produce sound welds.

6. Material 4.763 mm (0.1875 in.) thick or thicker is welded best in the flat position, whereas thinner material is welded best in the 45-deg downhill position.

7-4.3.4 Heat Sealing

This is a process that is being used increasingly since more and more products are made of plastics. The plastics are held together under light pressure while the heating element, at a slightly higher temperature than the melting point of the plastic, is brought into contact with the joint. The parts then fuse together.

Adhesives form a relatively new field for use on assembly machinery. Here, as for soldering, some further joining element is introduced between the mating parts. Heat setting adhesives, and, in fact, all forms of adhesive joining present a significant advance in fastening techniques.

Joining of plastics is described more fully in Chapter 5.

7-4.4 SOME SUGGESTED FASTENING METHODS

7-4.4.1 Integral Method

In this method there is no separate fastening component. Examples of this method, illustrated in Fig. 7-44, are press fits, integral rivets, twist lugs, and spot welding. Redesign of multiple components to be cast as a single unit is another method.

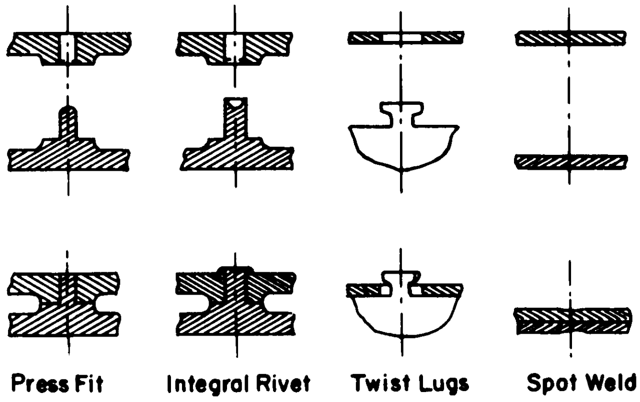

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Figure 7-44. Integral Method (Ref. 3)

7-4.4.2 Separate Fastening Medium

One separate component is applied unidirectionally. Examples of this method, illustrated in Fig. 7-45, are solid and tubular rivets, spire nut, drive screw, or other spring clip devices applied to an integral feature already present.

7-4.4.3 Self-Tapping Screws

These require rotational as well as axial pressures and are illustrated in Fig. 7-46.

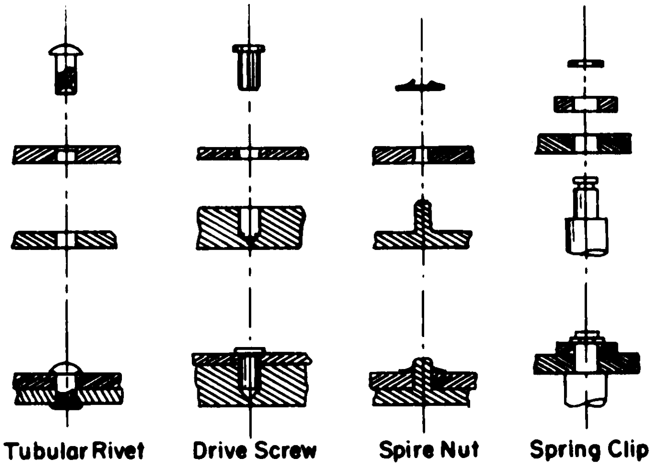

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Figure 7-45. Separate Fastener (Ref. 3)

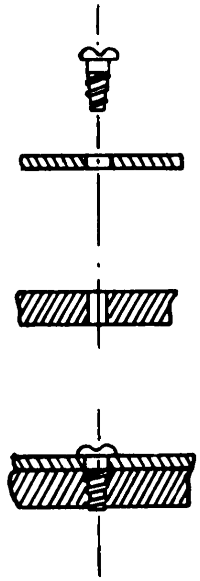


Figure 7-46. Self-Tapping Screw

7-4.4.4 Two-Component Fastening Medium

This is a simple fastening process that incorporates two components, e.g., headed pin and spring clip or free fit bolt and spire nut as illustrated in Fig. 7-47.

7-4.4.5 Screws

This type of fastener includes all types of screws entailing registration with a threaded hole both helically and axially and requiring rotation on assembly. Two types of screw fastening are shown in Fig. 7-48.

7-4.4.6 Encapsulation

A process favored by the electronic industry is complete encapsulation of the parts in epoxy resin or a

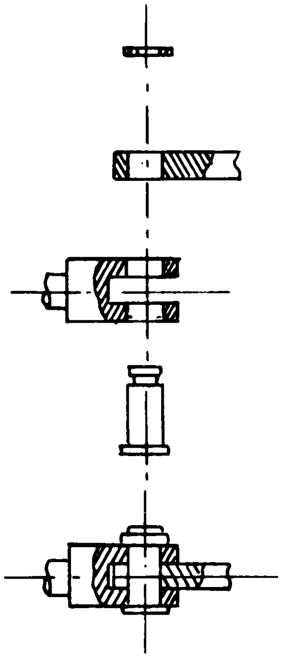
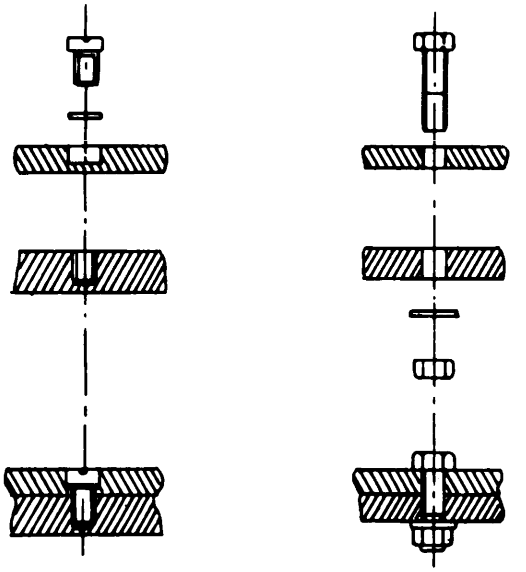


Figure 7-47. Two Components as Fastening Medium



(A) Machine Screw In Tapped Hole

(B) Bolt and Nut

Figure 7-48. Two Types of Screw Fastening

similar medium. A step has been taken toward this in the plastics field with molding onto metal. Many plastic gears are molded directly to spindles, and examples can be found in automotive accessories and alarm clocks. This form of assembly can be likened to process work, but the product designer must keep it in mind because it will undoubtedly become more widespread in the future.

7-4.4.7 Selecting a Fastener

In addition to the basic engineering design constraints of load and size, the following additional criteria should be considered when selecting a fastener for a particular application:

1. Length of fastener life cycle
2. Consequences of nonavailability in the future
3. Special tools required for installation
4. Availability of special tools during life cycle
5. Operational environment of the fastener
6. Consequences of fastening dissimilar materials
7. Desirability of nonmagnetic fastener
8. Affect of vibration on fastener.

7-5 BASIC RULES FOR PRODUCIBILITY IN ASSEMBLY

It should be realized that the fewer components there are in an assembly the better. Today the majority of products passes through the stage of value engineering, and it is reasonable to assume that only the essential items remain in the final assembly to be built.

The various points made in this discussion of parts and product design for mechanized assembly are summarized.

7-5.1 RULES FOR PRODUCT DESIGN

Rules for good product design follow:

1. Insure that the product has a suitable base part on which to build the assembly.

2. Insure that the base part has features enabling it to be readily located in a stable position in the horizontal plane,

3. If possible, design the product so that it can be built up in layer fashion, each part being assembled from above and positively located so that there is no tendency for it to move under the action of horizontal acceleration forces during the machine index period.

4. Try to facilitate assembly by providing chamfers or tapers to help guide and position the parts into the correct position.

7-5.2 RULES FOR DESIGN OF COMPONENTS

Rules for the good design of components follow:

1. Avoid projections, and holes or slots that will cause tangling with identical parts when placed in the feeder in bulk. This may be achieved by making the holes or slots smaller than the projections.

2. Attempt to make the parts symmetrical to avoid the need for extra orienting devices and the corresponding loss in feeder efficiency.

3. If symmetry cannot be achieved, exaggerate asymmetrical features to facilitate orienting or, alternatively, provide corresponding asymmetrical features to be used to orient the parts.

4. Determine whether "difficult" parts can be supplied in strip form, like electrical terminals, or in adhe-

sive form, like staples. Alternatively, consider whether the parts can be manufactured on the assembly machine.

7-6 NONTRADITIONAL ASSEMBLY TECHNIQUES

Probably one of the most significant developments to appear on the assembly scene in recent years has been the emergence of the industrial robot.

7-6.1 STATE OF THE ART

More than 17 types of robots are now available in the U. S., at least 12 of which are manufactured in this country. They range from minirobots, with payloads of only a few ounces and reaches of less than a meter (3.3 ft), to the larger universal robots, which can transport payloads of up to 68 kg (150 lb), over a reach distance of 0.8 m (2.5 ft), and can move at speeds up to 0.9 m/s (3 ft/s).

Besides the differences in payload and reach capabilities, many other variations exist among the industrial robots of today. The most simple robots, limited to pick-and-place operations over relatively fixed distances, are capable of a few primary and secondary movements and are limited to one or two input/output signals. On the other end of the spectrum, the highly sophisticated machines have several primary and secondary movements, have work envelopes in excess of 2.8 m^3 (100 ft^3), and move in complicated paths controlled by programs of up to 30 min duration.

Another important difference among the robots is their ability or lack of ability to stop movements at intermediate positions. In this quality, the least sophisticated robots have fixed strokes and may be positioned only at either end. The next level of sophistication—into which most of the robots fall—allows adjustment of both the minimum and maximum positions of all movements, but the movements are also limited to either one position or the other. Robots with the most sophisticated control systems can position all movements at several intermediate positions—the number being a function of the program capabilities.

All of the programming methods available today for robots fall into two classes: (1) point to point (P to P) or (2) continuous path (CP). In P to P programs, which are the most common, movements of the robots are from one distinct point in space to another distinct point. At any point, the robot may delay for a predetermined period of time, wait for a signal from associated equipment, then grip or release a part. The number of points available in any program is a function of the sophistication of the robot and the time duration of the program.

In the CP form of program, the robot gripper can move in a straight or a curved path for the entire length of the program, which may extend to 30 min duration. This type of movement is advantageous for operations such as welding, paint spraying, or laying a bead of adhesive along a complex path. Initial CP programming is normally accomplished by “teaching the path” to the robot which stores it in magnetic memory. In this type of programming the robot is manually led through the desired motions.

livery industrial robot is available with one or more, standard grippers to hold and release the parts being transported. In general, the grippers roughly simulate the movement of two fingers on a human hand, but robots are not nearly as limited as humans in this respect. They may be equipped with multiple grippers to hold several parts simultaneously, extended length grippers to hold large parts, grippers with built-in switches to detect the presence of parts, or vacuum or electromagnetic pickups in place of grippers. Most robots are designed for a variety of special grippers that hold specific parts, for ease of gripper removal and replacement, and for quick changeover from job to job. Some even include a screwdriver to complete assembly operations.

7-6.2 APPLICATIONS

industrial robots are reprogrammable, operatorless handling devices that can perform simple, repetitive jobs requiring few alternative actions and minimum communication with the work environment. They are well suited to handling parts that are extremely hot or cold, and they can function in corrosive, noisy, noxious, or extremely dusty atmospheres that would be injurious to human beings. Passage in the U.S. of the Occupational Safety and Health Act (OSHA) of 1970 has provided strong impetus for the use of industrial robots. The Act states that a human being cannot place his hands within punch press dies to load or remove parts, and it is imminent that OSHA standards will be extended to cover other fabricating and assembly operations, such as staking, spot welding, riveting, holding, clamping, electronic component insertion, and automatic screwdriving. In many cases the cost and time to retool an existing operation to conform to the standards, will be prohibitive compared to the cost and time required to purchase and program an industrial robot to perform the potentially dangerous operations.

7-7 INSPECTION AND TESTING

Combining testing with automatic assembly is becoming commonplace. Suitable gaging has been available for a long time. Simple linear measurements typically use strain gages and air gages. These usually interface to the assembly machine control system conventional relay, programmable controller, or computer. If sophisticated measurements are required, special gages are built. With computer control, self-calibration can be added to some systems.

7-7.1 GAGING FOR SELECTIVE ASSEMBLY

Using gage information for selective assembly is another approach that is occurring more often. An overall system approach for selective gaging should be used including statistical distributions and maybe a computer simulation of the process if the statistical calculations are lengthy and complex. Computer models of the statistical distribution are only as good as the accuracy of the input data.

7-7.2 BALANCING AT ASSEMBLY

Along with physical dimensions, the static or dynamic balancing of parts and subassemblies should be considered during design, Too frequently balancing is an afterthought. Parts should be designed with provisions for balancing in mind. The removal or addition of weight, the physical tolerances to balance an assembly or individual pieces, the unbalance produced by fit-up, and realistic specifications for unbalance are all questions that can and should be answered before the design is frozen.

7-7.3 LEAK TESTING

Another common test normally performed at assembly is leak testing. Again, product specifications are most important. To the extent possible, the designer should use standard leak specifications in units of standard cubic centimeters per minute or per second. Purchasing high low standard leak rate masters for calibration is most highly recommended. A part that has excessively high levels of contamination, oxidation, and aging stresses can almost never be tested as these can change the leak rate. Table 7-5 gives some comparison of equipment costs for various leak rates and equipment. The designer's specifications determine the degree of sophistication required for this instrumentation.

7-7.4 SUMMARY

Obviously, reading and settling time for weight balancing and leak testing are important in both processes. Relating these to cycle time is a job for line balancing, as described in par. 7-2.4.2. These two measuring problems, though unassociated, are very similar; both unbalance and leakage always exist to some degree. The best approach as to how and when to measure them and how long it will take requires careful consideration.

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4. Erik Oberg, F. D. Jones, and H. L. Horton, *Machinery's Handbook*, The Industrial Press, 93 Worth St., New York, NY, 20th edition, 1975.
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TABLE 7-5. EQUIPMENT COSTS FOR VARIOUS LEAK RATE TESTS, 1977

Detection Method	Leak Testing Leak Rate[1]	Cost[2]
1. Mass flowmeter	Greater than 1000 cc/min	$4,000 to $ 14,000
2. Pressure loss or pressure decay	1000 to 0.1 cc/min	$10,000 to $35,000
3. Mass spectrometer	0.1 to 0.000001 cc\min or smaller	$18,000 to $140,000

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[1] Depends on cycle time, volume tested, readouts required, masters, etc.

[2] Varies with type of display.

CHAPTER 8

PRODUCIBILITY CONSIDERATIONS FOR ELECTRONICS

This chapter addresses the major areas of consideration involved in designing with electronic components. The various categories of electronic components are introduced, and the characteristics of each component are presented along with discussions of correct applications of and potential problems using each component. Starting with components, the chapter also considers modules and packaging. The emphasis throughout is to give the readers adequate knowledge so that they can specify the optimum electronic equipment based on overall system and life cycle requirements.

8-1 INTRODUCTION

In the design **of** electronic equipment it is essential that manufacturing considerations and producibility be treated with the same respect and be pursued with the same vigor as any other design parameter. An electronic system, no matter how near the state of the art, is useful only if it can be readily produced in an economical manner. A designer has to design with what is available and has to ignore future projections. Therefore, the objective of the producibility engineer in electronics is to work with the designer to determine the most practical, cost-effective materials and manufacturing processes available for production of a specific design without compromising specified performance, reliability, and maintainability. Also he must be capable of identifying areas in which manufacturing technology of parts should be advanced to render the design more cost-effective.

In discussing producibility and how it relates to the reliability of electronic parts and equipment, it is beneficial to address briefly the concept of life cycle cost (LCC). Consider the curves shown in Fig. 8-1. The figure shows the relationship between reliability and cost. That is, as a system is made more reliable (all other factors held constant), the operating and support (O&S) costs will decrease because there are fewer failures. On the other hand, acquisition costs (both development and production) must be increased to attain the improved reliability. At a given point the amount of money spent on increasing reliability will result in exactly the same amount being saved in support costs. This point represents reliability for which total costs are minimized. Trade-offs between reliability and cost are of the essence. The same is true for maintainability and cost.

Figure 8-1. Reliability Cost Relationship

Therefore, it is incumbent upon the producibility engineer that he must strive for more than minimum reliability even if a higher order is not required so that LCC is minimized. Producibility performance is accomplished during development, and successful performance can only be attained through test assurance from component to module to the functional results and subsequent evaluation of the system. This is a step-by-step process evaluation. It is repetitive by nature in that a point may be found to be characteristically limited, which necessitates replacement (or redesign), which in turn results in retest and reevaluation for cost, maintenance, and reliability.

8-2 PART SELECTION AND CONTROL

A diversified complement of electronic parts is available to structure modern military electronic systems. These parts constitute the building blocks from which systems are fashioned and, as such, greatly impact hardware reliability. Since the reliability of the end-item is dependent upon these building blocks, the importance of selecting and applying the most effective parts cannot be overemphasized.

Assuring proper design application, selecting, specifying, and, in general, controlling parts used in complex electronic systems is a major engineering task. Part selection and control are multidisciplinary undertakings involving the best efforts of component engineers, failure analysts, reliability engineers, and design engineers. Numerous controls, guidelines, and requirements must be formulated, reviewed, and implemented during the development effort. Table 8-1 pre-

TABLE 8-1. GROUND RULES FOR CONTROL AND PARTS SELECTION (Ref. 1)

1. Determine part type needed to perform the required function and to meet the environmental conditions in which it is expected to operate.
2. Determine part criticality:
   a. Does part perform critical functions (i.e., safety or mission critical)?
   b. Does part have a limited life?
   c. Does part have long procurement lead time?
   d. Is the part reliability sensitive?
   e. Is the part a high cost item?
   f. Is component value tolerance critical?
   g. Is the vendor item going to be repairable and subject to Army maintenance support?
3. Determine part availability:
   a. Is part on Preferred Parts List?
   b. Is part a standard military item?
   c. Is part available from a qualified vendor?
   d. Does part require formal qualification testing?
   e. What is the normal delivery cycle?
   f. Will part continue to be available throughout the life of the equipment?
   g. Is there an acceptable in-house procurement document on the part?
   h. Are there multiple sources available?
4. Determine reliability level required for the part in its application.
5. Determine the efficiency of burn-in or other screening methods in improving the part failure rate (as required).
6. Prepare an accurate and explicit part procurement specification if nonstandard. Specifications should include specific screening provisions as necessary to assure adequate reliability.
7. Determine actual stress level of the part in its intended circuit application. Include failure rate calculations per MIL-HDBK-217.
8. Employ appropriate derating factors consistent with reliability prediction studies per MIL-HDBK-217.
9. Determine need for nonstandard part, and prepare a request for approval as outlined in MIL-STD-965.

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sents a simplified list of the ground rules and activities needed to assure that this task is adequately considered. The subparagraphs that follow provide detailed information, data, and specific guidelines for the general rules listed in Table 8-1. Specific- part selection data, guidelines as they apply to each generic part classification, part control, and part screening are also covered.

8-2.1 PART CONTROL

Part control activities comprise a large segment of the total effort for part selection, application, and procurement. The effort encompasses tasks for standardization, approval, qualification, and specification of parts which meet performance. reliability, and other requirements of the evolving design. This subparagraph provides further details with regard to these control tasks, indicates their importance within the part selection process, and provides appropriate design guidance. Electronic parts that comprise any electronic equipment constructed for military purposes are under the cognizance of the Military Parts Control Advisory Group, located in the Directorate of Engineering Standardization at the Defense Electronics Supply Center (DESC). This group promotes standardization in part selection and application.

8-2.1.1 Parts Selection

By using standard parts in new equipment design and development programs, much time and effort can be saved while obtaining better equipment performance in addition to simpler and better logistic support.

DESC promotes Usage of standard parts and manages standardization problems for parts that are initially charactcrized as nonstandard but whosv repetitive usage makes their standardizatif)ll ncIftIssary. Ilk%{;, as the Department of Defense (DoD) stal~(l:it(li/:itiot~ managet, ~vorks (losel y with the military stmi{ es and industry to dmelop an effective standard imtion program for new systems.

Therefore, the general rule for part selection is that wherever possible, standard devices should be used. Standard devices may be defined as those that—by virtue of systematic testing programs and a history of successful use in equipment—have demonstrated their ability to function consistently within specific electrical, mechanical, and environmental limits and, as a result, have become the subject of military specifications (MIL-SPEC'S). A military specification, which thoroughly delineates a part substance, form, and operating characteristic, does exist or is in preparation for practically every known type of electronic component. Military standards (MIL-STD's) cover the subject of testing methods applicable to military specified components; examples are

1. MIL-STD-202, *Test Methods for Electronic and Electrical Component Parts*
2. MIL-STD-750, *Test Methods for Semiconductor Devices*
3. MIL-STD-883, *Test Methods and Procedures for Microelectronic Devices.*

In addition, MIL-STD's exist that list by military designation those parts or devices preferred for use in military equipment; examples are:

1. MIL-STD-198, *Selection and Use of Capacitors*
2. MIL-STD-199, *Selection and Use of Resistors*
3. MIL-STD-200, *Selection of Electron Tube*
4. MIL-STD-454, *Standard General Requirements for Electronic Equipment*
5. MIL-STD-701, *Lists of Standard Semiconductor Devices*
6. MIL-STD-1132, *Selection and Use of Switches and Associated Hardware*
7. MIL-STD-1277, *Electrical Splices, Chips, Terminals, Terminal Boards, and Binding Posts*
8. MIL-STD-1286, *Selection and Use of Transformers, Inductors, and Coils*
9. MIL-STD-1346, *Selection and Application of Relays*
10. MIL-STD-1353, Selection and Use of *Connectors and Associated Hardware*
11. MIL-STD-1360, *Selection and Use of Fuzes, Fuzeholders, and Associated Hardware*
12. MIL-STD-1562, *List of Standard Microcircuits.*

In conjunction with part standardization, nonstandard part approval consists of activities to document and secure authorization to use the part in the system. MIL-STD-965 outlines the functions of a part control program and provides the necessary procedure for securing approval or nonapproval of nonstandard parts.

The qualification of nonstandard parts should include the detailed and formal submittal of data to support an approval request. These data must be (1) statistical test data, (2) analytical data for components that are similar to a standard part, or (3) a combination of statistical and analytical data. (Note: Those components that require statistical test data for qualification should be identified as critical items.)

The selection process should include design evaluation, reliability history review, construction analysis, failure mode and effects analysis, and cost-effectiveness studies as necessary. The control effort should include the development of meaningful procurement specifications that, when completed, reflect a balance between design requirements, quality assurance (QA), reliability needs consistent with apportionment studies, and vendor capabilities. The specifications should also cover lot acceptance testing, QA provisions (including incoming inspection), and qualification testing, if required.

8-2.1.2 Provision of Specifications

A well-controlled part program involves carefully preparing specifications (for nonstandard parts), establishing a vendor control program, auditing vendor processes, establishing source inspection where applicable, and preparing associated documentation. The part control effort includes identifying all critical parts, equipment or components, and other items considered critical from any of the following standpoints:

1. Mission and safety sensitive (failure impacts mission success and flight safety, i.e., flight safety critical)
2. Reliability sensitive (from early reliability studies, apportionments)
3. Have limited life
4. Are high cost items
5. Have long procurement lead times
6. Require formal statistical qualification testing
7. Require custom building or screening when exact part (including testing) cannot be bought off-the-shelf
8. Capability to repair item.

Planning for critical item control must include controls for special handling, the identification of critical item characteristics to be verified at the vendor's plant during incoming inspection, material review procedures, traceability criteria, and periodic audits. All items considered flight safety critical by the command must be so marked. Detailed documentation must be prepared that describes procedures, tests, test results, and efforts to reduce the degree of criticality of each item. Standardization, random access memory (RAM), and LCC considerations should be capable of taking precedence over design to unit production cost (DTUPC) cost reduction actions.

8-2.2 PART SELECTION GUIDELINES

This subparagraph presents reliability information to aid in the selection of electronic parts for a specific design application. Guidelines are included for microcircuits, semiconductors, resistors, capacitors, relays, electron tubes, transformers and inductors, switches and keyboards, connectors, microwave devices, and cables.

8-2.2.1 Microcircuits

In general, the two major classes of microcircuits are monolithic and hybrid. A monolithic microcircuit is characterized by a single silicon chip suitably packaged and performing well-defined functions. This characterization encompasses varying degrees of complexity up to and including large-scale integration, and it may include purely digital functions or linear applications. Monolithic microcircuits cover most forms of current technology, e.g., transistor-transistor logic (TTL), metal oxide semiconductor (MOS), complimentary metal oxide semiconductor (CMOS), P-type metal oxide semiconductor (PMOS), N-type metal oxide semiconductor (NMOS), complimentary silicon sapphire semiconductor (CSOS), and integrated injection logic, bipolar product (I^2L).

In contrast, hybrid microcircuits result from combining various electronic, component, material, and manufacturing technologies into miniature electronic interconnections and packaging. Normally, film circuits are combined with chips and discrete components on a substrate. Integrated and complex monolithic circuits can be included within a hybrid.

Before deciding which class of microcircuit best meets the needs of a particular application, careful consideration should be given to construction parameters, size, and cost and reliability constraints as they relate to the specific design. Trade-off studies should be performed covering such factors as

1. Comparison of total costs. This includes development costs for each type plus the cost of fabrication and testing (nonrecurring and recurring costs).
2. Comparison of circuit parameter requirements such as resistance tolerances, tracking, temperature coefficient, speed, voltage levels, and electrical isolation with the parameter limitations of monolithic and hybrid circuits
3. Comparison of package size requirements to the space available
4. Evaluation of circuit power dissipation and the thermal resistances of the packaged circuit to insure acceptable temperatures on the substrate.

Additional factors affecting trade-off studies are available power and cooling quantities to be built and used during research and development (R&D) vs production. For example, hybrid circuits may be less costly for low-volume R&D hardware to demonstrate capability and allow easier modifications.

For monolithic integrated circuits (IC) numerous standard devices (listed in MIL-STD-1562, List of *Standard Microcircuits)* are available from which selections can be made. Because hybrids are essentially custom-made devices, a similar standardizing document does not currently exist. In recognition of the increasing usage of hybrid devices, the approach to reliable hybrids has been via test and inspection techniques. MIL-STD-883, Test *Methods and Procedures* for Microelectronic- Devices, includes test methods for hybrid and multichip microcircuits (Method 5008). Method 5008 of MIL-STD-883 colers test procedures for hybrid and multichip microcircuits.

The selection of a specific microcircuit type is governed by the guidelines depicted in Table 8-2. As previously indicated, the expected reliability level of parts and of microcircuits in particular must be incorporated into the selection process.

Table 8-3 provides failure mode and rate information for digital and linear microcircuits. The information included in this table is intended for comparing the reliability aspects of microcircuits and for aid in selecting the optimum device for a given design application. The table lists the class and type of the device,

TABLE 8-2. MICROCIRCUIT SELECTION GUIDELINES (Ref. 1)

1. MIL-STD-1562, *List of Standard Microcircuits*
2. MIL-M-38510, *Microcircuits, General Specification For.* This document defines screening per MIL-STD-883, *Test Methods and Procedures for Microelectronics*
3. Historical test data (similar application) or other engineering information and/or data that provide assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in Air Force equipment, comparable application, or GFE).

Note: When a desired device is not covered by MIL-M-38510, a new specification or drawing should be prepared and coordinated with potential manufacturers of the device. To assist the contractor in these actions, the DoD Reliability Analysis Center located at Rome Air Development Center (RADC), Griffiss AFB, Rome, NY, maintains a comprehensive, up-to-date data base on environmental operating capabilities, failure rates, failure modes and mechanisms, and fabrication techniques covering hybrid and monolithic microcircuits.

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TABLE 8-3. APPLICATION NOTES FOR INTEGRATED CIRCUITS (Ref. 1)

Microcircuit Type	Application Notes	Failure Information	Failure Rate Range, $F/10^6$ h
Digital		Failure indicators: mechanical anomaly (VIS) - 1% Opens (pin to pin) - 20% Shorts (pin to pin) - 22% Operation degradation - 57%	0.032-0.344
TTL	*Standard:* Intended for use in implementing logic functions where speed and power requirements are not critical. This family offers a full spectrum of logic- functions in various packages. Typical gate power dissipation is 10 mW with a typical propagation delay time of 10 ns. These devices exhibit a fan out of 10 when driving other standard TTL devices usually used to perform general purpose switching and logic functions. *Low Power:* Employed in logic design where low power dissipation is the primary concern. These devices have a typical gate power dissipation of 1 mW with a typical propagation delay time of 30 ns. Typically, these devices will drive only one standard TTL device but exhibit a fan out of 10 when loaded by other low power devices. Low power generates less heat and, therefore, allows for greater board densities. Lower current levels also introduce less noise and reduce constraints on power supplies. *High Speed:* Used to implement high-speed logic functions in digital systems. These devices employ a Darlington output configuration to achieve a typical propagation delay time of 6 ns. The typical gate power dissipation is 23 mW. These devices can drive up to 12 standard TTL devices and exhibit a fan out of 10 when driving other high-speed devices. Commonly used in high-speed memories and central processor units. *Schottky:* Used when ultra-high speeds are desired. These devices employ shallow diffusions and smaller geometries which lower internal capacitance to reduce delay time and sensitivity to temperature variation. Typical delay	Constituent failure modes: Surface defects - 6% Oxide defects - 4% Diffusion defects - 2% Metallization defects - 50% Bond/wire defects - 13’% Die attach bond - 11% Cracked die - 1% Package - 13%	0.032-0.180

(cont’d on next page)

TABLE 8-3. (cont’d)

Microcircuit Type	Application Notes	Failure Information	Failure Rate Range, F/10^b h
	time is 3 ns, and power dissipation is 19 mW. However, this power dissipation increases with frequency. These devices can drive 12 standard TTL devices and up to 10 Schottky devices. Noise immunity is reduced due to the nonsaturated switching operation. A ground plane is recommended for interconnections over 15 cm (6 in.) long and twisted-pair lines for distances over 25 cm (10 in.).		
CMOS	Used where low power is extremely desirable and high speeds are not essential. The typical power dissipation is 10 mW (at 10 kHz) and increases with frequency. Typical delay time is 50 ns. **A** typical fan out for CMOS loads is 50, but only 1 for standard TTL loads. Noise immunity is typically 1.5 V for CMOS compared to 0.4 V for standard TTL devices. This makes these devices useful in high noise environments. Handling precautions should be given consideration due to susceptibility to overstress from electrostatic discharge. Most commonly employed in medical electronics, calculators, watches, clocks, and automotive systems. These devices are highly tolerant of power supply voltage variation and will operate anywhere in the range of 3 to 15 V.	Constituent failure modes: Surface defects - 27% Oxide defects - 16% Diffusion defects - 9% Metallization defects - 25% Bond/wire defects - 15% Package - 8%	0.044-0.344
ECL	Intended for use in digital systems requiring high switching speeds and moderate power dissipation. Typical propagation delay time is 2 ns and typical power dissipation is 25 mW. Operation requires a –5.2 V supply and properly terminated lines or control impedance circuit boards. The logic levels (–0.9 V and –1.7 V) are not as easily detected as those of TTL devices. Intended for use in high-speed systems such as central processors, memory controllers, peripheral equipment, instrumentation and digital communications. A typical fan out is 15 when driving ECL devices.	Prevalent failure modes: Bond die attach Metallization defect Bond ‘wire defects (Failure percentages not available)	0.056-0.088

(cont‘d on next page)

TABLE 8-3. (cont’d)

Microcircuit Type	Application Notes	Failure Information	Failure Rate Range, F/10^6 h
Programmable ROM	Used in systems having nonvolatile memory requirements. Nichrome fusible links allow for custom field programming to aid system prototyping. Programming procedures must be closely regulated to prevent fuse “grow back”. Useful in implementing hardware algorithms and microprogramming.	Learning factor (^{TT}L) is especially applicable due to additional step required for programming. Prevalent failure modes: Metallization defect Surface oxide defect Package defects (Failure percentages not available)	0.280
Linear	Intended for use in signal amplification, detection, transmission, and voltage regulation. Large power dissipation limits packaging density and requires consideration of thermal design parameters. Extensively used in communications, controls, instrumentation, and information systems,	Failure indicators: mechanical anomaly (VIS) - 1% Opens (pin to pin) -9% Shorts (pin to pin) - *7%* Operational degradation - 83’% Constituent failure modes: Surface defects - 54% Oxide defects - 2% Diffusion defects - 2% Metallization defects - 18% Bond/wire defects - 8% Die attach bond - 9% Cracked die - 1% Package - 6%	0.096-0.208

[1] Failure indicators are device failure modes which identify the failure condition by visual, electrical, or mechanical measurements without performing any destructive analyses. For the purpose of accumulating statistics, pin-to-pin testing should be performed on failures first— to establish an open or short and to verify the failure—that then is classified as an operational degradation. Mechanical anomaly occurs when a visual or mechanical defect exists and when electrical performance is still within specifications.

The operational degradation failure indicator subclassifications are as follows:

“Digital:
- Stuck High
- Stuck Low
- Output Unstable/Erratic
- No Output Signal (only refers to cases for which the failure cannot be classified as stuck high or low and there is no output response to an input signal)
- Parameter Out of Tolerance

Linear:
- Hardover Positive (latched/saturated)
- Hardover Negative (latched/saturated)
- Output Unstable/Fluctuates/Erratic
- Output Clipped
- Latched/Saturated (other than at extremes)
- No Output Signal (refers only to cases for which the failure cannot be classified in any of the above categories and there is no output response to an input signal)
- Parameter Out of Tolerance

Constituent failure modes identify the constituent of the microcircuit and its defective condition which resulted in the failure indicator.

The relative occurrence data presented were derived from malfunction reports collected industry-wide by the Reliability Analysis Center. The qualification and screening tests of MIL-M-38510 and JAN parts may shift these distributions to those modes not easily detected. For example, the high incidence of metallization defects in TTL may be reduced by appropriate emphasis on pre-cap visual inspection and metallization process control.

application notes, failure information, and failure rate range. The information presented in Table 8-3, when modified to eliminate the effects of packaging, is applicable to IC chips used within hybrid microcircuits. The range of failure rates listed for each type was computed from Military Handbook (MIL-HDBK) 217 by using values for adjustment factors ranging from worst case to optimum application conditions.

Table 8-4 lists the available microprocessors and depicts the type number, manufacturer, number of bits,

TABLE 8-4. MICROPROCESSORS (Ref. 2)

Type Number	Manufacturer	Number of Bits	Manufacturing Process	Number of Pins	supply volts
4004	Intel	4	PMOS	16	15
4040	Intel	4	PMOS	24	15
PPS-4	Rockwell	4	PMOS	42	17
PPS-4/2	Rockwell	4	PMOS	42	17
9209	AMI	4	PMOS	28/40	15
TMS1000	TI	4	PMOS	28/40	15
TMS1200	TI	4	PMOS	28/40	15
TMS1100	TI	4	PMOS	28/40	15
TMS1300	TI	4	PMOS	28/40	15
3001	Intel	2	TTL	40	5
3002	Intel	2	TTL	40	5
2901	AMD	4	TTL	40	5
5701	MMI	4	TTL	40	5
6701	MMI	4	TTL	40	5
IMP-4	National	4	PMOS	24	12,5
9405	Fairchild	4	TTL	24	5
F4705	Fairchild	4	CMOS	24	3-15
8008	Intel	8	PMOS	40	9,5
8080	Intel	8	NMOS	40	5,12
8080A	Intel	8	NMOS	40	5,12
PPS-8	Rockwell	8	PMOS	42	17
PPS-8/2	Rockwell	8	PMOS	42	17
MK5065	MOS	8	PMOS	40	12,5
6800	Motorola	8	NMOS	40	5
6501	MOS	8	NMOS	40,28	5
6502	MOS	8	NMOS	40,28	5
6503	MOS	8	NMOS	40,28	5
AM9080	AMD	8	NMOS	40	5,12
AM9080-1	AMD	8	NMOS	40	5,12
AM9080-2	AMD	8	NMOS	40	5,12
AM9080-4	AMD	8	NMOS	40	5,12
AM9080A	AMD	8	NMOS	40	5,12
F8	Fairchild	8	NMOS	40	5,12
2650	Signetics	8	NMOS	40	5
CDP1801	RCA	8	CMOS	40,28	3-15
EA9002	EA	8	NMOS	28	5
IM6100	Intersil	12	CMOS	40	5-10
SC/MP	National	8	PMOS	40	14
IMP-8	National	8	PMOS	40	5,9
IMP-16	National	16	PMOS	40	5,9

(cont’d on next page)

TABLE 8-4. (cont'd)

Type Number	Manufacturer	Number of Bits	Manufacturing Process	Number of Pins	supply volts
CP1600	GI	16	NMOS	40	5,12
MPS1600	W.Dig.	8	NMOS	40	5,12
MPS1600	W.Dig.	16	NMOS	40	5,12
SBP0400	TI	4	I^2L	40	0.9-5
SBP0400A	TI	4	I^2L	40	0.9-5
S6800	AMI	8	NMOS	40	5
SMS300	SMS	8	TTL		
CRD8	SSS	8	CSOS		
PACE	National	16	PMOS	40	5,12
TMS9900	TI	16	NMOS	64	5,12
CDP1802D	RCA	8	CMOS	40	3-15
CDP1802CD	RCA	8	CMOS	40	3-6

Note: Cutoff date for data in this table is July 1980.
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manufacturing process, number of pins, and the supply voltage. Table 8-5 shows the microprocessor design criteria for some 4-, 8-, and 16-bit Texas Instruments* (TI) IC families. Table 8-6 depicts the 1978 state of the art in memory technology. The microcircuits listed in Tables 8-4 through 8-6 are of commercial quality, and only recently is an effort being made to qualify a selected few microprocessors to MIL-M-38510 specifications, for example, the 8080A developed by Intel Corporation *, the 6800 developed by Motorola*, and the 2901 A developed by Advanced Micro Devices*.

TABLE 8-5. MICROPROCESSOR DESIGN CRITERIA FOR SOME 4-,8-, and 16-BIT TI INTEGRATED CIRCUIT FAMILIES (Ref. 3)

Design Criteria	4-Bit TMS 1000 Series	8-Bit TMS 8080A Family	16-Bit TMS 9900 SBP 9900 Family	4-Bit Slice SN74S481 SBP0400A/'401A Processor Elements
Component structure and technology	4-bit PMOS self-contained 1-chip *computer*	*8-bit* NMOS CPU system functionally partitioned logic *building blocks*	*16-bit* CPU system functionally partitioned *logic building blocks*	"N" *bit* Bipolar bit slice logic *building block* processor elements
Major hardware/software consideration	*Fixed* hardware/variable software-*Microprogrammable* instruction set	Variable hardware/variable software—fixed *second* generation *instruction set*	Variable hardware/variable software—*fixed third* generation *instruction set* with multiply, divide, etc.	Variable hardware/variable software—micro-*programmable* to emulate existing machines and software
Architecture features	*Internal:* 8-bit word ROM (1k X 8 or 2k X 8) RAM (64 X 4 or 128 X 4) programmable	Memory to register architecture addressing up to 64k X 8 bits of *memory*	Memory to memory architecture addressing up to *64k X 8* bits of *memory.* Uses typically 20 to 30% less	"N" bit machine elements for architectual freedom with virtually *unlimited* instruc-

(cont'd on next page)

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*The use of company names does not constitute an endorsement of the products of these companies by the US Army.

TABLE 8-5. (cont'd)

Design Criteria	4-Bit TMS1000 Series	8-Bit TMS 8080A Family	16-Bit TMS 9900 SBP 9900 Family	4-Bit Slice SN74S481 SBP0400A/401A Processor Elements
Architecture features (cent'd)	instruction decode, output PLA, and clock		memory than 8080A implementation	tions and *memory addressing* capability
Speed comparison				
Clock frequency	*400* kHz	2 MHz	3 MHz	Variable to 10 MHz
Instruction time	15 μs	2 μs (min)	2.7 μs (min)	1 clock micro
General classification	Moderate *l-chip* speed	Moderate *multichip* solution	Fast *multichip* about two times 8080A speed	Fastest *multielement* solution
Design support	. Hardware evaluator and debugging unit . System evaluator with external instruction memorv	. Compatibility with commercially available prototyping systems	l 990/4 prototyping board, upward compatible support through complete minicomputer hardware/ software	. Microprogrammable prototyping modules . Microassemblers
Software support	. Assembler and simulator on commercial time share services	. Assembler and simulator on commercial time share services	. Complete software support for cross and stand-alone systems . FORTRAN, BASIC, COBOL compliers	. Complete component specifications and application notes . Microassemblers
Cost advantages compared to TTL system	. 30:1 to 100:1 reduction in parts and assembly costs . 40 to 70% reduction in design costs	. 15:1 to 25:1 reduction in parts and assembly costs . 25 to 70% reduction in design costs	. 15:1 to 30:1 reduction in parts and assembly costs l 35 to 70% reduction in design costs	l5:1 to 10:1 reduction in parts and assembly costs . 10 to 20% reduction in design costs
General guidelines for typical system usage — Note: Environmental, size, weight, power, and production volume criteria will require further evaluation prior to finalizing microprocessor selection.	(4-Bit) ● Stand-alone systems: scales, games, vending machines, monitor and measurement systems, timers, copy equipment, and consumer applications ● Distributive computer systems: point of sale (POS), credit card verification, numerical control, factory automation systems	(8-Bit to 16-Bit) ● Terminals: intelligent, stand-alone, slave, point of sale (POS) ● Navigational systems ● Telecommunications ● Microcomputer and minicomputer applications ● Distributed computing systems ● Controllers: process control, machine control, communications control, factory automation ● Instrumentation ● Measurement systems		("N" Bit) ● Large computer systems with > 64k memory ● Military/airborne computers ● Small, hard-wired logic controls ● Emulation of existing computers with maximum memory efficiency ● Tailored sof[-ware designs

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TABLE 8-6. THE 1978 STATE OF THE ART IN MEMORY TECHNOLOGY (Ref. 4)

Device Type	Access Time, ns	Active Power Dissipation per Chip, mW	Application
4- to 16-k MOS dynamic RAM	150-300	400-500	Large mainframe and microcomputer based systems
4-k fully static 2114-type MOS statics	150-300	500	Peripheral and microcomputer systems
4-k clocked 4104-type MOS statics	150-200	120 (30 standby)	Peripheral and microcomputer systems
1- to 4-k fast MOS statics	50-100	500	Fast mainframe, cache, or microcomputer based systems
4- to 16-k I^3L dynamic RAM	90-125	500	Fast mainframe and microcomputer systems
4- to 16-k I^2L static RAM	*70-125*	500 (20 standby)	Fast mainframe, peripheral, and microcomputer systems
1- to 4-k, TTL/ECL static RAM	30-70	500 1 watt	Cache
32- to 64-k MOS ROM	200-500	500	Fixed memory and program storage
1- to 8-k, TTL ROM	50-100	*700*	Fixed storage
8- to 16-k, EPROM (UV erasable)	500	500	Prototype program storage
8-k EAROM			Nonvolatile RAM; reprogrammable ROM
nitride types	1 µs	500	
Fames types	500	500	
64-k CCD, memory	1 µs	500	Disk replacement; auxiliary serial memory
100- to 1000-k bubble memorv	10 µs	500	Nonvolatile disk replacement; microcomputer storage

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8-2.2.2 Semiconductor Devices

Expanding technology, widespread use, and the economics of large volume production have resulted in a proliferation of discrete semiconductor devices. A wide variety of functional classifications exists based upon electrical characteristics available to the designer, such as low or high power, switching time, internal capacitance, and forward current. In addition, there are several categories relating to semiconductor device material and its physical configuration. In total, there are 35 officially recognized functional and constructional classifications of semiconductor device types. These types can be found in MIL-STD-701.

The selection of a specific semiconductor device is governed by the guidelines depicted in Table 8-7. As shown in this table, the governing specification for discrete semiconductor devices is MIL-S-19500. This basic document and its appended detailed specification sheets establish the general and specific requirements, including definitions, abbreviations and symbols, electrical characteristics, electrical, mechanical, and environmental requirements, styles, test methods, QA pro-

TABLE 8-7. SEMICONDUCTOR SELECTION GUIDELINES (Ref. 1)

1. MIL-STD-701, *Lists of Standard Semiconductor Devices*
2. MIL-S-19500, *Semiconductor Devices, General Specification For* (JANTXV or JANTX devices)
3. Historical test data (similar application) or other engineering information and/or data that provides assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in military equipment).

Note: In selecting semiconductor devices, it is important to remember that in MIL-S-19500 the values specified for ratings, maximum ratings, or absolute maximum ratings are based on the absolute system and are not to be exceeded under any service or test conditions. These ratings are limiting values beyond which the serviceability of any individual semiconductor device may be impaired. It follows that a combination of all the absolute maximum ratings cannot normally be attained simultaneously. Combinations of certain ratings may be obtained only if no other single maximum rating is exceeded. Unless otherwise specified, the voltage, current, and power ratings are based on continuous dc power conditions at free air ambient temperature of 25° ±3 deg C. For pulsed or other conditions of operation of similar nature, the current, voltage, and power dissipation ratings are a function of time and duty cycle.

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visions, and qualification and inspection procedures for all semiconductor devices. MIL-STD-701 provides a listing of those MIL-S-19500 devices that are considered to be standard or are preferred for use in DoD equipment. Failure rates for these devices can be calculated in accordance with MIL-HDBK-217.

Table 8-8 provides additional information for discrete semiconductor devices. Included in this table are typical applications for the type of semiconductor listed, a cross-referencing of standard types derived from MIL-STD-701, and a list of failure rates against each semiconductor type. Because of the proliferation of device types, proven technology, and device standardization, semiconductor failure modes are well-established and can be effectively controlled during processing. Consequently, failures usually occur on a random basis during normal operation within the useful life of the device. Table 8-8 also includes failure rate information for each semiconductor type. The failure rates shown were taken from Section 3.0, MIL-HDBK-217, under the airborne inhabited environment.

8-2.2.3 Resistors

As a generic class of electronic devices, resistors have been well-documented by military specifications and standards. Consequently, a selection from among a variety of available standard types and styles can be made. For economic reasons standard resistors are normally produced in large production runs that make the selection of standard devices even more attractive. Note, however, that there are exceptions. Extremely tight-tolerance fixed resistors and certain precision-type variable resistors (which require a unique output voltage curve, taps, or stacking configuration) may be difficult or expensive to procure or may possess questionable reliability. Resistor selection is governed by the guidelines given in Table 8-9.

TABLE 8-8. APPLICATION AND SELECTION GUIDELINES FOR SEMICONDUCTORS (Ref. 1)

Semiconductor Type	Application	MIL-STD-701 Table	Failure Rate, F\10^{6}h
Diodes, silicon general purpose	Low-power rectifiers	I	0.68
	Axial lead-power rectifiers	II	0.68
	Power diodes	III	0.68
	High-voltage rectifier assemblies	Iv	0.68
	Switching diodes	v	0.68
	Multiple diode arrays	VI	0.68
Diodes, silicon voltage reference	Voltage reference diodes	VII	0.85
	Low-level, forward-voltage reference diodes	VIII	0.85
	Voltage regulator diodes	IX	0.85
	Current regulator diodes	XIV	0.85

(cont'd on next page)

TABLE 8-8. (cont'd)

Semiconductor Type	Application	MIL-STD-701 Table	Failure Rate, F/10^6 h
Rectifiers, silicon controlled	Thyristors	XIX	0.90
		x x	0,90
Diodes, silicon	Fast recovery	XI	8.10
microwave detector	Detector	x	12.00
microwave mixer	Mixer	x	16.00
Diodes, germanium	Tunnel diodes	XII	1.70
microwave detector	Detector	x	35.00
	Mixer	x	61.00
Diode, varactor	Voltage variable capacitor	XIII	8.10
Transistor, silicon NPN	Low power and switching	XXI	0.98
	High power >5 W	XXIII	0.98
	Radio frequency	XXV	0.98
	Darlington	XXVIII	0.98
	Dual transistor, differential amplifier	XXVI	1.96
	Low-power chopper	XXXII	0.98
	Low-power, dual-emitter chopper	XXXIII	0.98
Transistor, silicon PNP	Low power and switching	XXII	1.60
	High power >5 W	XXIV	1.60
	Radio frequency	XXV	1.60
	Dual transistor, differential amplifier	XXVI	3.20
	Low-power chopper	XXXII	1.60
Transistor silicon, dual	Complimentary NPN/PNP	XXVII	2.58
Transistor, silicon, FET	Field effect N-channel	XXX	*2.70*
	Field effect P-channel	XXX	2.70
	Field effect, dual unitized N-channel	XXXI	5.40

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TABLE 8-9. RESISTOR SELECTION GUIDELINES (Ref. 1)

1. MIL-STD-199, *Resistors, Selection and Use of*
2. The 39000 series of *Established Reliability Military Specifications*
3. Historical test data (similar application) or other engineering information and/or data that provide assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in military equipment, comparable application, or Government furnished equipment (GFE)).

Note: For selecting particular resistors for specific applications, the qualified product list (QPL) should be consulted for a list of qualified sources prior to procurement commitments.

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In addition to these selection criteria, Table 8-10 presents further (considerations to be employed when selecting resistors. The resistor types shown, together with their appropriate military specification style designations and applicability to new design, reflect the provisions of MIL-S-I-D-199. The generic failure rates given in the table are taken from MIL-HDBK-217 and are provided for purposes of comparison. The failure rates reflect an airborne inhabited environment and 1 % failure per 10^3 h quality level.

8-2.2.3.1 Variable Resistors

There are several types of variable resistors (trim pots) available to the circuit designer. Table 8-11 lists

TABLE 8-10. APPLICATION AND SELECTION GUIDELINES FOR RESISTORS (Ref. 1)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
MIL-R-11	Composition (insulated)		Inactive for new design. Use MIL-R-39008.		
MIL-R-26	Wire-wound (power type)	RW29 RW37 RW31 RW38 RW33 RW47 RW35 RW56	These are not recommended, see MIL-R-39007.		0.33
MIL-R-93	Wire-wound (accurate)		Inactive for new design. Use MIL-R-39005.		
MIL-R-10509	Film (high stability)	RN75	These are not recommended, see MIL-R-55182.		0.023
MIL-R-11804/2	Film (power type)	RD60 RD65 RD70	Use where power dissipation equivalent to MIL-R-39007 is required and where ac performance must be considered. RD60, RD65, and RD70 are considered uninsulated.	Shorts—humidity or salt air can cause shunt paths on surface of resistor and shorting between spirals. Opens—can be caused by mechanical damage. Operation at RF above 100 MHz may produce inductive effects on spiraled units.	1.3
MIL-R-18546/2	Wire-wound power type (chassis mounted)	RE77 RE80	These are not recommended, see MIL-R-39009.		0.65
MIL-R-22684	Film, insulated		Inactive for new design. Use MIL-R-39017.		
MIL-R-39005	Wire-wound (accurate) established reliability	RBR52 RBR56 RBR53 RBR57 RBR54 RBR71 RBR55 RBR75	Styles RBR52, 53, 54, 55, and 71 are preferred for new design. Preferred resistance tolerances are ± 0.1% and ± 1.0%.	Shorts—application of overvoltage can cause insulation breakdown between windings. Opens—resistors employ plastic or ceramic bobbins which are subject to mechanical damage, which results in open windings. Operation over 50 kHz can produce inductive and intrawinding capacitive effects.	0.15

MIL-R-39007	Wire-wound (power type) established reliability	RWR74 RWR81 RWR78 RWR84 RWR80 RWR89	Use for large power dissipation where ac performance is not vital (e.g., as voltage dividers or bleeders in power supplies). Satisfactory for use at frequencies up to 20 kHz even though the ac characteristics are controlled. The use of tapped resistors should be avoided; the insertion of taps weakens the resistor mechanically and lowers the effective power rating. Resistors are not suitable for use above 50 kHz.	Shorts—rarely occur, but can happen due to intrawinding insulation breakdown. Opens—usually occur due to mechanical damage suffered by the resistor or from winding burnout due to the wattage rating or the rated continuous working voltage being exceeded.	0.66
MIL-R-39008	Composition (insulated)	RCR05 RCR32 RCR07 RCR42 RCR20	Use for general applications where initial tolerance needs to be no tighter than ± 5%, and long-term stability under fully rated operating conditions needs to be no better than ± 15%. Resistance increases up to 20% during storage in humidity. Operation of the resistor at rated load will drive out the moisture and bring the resistor value back to within tolerance.	Both shorts and opens very rarely occur unless resistor is so overloaded or overheated as to cause the phenolic case or thermosetting binder material to carbonize. In high impedance circuits, the failure mode is generally a short; in low impedance circuits, the failure mode is open. High "JOHNSON" noise levels are present in resistance values above 1.0 Mohm. Drift—RF will produce capacitive effects end-to-end. Operation at VHF or higher frequency reduces effective resistance due to dielectric losses (the "Boello" effect).	0.0048

(cont'd on next page)

TABLE 8-10. (cont'd)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
MIL-R-39009	Wire-wound (power type) established reliability	RER40 RER60 RER45 RER65 RER50 RER70 RER55 RER75	Use where a lower tolerance and a greater power dissipation are required for a given unit size than are provided by MIL-R-39007 resistors and where ac performance is not critical. The power dissipating capacity of these resistors is dependent upon the area of heat sink upon which they are mounted.	Shorts—may occasionally occur due to intrawinding insulation breakdown. Opens—may occasionally occur due to damage to the winding, poor winding to terminal connection, etc., suffered during fabrication.	0.13
MIL-R-39017	Film (insulated) established reliability	RLR05 RLR07 RLR20 RLR32 RLR42	Resistors have semiprecision characteristics and small sizes. The sizes and wattage ratings are comparable to MIL-R-39008 units, and stability lies between MIL-R-39008 and MIL-R-55182. Full-power operating temperature should not exceed 70°C. Resistance-temperature characteristic is ± 200 PPM/°C.	Shorts or opens may occur if resistor is poorly fabricated or overloaded in application. Operation at RF above 100 MHz may produce inductive effects on spiral-cut types.	0.02
MIL-R-55182	Film established reliability	RNR50 RNR55 RNR60 RNR65 RNR70	Use where high stability, long life, reliable operation and accuracy are required. Resistors are particularly suited for high-frequency applications. Application examples include: high-frequency, tuned circuit loaders, television side-band filters, rhombic antenna terminators, radar pulse equipment, and metering circuits.	Shorts—may occasionally occur because of protuberances on adjacent resistance spirals. Opens—may occasionally occur due to nonuniform spirals resulting in a too-thin resistance path. Operation at 400 MHz and above will result in resistance decrease due to shunt capacitance effects.	0.023
MIL-R-19	Wire-wound (low operating temperature)	RA20 RA30	Use for noncritical, low-power, low-frequency applications where the characteristics of wire-wound devices are more desirable than those of compo-	Variable resistors as a class of components share many common failure modes: ● Wire-wound units are inductive, winding-to-winding,	6.4

			sition. Common applications are bias controls and voltage dividers. Wattage rating depends upon the size and type of heat sink unit is mounted on. Resistors have high inductance between windings.	causing resistance drift and affecting circuitry accuracy. ● Wire-wound units suffer shorts between winding loops due to insulation breakdown or contaminants which bridge the insulation. ● Windings will rupture with sufficient wear by the wiper arm, which results in an open circuit. ● All variable resistors can suffer movement of the wiper on the resistance element as the result of shock or vibration. In critical applications, the resultant change of the output voltage can constitute a "failure" of the resistor. ● Nonwire-wound units become noisier with wear life and will suffer resistance change due to humidity. ● Power ratings for all variable resistors are based upon the engagement of the maximum resistance by the wiper. Excessive currents can be drawn when less than maximum resistance is engaged. The result is a burnout of the resistance element.	
MIL-R-22	Wire-wound (power type)	RP05 RP20 RP06 RP25 RP10 RP30 RP15	Use in such applications as motor speed controls; lamp dimming; heater and oven controls; potentiometric uses; applications where voltage or current variation is required, such as voltage-divider or bleeder circuits.		6.0
MIL-R-94	Composition (insulated)	RV4 RV6	Rate for full-load operation at 70°C, otherwise see data in MIL-R-23285.		20.0
MIL-R-23285	Nonwire-wound	RVC5 RVC6	Use where initial setting stability is not critical and long-term stability needs to be no better than ± 20%. Rated for full-load operation at 125°C.		6.7

(cont'd on next page)

TABLE 8-10. (cont'd)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
MIL-R-12934	Wire-wound precision	RR0900 RR1000 RR1100 RR1300 RR1400 RR2000 RR2100 RR3000	Use in applications requiring close conformity of the electrical output (in terms of applied voltage) to the angular position of the wiper arm on the resistance element. This functional conformity (whether producing a linear or nonlinear output curve with shaft rotation) is available in tolerances ranging from 0.025% through 1.0%. Power rating is dependent on the size and type of heat sink upon which resistor is mounted.	Variable resistors as a class of components share many common failure modes: ● Wire-wound units are inductive, winding-to-winding, causing resistance drift and affecting circuitry accuracy. ● Wire-wound units suffer shorts between winding loops due to insulation breakdown or contaminants which bridge the insulation. ● Windings will rupture with sufficient wear by the wiper arm, which results in an open circuit. ● All variable resistors can suffer movement of the wiper on the resistance element as the result of shock or vibration. In critical applications, the resultant change of the output voltage can constitute a "failure" of the resistor. ● Nonwire-wound units become noisier with wear life and will suffer resistance change due to humidity. ● Power ratings for all variable resistors are based upon the engagement of the maximum resistance by the wiper. Excessive currents can be drawn when less than maximum resistance is engaged. The result is a burnout of the resistance element.	5.8
MIL-R-22097	Nonwire-wound (lead-screw actuated)	RJ12 RJ24 RJ22 RJ26 RJ50	These are not recommended, see MIL-R-39035.		9.5
MIL-R-27208	Wire-wound (lead screw actuated)	RT26	These are not recommended, see MIL-R-39015.		0.70
MIL-R-39002	Wire-wound semiprecision	RK09	Use where the precision needed is better than that supplied by MIL-R-19 units and less than that supplied by MIL-R-12934 units. Power rating is dependent on size and type of heat sink upon which resistor is mounted.		6.4
MIL-R-39015	Wire-wound (lead-screw actuated) established reliability	RTR12 RTR22 RTR24	Use for matching, balancing, and adjusting circuit variables in critical applications. For extremely critical applications, use in conjunction with a fixed resistor, so that change in wiper setting due to shock or vibration limits output voltage change to a negligible minimum.		0.14
MIL-R-39035	Nonwire-wound (lead-screw actuated) established reliability	RJR12 RJR24	Same as MIL-R-39015.		7.96

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TABLE 8-11. CHARACTERISTICS OF TRIMMING POTENTIOMETER ELEMENTS (Ref. *5)*

Characteristic	Carbon	Cermet	Wire-Wound
Resistance range	100 ohm to 5 Mohm	10 ohm to 2 Mohm	10 ohm to 50 kohm
Power	0.5 W at 70°C	1 W at 70°C	1 W at 70°C
Potentiometer resettability	0.05%	0.05%	0.11 to 1.0%
Rheostat resettability	0.5%	1 .0%	0.11 to 1.0%
Stability in load life	± 10% AResistance	± 3%Δ Resistance	± 2%Δ Resistance
Temperature coefficient	± 400 PPM/°C to* 800 PPM/°C	± 100 PPM/°C	± 50 PPM/°C
Trade-Off in Characteristics			
Resistance range	Broad	Broad	Broad
Resolution	Essentially infinite	Essentially infinite	Finite
Temperature characteristic	Poor	Good	Excellent
Rotational life	Very good	Good	Good
Power rating	Low	High	High
Environmental stability	Poor	Excellent	Excellent

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the three most commonly used varieties of potentiometers and the characteristics of each. In addition to these characteristics, one should compare

1. Wiper arm contact-resistance noise
2. End of rotation-resistance taper
3. Survival after sonic or other board cleaning
4. Size, mounting, bearing, bushing stops, and other mechanical details.

Part size and reliability are of prime importance in selection of trimmers. However, when cost limitations are imposed, one must make trade-offs in adjustability and reliability. Designers have used multiturn trimmers and, as a result, boost costs by employing cermet trimmers to get good resolution. In many cases the same performance can be achieved by using less expensive carbon trimmers. Often by adding fixed resistors at nominal cost, one can obtain the same results the multiturn cermet units offer.

8-2.2.3.2 Resistor Networks

Ever since their inception over 30 yr ago, resistor networks have enabled packaging engineers to conserve space on their printed circuit board (PCB) layouts. Though device sizes have not reached a relatively stable state, refinements in specifications are still occurring.

A resistance network consists of a group of resistors interconnected and packaged as a single-piece part. As such, these networks can be substituted for discrete devices in many layouts but should not be evaluated on the basis of part cost alone. Discrete resistors are inexpensive, reliable, offer machine insertability, and permit the board designer to change resistance values easily. Despite these competitive features, resistor networks are able to provide cost advantages to packaging engineers who recognize and make use of their special capabilities.

There are several hundred network arrays currently available directly from distributors. Generally, it is not cost-effective to make special orders of lots less than 5000 devices. To calculate the break-even point for the use of discrete resistors versus network arrays, the cost of PCB space, labor, insertion, and waste must be considered as well as part cost. At a 10k volume, for example, a discrete resistor may cost 1.6¢ and insertion and printed circuit (PC) space another 4.2¢ for a total of 5.8¢, whereas a 12-pin, 11-resistor network package would only cost 5.9@ and would take about one-tenth the PCB space per resistor.

Resistor networks are available in two basic packages, dual-in-line package (DIP) or single-in-line package (SIP). A DIP has layout advantages when it becomes necessary to locate as many resistors as possible in one package. The extra set of leads on a DIP (as compared to an SIP) provides greater internal device layout flexibility, but the extra devices in the package can sometimes create unexpected difficulties when the user must run longer interconnection paths on the PCB to get the DIP pins. This could become a problem for higher speed circuits. An SIP, on the other hand, takes up less PCB surface area when compared to a DIP or to the discrete devices it replaces. It is desirable to use an SIP where the lead lengths from the resistor to the active device must be kept short. This is important when working with high-speed circuits such as emitter coupled logic (ECL) and Schottky TTL.

Table 8-12 presents the general types of DIP, SIP, and custom networks that are offered by various suppliers.

8-2.2.4 Capacitor

Although similar to resistors, capacitors have been thoroughly investigated for operational characteristics, identified for form, function and applicable ratings; documented for procurement, test, qualification approval, quality control; and standardized by military specifications and other standards. Like resistors, they are normally produced in large production runs that tend to keep unit prices low and promote standardization. Capacitor selection is governed by the guidelines given in Table 8-13.

Table 8-14 presents additional considerations to be employed when selecting capacitors. The capacitor types shown, together with their appropriate military specification style designations and application notes, reflect the provisions of MIL-STD-198. The failure rates given in Table 8-14 have been provided for the sole

TABLE 8-12. RESISTOR NETWORK SUPPLIERS (Ref. 6)

	Standard Thick Film Arrays		Standard Thin Film Arrays		User-Trimmable Arrays	Custom Arrays	
	DIP	SIP	DIP	SIP		Thick	Thin
Airco Speer			x				x
Allen-Bradley	x	x	x		x	x	x
Alpha Electronics	x	x				x	
Analog Devices			x				x
Beckman	x	x	x				
Bourns	x	x					
Centralab	x	x				x	
CTS Berne	x	x			x	x	
Dale Electronics	x	x				x	
Hybrid Systems			x				x
Hycomp			x	x			x
KDI Pyrofilm	x	x				x	
Mills Resistor[1]							
National Semiconductor			x				
Sprague	x	x			x	x	
Stackpole	x	x				x	
TRW/IRO			x	x			x

[1] Wire-wound types

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TABLE 8-13. CAPACITOR SELECTION GUIDELINES

1. MIL-STD-198, *Capacitors, Selection and Use of*
2. The 39000 series of *Established Reliability Military Specifications*
3. Historical test data (from similar application) or other engineering information and/or data providing assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in military equipment, comparable application, or GFE).

Note: In selecting particular capacitors for specific applications, the qualified product list should be consulted for a list of qualified sources prior to procurement commitments or specification of the part in the engineering data package.

purpose of demonstrating the comparative reliability levels of the various capacitor types. These are generic failure rates taken from MIL-HDBK-217.

In summary, among design engineers volumetric efficiency and reliability are of primary importance in the selection of capacitors. In power and switching applications the degree of volumetric efficiency is critical to prevent high ripple outputs. One indicator of capacitor efficiency is equivalent series resistance (ESR). Low ESR ratings perform best under these conditions. Capacitor reliability is an important consideration because capacitor failures can often lead to catastrophic failures in entire PCB subassemblies.

Text commences on p. 8-30.

TABLE 8-14. APPLICATION AND SELECTION GUIDELINES FOR CAPACITORS (Ref. 1)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10⁶ h
			FIXED, GLASS, AND MICA		
MIL-C-5	Mica dielectric	CM05 CM07 CM06 CM08	Inactive for new design. See MIL-C-39001.		
		CM15 CM35 CM20 CM45 CM30 CM50	Use in circuits requiring precise, high-frequency filtering, bypassing, and coupling. Use where close impedance limits are essential with respect to temperature, frequency and aging—such as in tuned circuits that control frequency, reactance, or phase. Use as padders in tuned circuits, as secondary capacitance standards, and for tuning of high frequencies. These capacitors have good stability and reliability.	Shorts can occur due to moisture absorption or due to internal solder flow resulting from excessive heat generated during external lead soldering. Opens usually result from rupture of weak internal connections due to vibration or shock.	0.06
MIL-C-10950	Mica dielectric	CB50 CB61 CB55 CB62 CB56 CB65 CB57 CB66 CB60 CB67	Intended for use at frequencies up to 500 MHz. Use in tuned circuits and in coupling and bypassing applications in VHF and UHF circuits. Units have high reliability if properly protected from high ambient temperature and humidity conditions.	Capacitors are very susceptible to silver-ion migration, resulting in shorts. Migrations can occur in a few hours when capacitors are simultaneously exposed to dc voltage stress, humidity and high temperature.	0.93
MIL-C-23269	Glass dielectric established reliability	CYR10 CYR20 CYR13 CYR22 CYR15 CYR30 CYR17 CYR32	Capacitors should be used as substitutes for mica units in applications requiring known reliability and where the differences in temperature coefficient and dielectric loss are taken into account. They are stable in extreme environmental condi-	Degradation of dielectric crystalline structure can occur as the result of storage below 45°C. The capacitance will decrease with the decrease in dielectric constant, and the unit will drift out of tolerance. Opens are frequently due to poor connections	0.021

			tions, have long life (30,000 h and more) and are very satisfactory for use in missile-borne and space equipment. These physically small units are resistant to high G loads but are susceptible to damage from mild mechanical shocks. Therefore, they should be handled carefully. They exhibit a much higher Q over a wider capacitance range than mica dielectric units.	of leads to the plates or mechanical damage to the capacitor. Overheating during external soldering can result in internal solder flow (shorts) or rupture of internal solder connection (opens).	
MIL-C-39001	Mica dielectric established reliability	CMR04 CMR07 CMR05 CMR08 CMR06	Intended for use where known orders of reliability are required. Failure rate depends almost exclusively on unit application, e.g., (1) with constant temperature, capacitor life is inversely proportional to the eighth power of the applied dc voltage or (2) with constant dc voltage life decreases approximately 50% per each 10 deg C rise in temperature. Life expectancy at rated conditions is 50,000 h, minimum. (Failure rate shown in last column is taken from MIL-STD-198.)	Same comments as given for MIL-C-5.	0.006
			FIXED, ELECTROLYTIC		
MIL-C-62	Electrolytic (dry electrolyte) aluminum	CE11 CE13 CF71	Not suitable for airborne equipment. Lowest volume, mass, and cost per microfarad with exception of tantalum electrolytic capacitor. Suitable where low frequency, pulsating, dc signals or components are to be filtered out.	Will fail at low barometric pressure and low temperature, such as at high altitude. Even though they have vents designed to open at dangerous pressures, explosions can occur because of gas pressure or a spark ignition.	
MIL-C-3965	Electrolytic (nonsolid electrolyte tantalum)		Inactive for new design. See MIL-C-39006.		

(cont'd on next page)

TABLE 8-14. (cont'd)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
MIL-C-39003	Tantalum (solid electrolyte) established reliability	CSR13	Intended for use where a known order of reliability is required. These capacitors are the most stable, reliable, and long-lived electrolytics available. These units are not temperature sensitive. Limitations are relatively high-leakage current, small voltage range (6 to 120 V), and a maximum allowable reverse current of 5% of rated dc voltage at +25°C to 1% at +125°C. Capacitors are used where low-frequency, pulsating dc components are to be bypassed or filtered out and for uses requiring large capacitances, small size, and the ability to withstand significant shock and vibration levels. Use for filtering, bypass, coupling, blocking, energy storage, and other low-voltage dc applications. Capacitors are available only in polarized form; use only in dc circuits with the polarity observed.	Shorts can occur due to solder balls created by internal solder flow resulting from heat generated during the external soldering of leads. Shorts due to dielectric breakdown are rare due to self-healing effect of high-leakage current on the MnO_2 provided current is limited to use of a 3-ohm/V line resistance in series with the capacitor. Opens occur mainly due to poor solder or weld internal connections which rupture during vibration or shock.	0.052
MIL-C-39006	Electrolytic (nonsolid electrolyte) tantalum established reliability	CLR25 CLR27 CLR35 CLR37 CLR65	Polarized foil capacitors (styles CLR25 and CLR35) should be used where large capacitance values are required and wide tolerances are acceptable. Use for bypassing or filtering out low-frequency pulsating dc components. When used for low-frequency coupling in vacuum tube and transistor cir-	Capacitors are subject to failure (shorts) due to leakage of the electrolyte which can be caused by wide-range temperature cycling, vibration, or factors which damage the seal. The application of reverse voltage will also result in shorts. Opens are usually associated with faults in external lead welds.	0.11

			cuits, allow for leakage current. Units should be used only in dc circuits with polarity properly observed. If ac components are present, the sum of the peak ac voltage plus the applied dc voltage must not exceed the dc rated voltage. Also peak ac voltage shall not exceed the applied dc voltage. Nonpolarized foil capacitors (styles CLR27 and CLR37) are suitable for use in ac applications where dc voltage reversals occur. Examples: tuned, low-frequency circuits; phasing low-voltage ac motors; computer circuits, in which dc voltage reversal occurs; servo systems. Sintered slugs (style CLR65) are used primarily in low-voltage power supply filtering circuits. Use in dc applications only; no reverse voltage can be tolerated.		
MIL-C-39018	Electrolytic (aluminum oxide electrolyte)	CU13 CU15 CU17	Use in filter, coupling, and bypass applications in which large capacitances are needed, and capacitance excesses over the nominal value can be tolerated. For polarized units (styles CU13 and CU17) the applied ac peak voltage should never exceed the applied dc voltage. The sum of the applied ac peak and dc voltages should never exceed the dc-rated weakening voltage. Use where low-frequency, pulsating, dc signal components are to be filtered out, such as in B power supplies	Capacitance loss (drift) will occur as the result of the aluminum oxide dielectric electric electrochemically combining with the electrolyte. Opens can occur by the dissolution in the electrolyte of the lead between an electrode and the aluminum. Seal degradation can result from use of any type of halogenated solvent wash. Application of voltage in reverse polarity will burnout (open) these units.	1.6

(cont'd on next page)

TABLE 8-14. (cont'd)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
MIL-C-39018 (cont'd)			up to 250 dc working volts; at plate and screen connections to B+; and as cathode bypass units in self-biasing circuits.		
FIXED, PAPER AND PLASTIC					
MIL-C-25	Paper (dielectric)		Inactive for new design. See MIL-C-19978.		
MIL-C-11693	Feed through, radio-interference reduction	CZ23 CZ33 CZ42	Use in applications for which it is necessary to pass low-frequency currents through a chassis or from point-to-point in equipment and to pass the RF currents (which can cause interference) to ground by the shortest possible path. Typical equipment for the above applications are: (1) rotating machinery; (2) ignition systems; (3) electromechanical voltage regulators, vibrators, and switches; (4) electronic devices (transmitters, radar modulators, thyratrons, etc.).	Same comments as given for MIL-C-19978.	0.01
MIL-C-12889	Bypass radio-interference reduction paper dielectric, ac and dc	CA32 CA36 CA47	Use for general purpose applications where suppression of broadband radio interference is needed. These capacitors are useful in limiting electrical disturbances of the conducted type only. Where maximum insertion loss from a bypass capacitor above 1 MHz is desired, the feed-through type covered by MIL-C-11693 will provide attenuation over the useful frequency range.	Principal failure modes are shorts due to entrance of moisture or contaminants if hermetic seal is ruptured. Opens are due to poor internal connections which can rupture due to shock or vibration.	0.02

MIL-C-14157	Plastic (paper-plastic) or plastic dielectric, dc, hermetically sealed in metal cases, established reliability		Inactive for new design. See MIL-C-19978.		
MIL-C-18312			Inactive for new design. See MIL-C-39022.		
MIL-C-19978	Plastic (or paper plastic) dielectric	CQR07 CQR29 CQR09 CQR32 CQR12 CQR33 CQR13	Capacitors are intended for use in applications which require high insulation resistance, low dielectric absorption, or low loss factor over wide temperature ranges and for which the ac components of the impressed voltage are small compared to the dc voltage rating. If ac components are present, the sum of the dc peak voltage and the ac peak voltage shall never exceed the rated dc voltage nor shall the peak ac voltage exceed 20% of the dc voltage rating at 60 Hz, 15% at 120 Hz, or 1% at 10,000 Hz. For equipment applications, do not use these capacitors above 85°C ambient temperature.	Principal failure modes are open due to poor internal connections and use at rated voltage levels in high temperatures. Shorts can occur due to internal solder flow caused by excessive heat being applied to the terminals during external soldering. Shorts also occur due to contaminants in the dielectric causing momentary breakdown which can result in a carbonization of the plastic, which, if extensive enough, will result in a permanent short.	0.0012
MIL-C-39022	Metallized dielectric, dc (hermetically sealed in metal cases), established reliability	CHR09 CHR19	Intended for use in applications where the ac voltage component is small compared to the dc voltage rating and where occasional periods of low insulation resistance and momentary breakdown can be tolerated. If ac component is present, the sum of the applied dc and the peak ac voltage shall not exceed the rated dc voltage, and the ac voltage shall not exceed 20% of the dc voltage rating.	Opens occur due to poor internal connections which, under strong electrical or mechanical stress, will rupture. Shorts can occur due to internal solder flow as the result of overheating the leads during external soldering. Momentary shorts occur very frequently because the dielectric is so thin but will heal themselves and lose a small amount of capacitance in the process.	0.0012

(cont'd on next page)

TABLE 8-14. (cont'd)

Military Specification	Type	Style	Application Note	Failure Mode	Failure Rate, F/10^6 h
			FIXED, CERAMIC		
MIL-C-11015	Ceramic dielectric (general purpose)	CK60 CK67 CK62 CK68 CK63 CK69 CK65 CK70 CK66 CK80	Intended for use where small size, comparatively large capacitance, and high insulation resistance are required. Capacitors are suitable for use as bypass, filter, and noncritical coupling elements in high-frequency circuits where applicable capacitance change caused by temperature variations can be tolerated. Typical cases include resistive-capacitive coupling for audio and radio frequency, RF and IF cathode bypass, etc. Use where dissipation factor is not critical and moderate changes due to temperature, voltage, and frequency variations do not affect proper circuit function.	Shorts can occur due to silver ion migration caused by high humidities coupled with the application of high dc voltage. Opens generally result from damage done to the capacitor by handling or by the application of excessive heat during soldering which ruptures internal connections. Shorts can also occur by internal solder reflow due to excessive heat applied to leads during external soldering without use of a proper heat-sink procedure.	0.44
MIL-C-39011			Not applicable, specification cancelled.		
MIL-C-39014	Ceramic dielectric, established reliability	CKR05 CKR64 CKR06 CKR72 CKR11 CKR12 CKR14	Use in applications where the required reliability level is known. Otherwise, application notes are the same as given for MIL-C-11015.	Same as for MIL-C-11015.	0.044
			VARIABLE		
MIL-C-81	Ceramic dielectric	CV11 CV21 CV31	Capacitors are intended for use where fine tuning adjustments are periodically required. They are frequently used in RF, IR, oscillator, phase shifter, and discriminator stages. Capacitance and adjustment are rela-	Same comments as given for MIL-C-11015.	2.4

			tively linear. Capacitance change with temperature change is nonlinear; also the temperature sensitivity over the capacitance range is nonlinear. Do not use these units for temperature compensation. These are small size trimmers which are relatively stable under shock and vibration. Where greater stability is required, air trimmers should be used.		
MIL-C-92	Air dielectric (trimmer)	CT04 CT12 CT16	Same applications as given for MIL-C-81 units, except that these units are more stable with temperature. Voltage ratings for these units range from 50 dc (CT04) through 700 dc (CT12).	Shorts can occur due to presence of contamination within the capacitor. Contaminants frequently are due to thread wear or to gold plating shaken loose by vibration. Opens result from cold, internal solder connections rupturing during external soldering operations.	1.0

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8-2.2.5 Relays

Relays, as a class of electronic devices, are controlled and documented by military standards and specifications. Consequently, a selection from a variety of available standard types and styles can be easily made. For economic reasons standard relays normally are produced in large production runs, which make the selection of standard devices even more attractive. Relay selection guidelines are presented in Table 8-15.

In addition to these selection criteria, Table 8-16 lists the applicable military specifications for the more commonly used military relays. A list of failure rates for generic types of relays is given in Table 8-17. This list, derived from MIL-HDBK-217, provides comparative values for various relay types.

Many authorities have predicted that solid-state relays (SSR) will eliminate the use of electromechanical types of relays. All SSR are of the form A-contact configuration (normally open contact), and with effort they can be made into a form B-contact (normally closed contact). Combining the form A and form B types of SSR, a user may obtain a form C-contact (single-pole, double-throw) configuration.

As described in "Relay Problems", (Ref. 7) one difficulty is that SSR cannot be selected in the same manner as an electromechanical relay. There are three main areas of concern during the SSR selection process:

1. Temperature range that will be encountered in the application
2. Leakage current
3. Effects of the load.

The performance of all SSR is affected by the operating temperature range. Most SSR manufacturers describe the effects of temperature on the operation of their relays. The engineer must be aware of the operating temperature range of his equipment and from the manufacturer's data must select a relay that will switch the desired current throughout this temperature range.

TABLE 8-15. RELAY SELECTION CRITERIA (Ref. 1)

1. MIL-STD-1346, *Relays, Selection and Application* (Applicable military specifications are listed in Table 8-16.)
2. MIL-STD-454, *Standard General Requirements for Electronic Equipment,* Requirement 57
3. MIL-R-39016, *Relays, Electromagnetic, Established Reliability, General Specification for*
4. Historical test data (from similar applications or other engineering information and or data that provide assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in military equipment, comparable application or GFE).

When use of a nonstandard device is necessary, request for approval of this device shall be made to military agencies according to the requirements and procdures of MIL-STD-9W.

TABLE 8-16. APPLICABLE MILITARY SPECIFICATIONS FOR RELAYS

1. *Low-current relays (up to* 10 A). Low-current relays shall conform to MIL-R-5757. However, relay applications requiring high, in-rush current capabilities (i.e., motor and contloller" functions) may be in accord with MIL-R-6106, as applicable.
2. *High-current* relays. Relays used in high-current applications shall coform to MIL-R-6106.
3. *Time delay relays.* Thermal time delay relays shall confrom to MIL-R-l948. Electronic, including solid-state, time delay relays shall conform to MIL-R-83726.
4. *Solid-state telegraph relay assemblies. Solid-state, passive* telegraph relays shall conform to MIL-R-27777.
5. *Established reliability relays.* Established reliability relays shall conform to MIL-R-39016.
6. *Reed relays.* Reed relays shall conform to MIL-R-5757.
7. *Relay sockets.* Relay sockets shall conform to MIL-S-128W.

TABLE 8-17. GENERIC FAILURE RATES FOR RELAYS, ($h \times 10^{-6}$)*

Part Type	Use Environment— Increasing Severity→								
	Ground Benign	Space Flight	Ground Fixed	Airborne Inhabited	Naval Sheltered	Ground Mobile	Airborne Uninhabited	Naval Uninhabited	Missile Launch
1. General purpose	0.13	0.13	0.30	1.30	1.60	2.60	2.60	3.20	16.00
2. Contractor, high current	0.43	0.43	1.00	4.50	5.50	5.60	8.80	11.00	36.00
3. Latching	0.12	0.12	0.29	1.30	1.60	1.60	2.50	3.10	16.00
4. Reed	0.11	0.11	0.26	1.10	1.40	1.40	2.20	2.70	14,00
5. Meter movement and bimetal	2.40	2.40	5.70	25.00	30.00	31.00	49.00	61.00	310.00

* Information for this table was obtained from MIL-HDBK-217.

All solid-state devices (SSR included) have a measurable leakage current present in the "off" state. If low current loads are being switched, this leakage current could be a problem. The SSR manufacturer will specify the anticipated leakage current for his device, and the design engineer should determine whether the SSR can satisfy these leakage current requirements.

The third area that should be considered when selecting an SSR is the effect of the electrical load. Lamp loads have an extremely high in-rush current. Peak surge current can cause a loss of control, and most relays are rated to carry their peak load current only a finite number of times. A reliable SSR manufacturer realizes these conditions are possible and rates his relay for repetitive surge currents with control being maintained. If the load is an inductive device and if the relay is turned off when the line voltage is maximum, the rate of change of this voltage with respect to time may exceed the *dV/dt* rating of the relay, and the relay may turn on again. An SSR is selected with a *dV/dt* chosen for a particular inductive, load-switching application. If an active inductive load, such as a motor load, is to be the SSR load, then maximum in-rush currents must be taken into account to insure that the SSR temperature ratings are not exceeded.

The advantages of a long-lived SSR can be achieved only if the previous] y mentioned operating characteristics are taken into consideration. A reliable SSR manufacturer will provide complete specifications on his devices. Figs. 8-2 through 8-5 show the spread of ratings that are to be found on SSR with regard to current ratings, dV/dt ratings, and thermal ratings.

8-2.2.6 Other Parts

The selection of electron tubes, transformers, and inductors is governed by the guidelines depicted in Tables 8-18 through 8-20. A list of failure rates for generic types of transformers and inductors is given in Table 8-20. This list, derived from MIL-HDBK-217, provides comparative values for various inductive devices.

The selection of switches and keyboards is governed by the guidelines depicted in Tables 8-21 through 8-23. The term "switches" applies to a great variety of devices used to make or break an electric circuit or to combine the functions in many ways. In the past, switches have been electromechanical devices and were subject to both electrical and mechanical failures; however, recently solid-state switching devices and keyboards have come into general use. The keyboards are subject to the same type of failure modes as the integrated circuits. A list of failure rates for generic switch types is given in Table 8-22. The relationship between contact life versus load characteristics is shown in Fig. 8-6.

Switches are a major electronic component and require careful evaluation prior to inclusion in equipment. The need for this evaluation has increased because the equipment must withstand rigorous environmental conditions, many of which are still not completely known or understood.

Connectors have been thoroughly intvestigated for operating characteristics; identified for form, function, and applicable ratings; and documented for procurement, test, qualification, approval, qualit~ control, and standardization within military specifications. Connector selection should be governed by the criteria given in Table 8-24.

Some industries, such as the semiconductor industry. are concerned with basically the same materials. The connector industry, however, is moving into an era of both changing technologies and changing materials. These changes are discussed briefly.

Of immediate interest to both connector manufacturers and users is continuing improvement to connectors without accompanying increases in material costs. The introduction of tin alloy contacts has found some

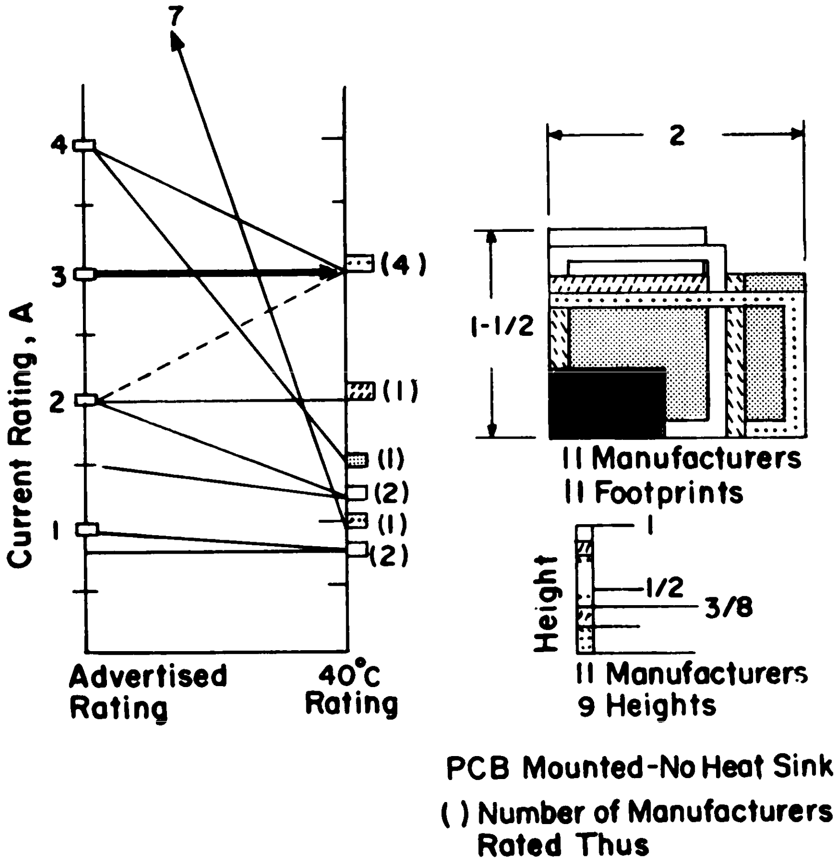

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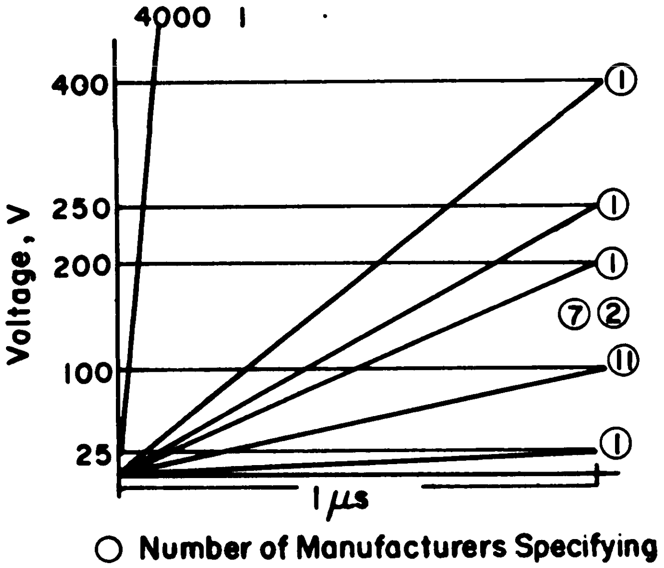
Figure 8-2. PCB Relays Rating Comparison (Ref. 8)



This graph indicates that the majority of SSR manufacturers have a published dV/dt of 100 V/μs. However, the range goes from 4 to 4000 V/μs. This parameter is difficult for the user to measure, but what is more important is the ability of the relay to handle inductive loads.

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Figure 8-3. Voltage-Time Relationship (dV/dt) (Ref. 8)

A sample of SSR, all rated at 10 A, shows that the base temperature for this rating varies from about 40° to 80°C.

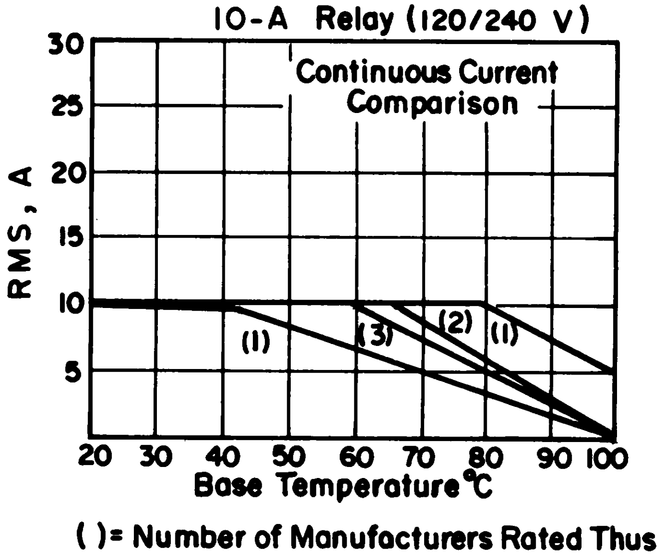

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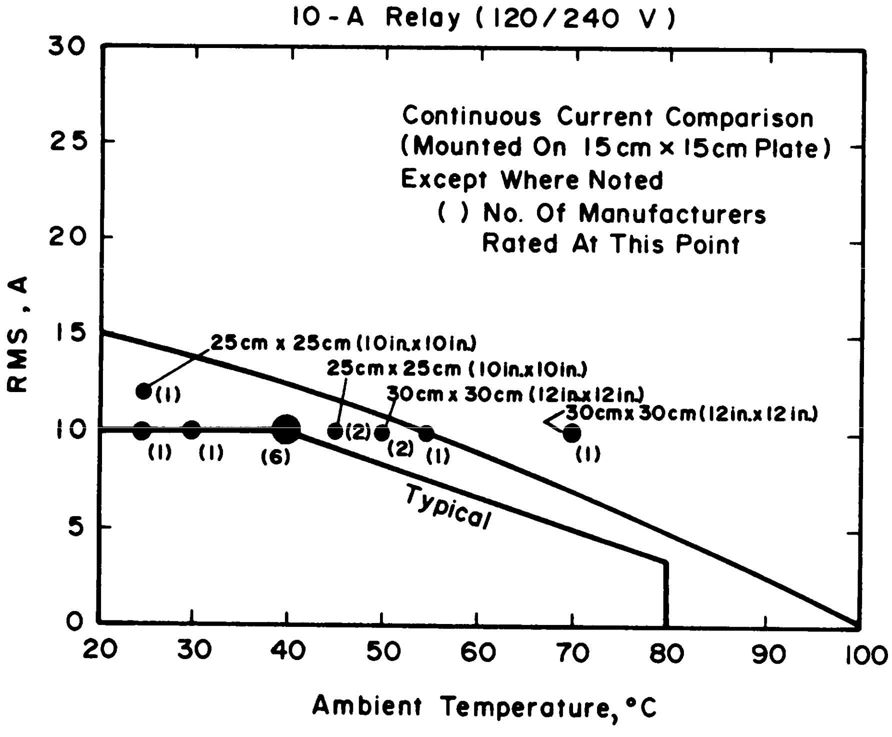
Figure 8-4. Thermal Ratings (no heat sink) (Ref. 8)



All SSR manufacturers have plots of RMS current versus ambient temperature. The relays are supposed to be able to handle 10 A. However, there are at least three different size heat sinks that go along with these ratings.

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Figure 8-5. Thermal Ratings (heat sink) (Ref. 8)

TABLE 8-18. ELECTRON TUBE SELECTION CRITERIA (Ref. 1)

1. MIL-STD-200, *Electron Tubes, Selection of*
2. MIL-E-1, *Electron Tube, General Specification For*
3. *MIL-STD-454, Standard General Requirements For Electronic Equipment,* Requirement 29

Tube types listed in MIL-STD-200 are those devices which meet the following criteria:

- a. The tube is considered the best available type for current application by representatives of the military departments.
- b. The tube has been in production, and continued availability shall be reasonably certain.
- c. The tube has an approved military specification.

Failure rates for tubes are listed in MIL-HDBK-217. These failure rates are from one to three orders of magnitude greater than the semiconductor devices currently in use. These failure rates are provided mainly for comparison and should be used only when no semiconductor device can be found to cover the specific design situation. In the case of high-power/high-frequency tubes, careful coordination with the tube manufacturers is recommended, Note that tubes, in general, possess much shorter useful life periods than semiconductor devices.

4. Historical test data (similar applications) or other engineering information and/or data that provide assurance that the device is sufficiently rugged and reliable for the application (e.g., previous use in military equipment, comparable application, or GFE).

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TABLE 8-19. SELECTION CRITERIA FOR TRANSFORMERS AND INDUCTORS (Ref. 1)

1. MIL-STD-1286, *Transformer, Inductors and Coils, Selection And Use Of*
2. Established reliability specifications:
   - a. MIL-T-39013, *Transformers And Inductors, Audio And Power*
   - b. MIL-T-21038, *Transformers, Pulse, Low Power, General Specification For*
3. In accordance with military specifications:
   - a. MIL-T-27, *Transformers and Inductors*
   - b. MIL-C-15305, *Coil, Fixed And Variable, Radio Frequency, General Specification For*
   - c. MIL-T-21038, *Transformers, Pulse, Low Power, Genera 1 Specification For*
4. Historical test data (from similar applications) or other engineering information and/or data providing assurance that the device is sufficiently rugged and reliable for the application, e.g., previous use in military equipment, comparable application, or GFE.

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TABLE 8-20. GENERIC FAILURE RATES FOR INDUCTIVE DEVICES, (h X 10^{-6})*

	Use Environment—Increasing Severity→								
Part Type	Ground Benign	Space Flight	Ground Fixed	Airborne Inhabited	Naval Sheltered	Ground Mobile	Airborne Uninhabited	Naval Uninhabited	Missile Launch
Pulse transformer	0.0012	0.0012	0.0027	0.0075	0.0083	0.0045	0.014	0.011	0.015
Audio transformer	0.0025	0.0025	0.0066	0.0180	0.0200	0.0110	0.034	0.027	0.036
Power transformers and filters	0.0075	0.0075	0.0210	0.0560	0.0640	0.0340	0.120	0.096	0.110
RF Transformers and coils	0.0096	0.0096	0.0220	0.0600	0.0660	0.0360	0.110	0.084	0.120

l Information for this table was obtained from MI L-HDBK-2 17.

TABLE 8-21. SELECTION CRITERIA FOR SWITCHES (Ref. 1)

1. MIL-STD-1132, *Switches and Associated Hardware, Selection And Use Of*
2. Requirement 58 of MIL-STD-454, *Standard General Requirements For Electronic Equipment. MIL-STD-454,* Requirement 58, requires that:
   a. Switches and associated hardware shall be selected from MIL-STD-1132 and shall conform to the applicable specifications listed therein.
   b. Switches other than those listed in MIL-STD-1132 shall conform to one of the following specifications:
      (1) MIL-S-12285, *Switch, Thermostatic*
      (2) MIL-S-15743, *Switch, Rotary, Enclosed*
      (3) MIL-S-18396, Switch, Meter and Control, Naval Shipyard
      (4) MIL-S-21604, Switch, Rotary, Multipole and Selector Type
      (5) MIL-S-28705, Switch, Leaf Spring, (Pile-Up Contacts; Lever, Push, Turn; Illuminated and Nonilluminated) General Specifications for
3. Historical test data (from similar applications) or other engineering information and/or data providing assurance that the device is sufficiently rugged and reliable for the application, e.g., previous use in military equipment, comparable application, or GFE.

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TABLE 8-22. FAILURE RATES FOR GENERIC SWITCH TYPES, (h X 10^{-6})

	Use Environment—Increasing Severity→								
Switch Type	Ground Benign	Space Flight	Ground Fixed	Airborne Inhabited	Naval Sheltered	Ground Mobile	Airborne Uninhabited	Naval [Uninhabited	Missile Launch
Toggle	0.17	0.17	0.57	6.8	0.68	2.9	8.6	4.0	114.0
Push-Button	0.11	0.11	0.38	4.6	0.46	1.9	5.7	2.7	76.0
Sensitive	0.27	0.27	0.90	11.0	1.10	4.5	14.0	6.3	180.0
Rotary	0.42	0.42	1.40	17.0	1.70	6.9	21.0	9.7	280.0

TABLE 8-23. SWITCHES AND KEYBOARD TRENDS

Solid-state keyboards are replacing electromechanical types and switches in microprocessor-based applications.

"Low-profile" capacitance keyboards using the x – y matrix configuration are expected to become most popular among users.

Microprocessor-based, low-profile keyboards offering ease of programming and coding are around the corner.

Trend to solid-state switching is seen with pricing versus reliability remaining as the trade-off.

More PC-mountable, thumbwheel, low-profile switches are coming, but they will face strong competition from low-cost keyboards.

General trend is to snap-in, bezel-mount switches to aid assembly.

New and improved designs in subminiature PCB switches are anticipated.

More illuminated push-button switches of the electromechanical and solid-state type are coming.

Manufacturers are turning attention to low-level (logic), dry-circuit switching for each interfacing with microprocessors.

(cont'd on next page)

TABLE 8-23 (cont'd)

DIP switches continue in popularity. Stiff competition should benefit the user as prices drop.

Toggle and rocker switch manufacturers are introducing "all plastic" switches, which reduce shock hazard and price.

Slide-switch manufacturers are going to molded bases and conformal coating to eliminate contamination during wave soldering of PCB. Other switch areas are expected to follow.

Manufacturers are expanding distributor assembly programs to shorter delivery times.

Across-the-board price hikes are forecast by most manufacturers. The popular figure seems to be 10%.

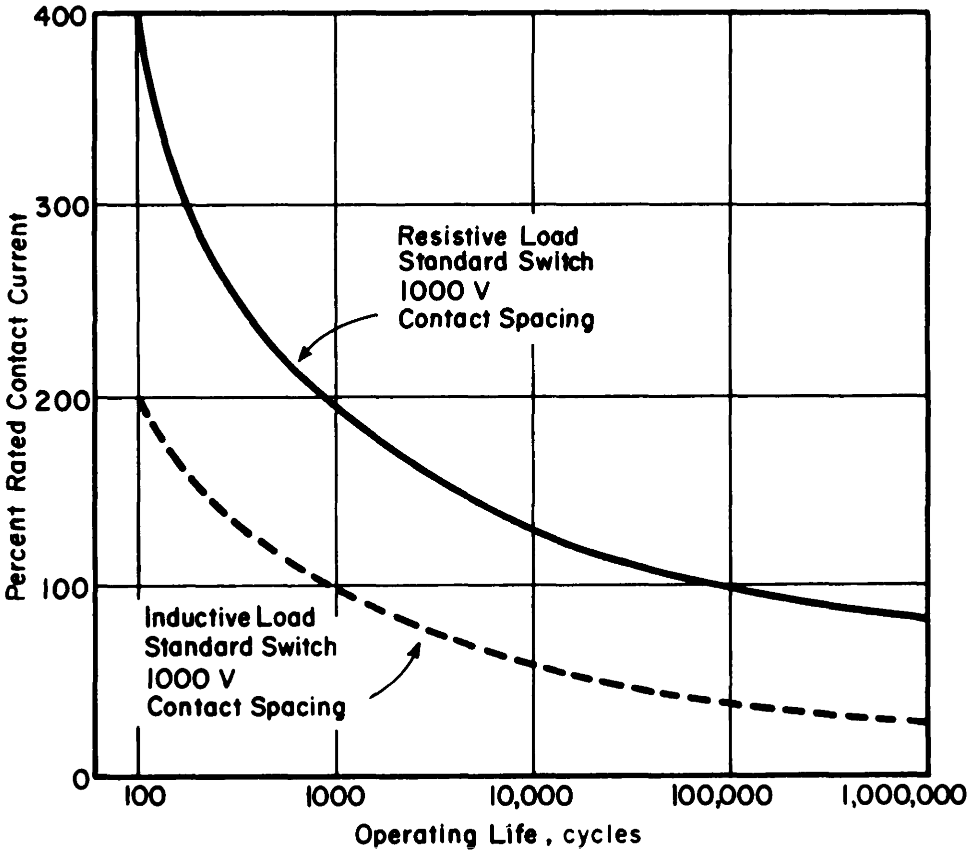

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Figure 8-6. Effect of Current on Operating Life (Typical Characteristic) (Ref. 1)

TABLE 8-24. CONNECTOR SELECTION CRITERIA (Ref. 1)

1. Approved style of military specification
2. MIL-STD-454, *Standard General Requirements For Electronic Equipment,* Requirement 10, Notice 3
3. Historical test data (from similar applications) or other engineering information and/or data providing assurance that the device is sufficiently rugged and reliable for the application, e.g., previous use in military equipment, comparable application, or GFE.

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application, mostly in high-power devices, but gold plating is still the most commonly used surface treatment.

One method of holding down connector costs when gold contacts are necessary is the use of underplating materials with from 0.8 to 1.3 µm (30 to 50 µin.) of gold plating. Thickness is not the only consideration in gold plating; porosity is also important. A thin, nonporous coating will perform much better than a thick, porous coating.

Among technology advancements in connectors is the zero insertion force (ZIF) connector. ZIF connectors exist for PC, panel-to-cable, and DIP applications. ZIF panel-to-cable connectors are used where high pin count cable connectors must be mated repeatedly; ZIF DIP receptacles are used for semiconductor burn in, testing, or simply for protection of expensive packages with many leads. In ZIF applications, PC cards are receiving much attention. The emphasis on insertion force has also spawned low insertion force (LIF) connectors. LIF connectors normally are not radically different from their more conventional predecessors; ZIF connectors, however, represent a whole new set of design approaches.

The selection criteria for microwave devices and cables are presented in Tables 8-25 through 8-27. Table 8-26 provides additional guidelines for application of waveguides and related equipment.

8-2.2.7 Cabling

Wiring and cabling in the electronic application is a vast area, and unfortunately, it is beyond the scope of this chapter; some trends, however, in the development of new cabling methodology will be presented. Wiring

TABLE 8-25. SELECTION CRITERIA FOR WAVEGUIDES AND RELATED EQUIPMENT

1. MIL-STD-1327, *Flange, Coaxial And Waveguide; And Coupling Assemblies, Selection Of*
2. MIL-STD-1328, *Coupler, Directional (Coaxial Line,* Waveguide And Printed *Circuit), Selection Of*
3. MIL-STD-1329, *Switches, RF Coaxial, Selection 0f*
4. MIL-STD-454, *Standard General Requirements For Electronic Equipment,* Requirement 53

Table I of MIL-STD-454 relates specific types. of waveguide equipment to the applicable military Specification”

Listings of waveguides, directional couplers, flanges, coupling assemblies, and RF switches are given in MIL-STD-1327,-1328, and -1329, respectively. Microwave equipments listed in MIL-STD-1327, -1328, and -1329 are those that meet the following criteria:

- a. The microwave equipment is considered the best available type for the current application by Government representatives.
- b. The microwave equipment has been in production, and continued availability is assured.
- c. The microwave equipment has an approved military specification.

TABLE 8-26. APPLICATION AND USE OF WAVEGUIDES AND RELATED EQUIPMENT

1. The following requirements of MIL-STD-1327, -1328, and -1329 apply to the use, in military equipment, of waveguides and related equipment:
    - a. Military equipment and assemblies shall comply with their performance specification requirements when using listed flanges and coupling assemblies that are from manufactured lots possessing acceptable material and physical characteristics.
    - b. Directional couplers used in militarv equipment shall be from lots possessing acceptable material, physical, and electrical characteristics. and they shall in no manner degrade the operational characteristics of the equipment in which used.
    - c. Coaxial switches used in military applications shall be representative of manufactured lots possessing acceptable material, physical, and electrical characteristics, and they shall in no manner degrade the operational characteristics of the equipment in which used.
    - d. When it is determined that a flange or coupling assembly not listed in these standards is required, a written request for use of a nonstandard part shall be made in accordance with MIL-STD-965.
2. General design considerations:
    - a. *Materials.* When selecting parts, consideration shall be given to the corrosion resistance of materials and the proper protection where combinations of dissimilar metals are used.
    - b. *Fabrication or rigid assemblies. MIL-HDBK-660* shall be used as a guide in the fabrication of rigid assemblies.

TABLE 8-27. SELECTION CRITERIA FOR CABLES (Ref. 1)

1. MIL-STD-454, *Standard General Requirements For Electronic Equipment,* Requirement 66
2. An approved military specification style
3. Historical data (similar application), test data, or other engineering information that provide assurance that the cable is sufficiently rugged and reliable for the application, e.g., previous use in military equipment, comparable application, or GFE. Note: When the use of a nonstandard cable is considered necessary, request for approval for its use shall be submitted to the military according to the procedures of MIL-STD-965.

The following requirements of MIL-STD-454 apply to the selection of cables:

a. *Solid or stranded.* Either solid or stranded conductors maybe used—within the restrictions of the particular wire or cable specification—except that (1) only stranded wire shall be used in aerospace applications, and (2) for other applications stranded wire shall be used when indicated by the equipment specification. Specifically, stranded wire shall be used for wires and cables that normally are flexed in the use and the servicing of the equipment, such as cables attached to the movable half of detachable connectors.

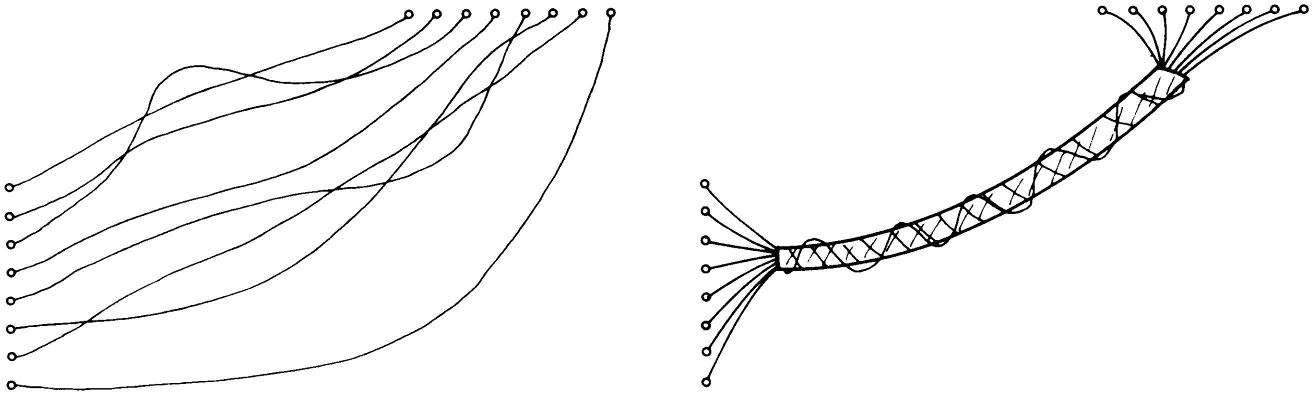
b. Size. Conductors shall be of such cross section, temper, and flexibility as to provide ample and safe current-carrying capacity and strength. In general, wire shall not be smaller than size 22. Smaller wire may be used when benefits can be obtained with no loss in performance. Specifically, smaller wire may be used in cables having larger numbers of wires and adequate support against vibration. Smaller size wire may be used when necessary for the welding of electronic interconnections.

harness was introduced to avoid the problem of having many individual wires, as shown in Fig. 8-7. Wiring harness has been the traditional wiring approach and is still widely used.

Basically there are two types of harnesses:

1. Bundled harness (Fig. 8-8)
2. Cabled harness (Fig. 8-9).

Bundled harness is a preassembled group of wires that conducts current or signals to predetermined components in the particular assembly. It has an appearante of a tree trunk with many branches. The wires are held together by means of braiding, wire ties, heat shrinkable tubing, tapes, and/or spiral wrap. An



(A) Point-To-Point Wiring Using Single Wires

(B) Use Of A Wiring Harness

Figure 8-7. Single Wires and Wiring Harness

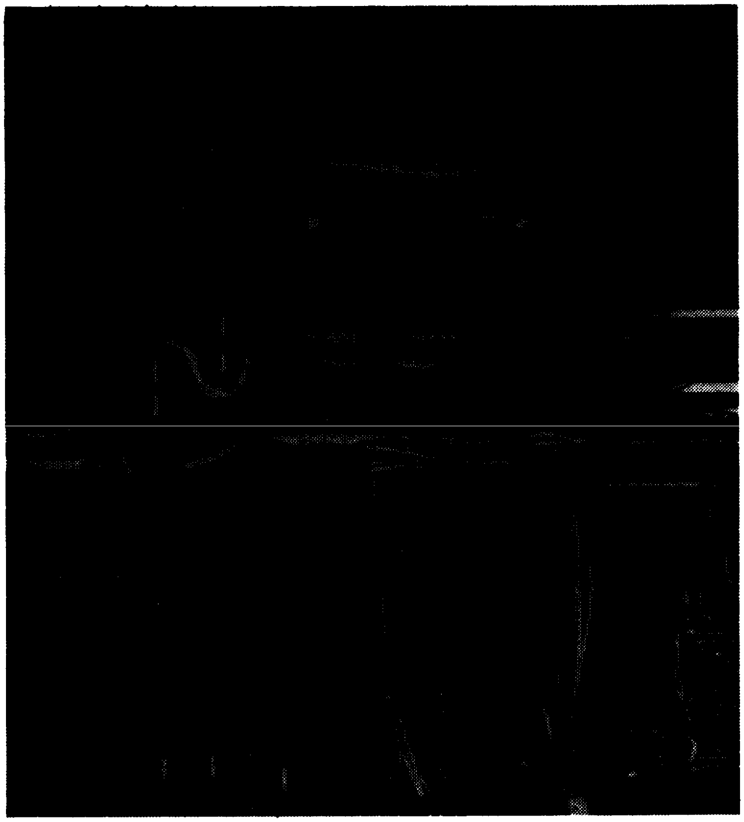


Figure 8-8. Example of a Bundle Harness

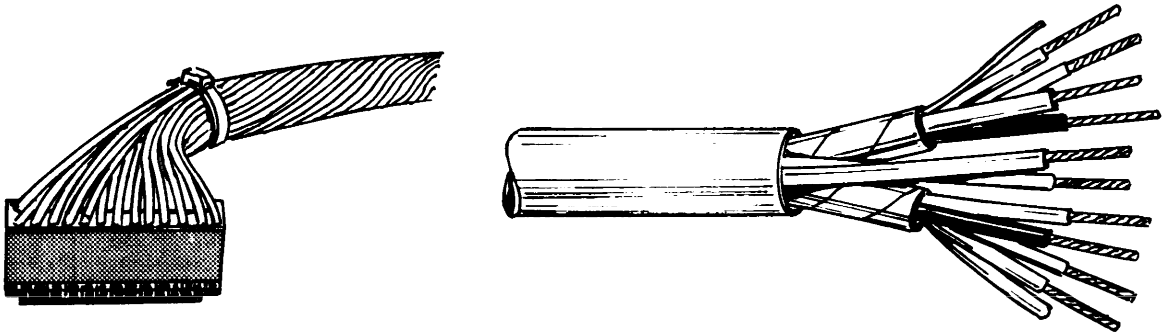


Figure 8-9. Examples of Unprotected and Protected Cable Harnesses

example of a harness manufacturing template is shown in Fig. 8-10.

Cabled harnesses consist of several conductors, equally long, tied together, and terminated only at each end. The body of the cable can be covered by a jacket, which protects the individual wires from harmful environmental effects.

The cost of labor associated with the manufacture of wiring harnesses exceeds the cost of the material involved. The cost can be minimized by using standard cables, especially in low-volume production programs. Standardization is being partially achieved by introduction of flat or ribbon cables.

Flexible, flat cable can be defined as several conductors arranged parallel in one plane and secured in that plane by layers of insulating material *or weaving.* Flat cable can be constructed of a flat or round conductor. Flat conductor can be either flat wire placed and sealed between two layers of insulating material, or it can be etched by using a process similar to that used for etch-

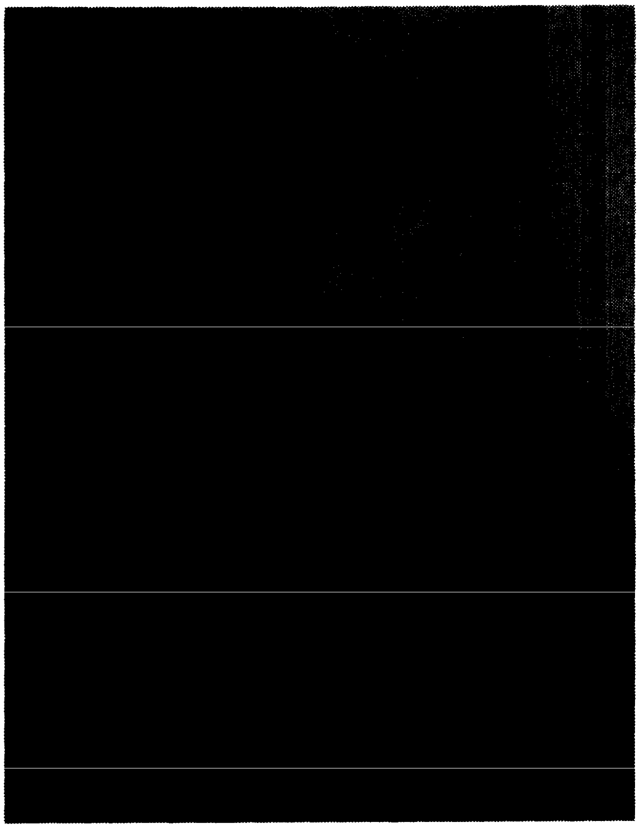


Figure 8-10. Bundled Harness Manufacturing Template

ing PCB, Flat cable constructed with round conductors can be manufactured by various methods:

1. Round wires laced or woven together in one plane
2. Insulated wires bonded or fused together in one plane
3. Round wires laminated between two layers of insulation,

Some advantages of flexible, flat cable are

1, Simplified assembly process. Cable can be mounted on a flat surface by using adhesive tape or clamps; no lacing is necessary.
2. Reduced weight and space
3. Reduced assembly labor cost.

Fig. 8-11 shows examples of cable and wire branching. Sevreral examples of flexible, flat cable are shown in Fig. 8-12.

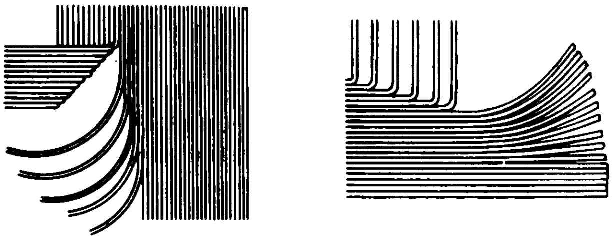
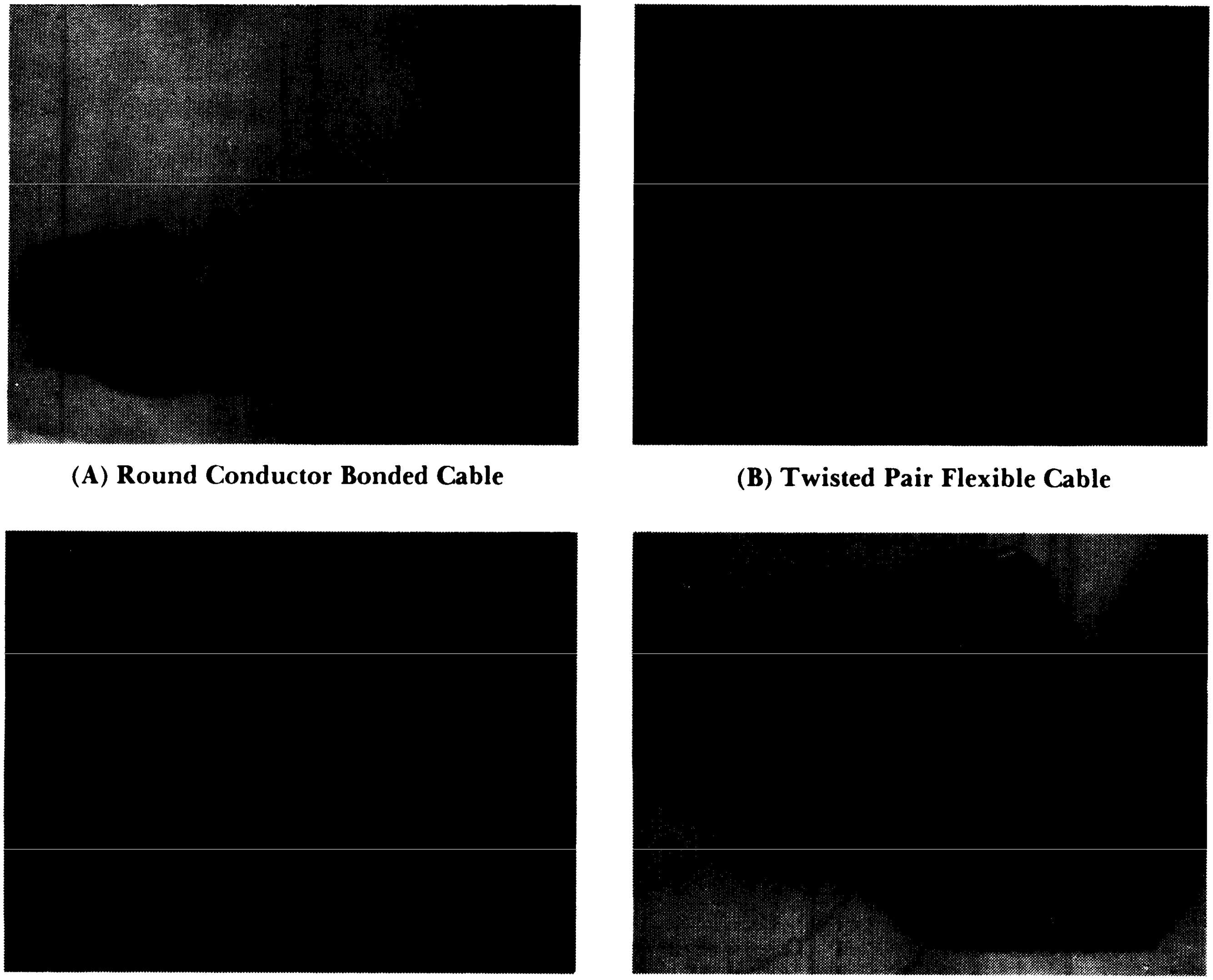


Figure 8-11. Examples of Flat Cable Branching

8-2.3 PART SCREENING

As previously mentioned, virtually all manufactured devices exhibit a life characteristic that is best represented by the bathtub curve shown in Fig. 8-13. This subparagraph deals with the first segment of the curve, namely, the “infant mortality” or the “early failure” period of equipment life. Experience shows that a newly constructed equipment fails more often during its early life, i.e., during assembly, testing, and startup, than later during use in the field. Piece parts received from the supplier often contain a certain number of weak devices that fail during the initial testing of subassemblies or of complete equipments and during early use of the equipment.

To eliminate the incipient failures from the manufacturing process, quality and screening tests can be employed. The quality tests are those that reduce the number of defective devices from production lines by means of inspection and conventional testing. The screens are those that remove inferior devices and reduce the hazard rate by methods of stress application. In selected cases, a prescribed “burn in” period is used to screen out weak parts or devices, This method is used



(A) Round Conductor Bonded Cable

(B) Twisted Pair Flexible Cable

(C) Webbed Cable

(D) Flexible Circuiting Flat Cable

Figure 8-12. Examples of Flexible, Flat Cable

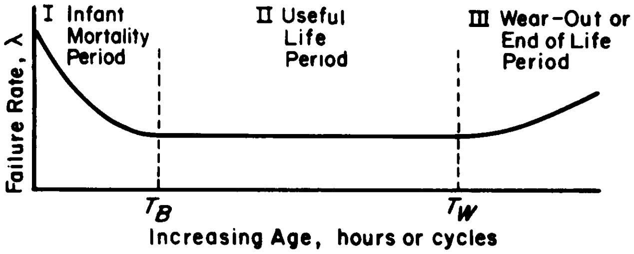


Figure 8-13. Life Characteristic Curve

where reliability is of particular concern.

The purpose of reliability screening is to compress the early failure period and reduce the failure rate to acceptable levels as quickly as possible. Fig. 8-14 illustrates the application of a time stress at the part level and shows, comparatively, how reliability screening can improve the part failure rate. It also shows that, by applying a higher temperature stress at 125°C instead of 100°C, comparable failure rate levels can be achieved in 100 h instead of 240 h.

The term "screening" means the application to an electronic device of a stress test, or tests, that will reveal inherent weaknesses (and thus incipient failures) of the devices without destroying the integrity of the devices. When applied equally to a group of similar devices manufactured by the same processes, this procedure is used to identify subpar members of the group without impairing the structure or functional capability of the "good" members of the group.

The rationale for such action is that the inferior devices will fail and the superior devices will pass if the

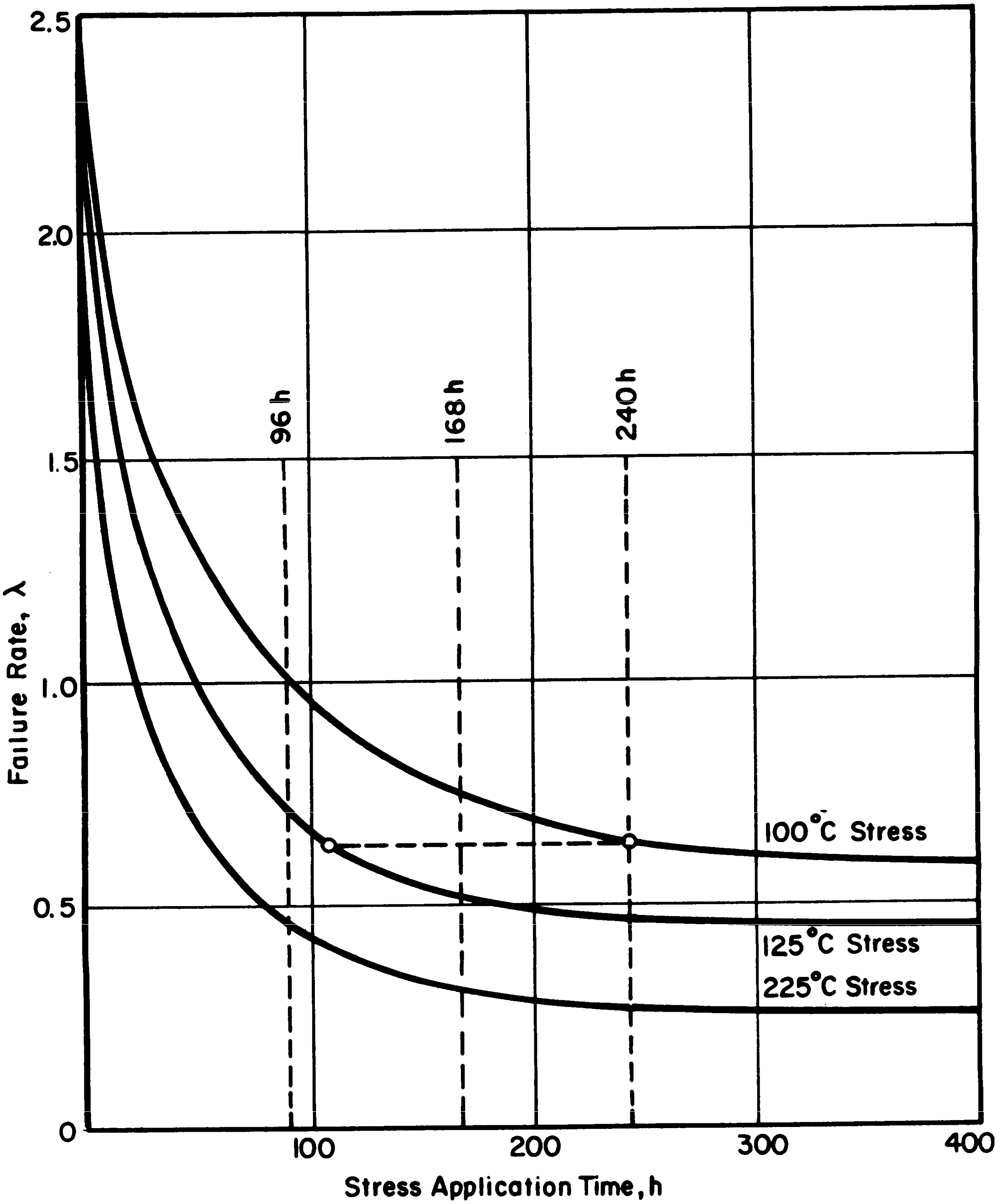


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Figure 8-14. Reliability Screens (Ref. 1) tests and stress levels are properly selected. If the failed units are removed from the group, the remaining devices are those that have demonstrated the ability to withstand stress, and their reliability under normal-rated operating conditions can, therefore, be assumed.

Screening can be done (1) by the part manufacturer, (2) by the user in his own facilities, or (3) by an independent testing laboratory. No matter which activity is employed to do the screen tests, the user should first acquaint himself with the efficacy of the screening tests used by the vendor in normal production. If such screens exist and are effective, more screens can be designed to supplement the vendor's tests, whereas if the vendor's tests are unsatisfactory, the screening program will have to be a comprehensive one.

When particular failure modes or mechanisms are known or suspected to be present, a specific screen should be selected to detect these unreliable elements.

Table 8-28 shows the failure mode distribution for standard silicon transistors and integrated circuits: small-scale integrated (SSI), medium-scale integrated (MSI), large-scale integrated (LSI) [TI data], and integrated circuit technologies, TTL, CMOS [Reliability Analysis Center (RAC) data].

A detailed understanding of the device characteristics, materials, packaging, and fabrication techniques relative to the failure mode distribution shown in Table 8-28 is essential in selecting a meaningful screen at reasonable cost. Devices performing the same function may be fabricated with different materials, e.g., aluminum leads instead of gold on an integrated circuit. The effectiveness of a screen is material dependent. For example, the stress level effective for gold may be ineffective for aluminum because of the difference in mass; the X-ray screen that is effective for gold may be transparent for aluminum and silicon. Some screens are effective for PN-isolated integrated circuits but are ineffective for dielectrically isolated devices. Only a thorough knowledge of the device to be screened and the effectiveness and limitations of the various tests can produce a useful and reliable screening procedure.

Screening tests are particularly well suited to discrete semiconductor and microelectronic devices because of their material/process dependency. MIL-STD-883 forms the basis for selecting meaningful screening tests for microelectronic devices. Note that TX semiconductors are screened and burned in in a manner comparable to MIL-STD-883.

Tables 8-29 and 8-30 provide a listing of microcircuit defects/screens and a comparison of screening methods, respectively.

The criticality of the component part application and the required level of reliability have an important bearing on the stress levels and the number of tests that should be included in the overall part screening procedure. The part screening procedure must also be cost-effective and must meet time and funding constraints.

Figure 8-15 shows relative cost estimates for various part classes. The most cost-effective screen is Class B of MIL-STD-883.

Table 8-31 lists all the required screens for Classes A, B, and C of MIL-STD-883, Method 5004. (Note that a burn in test is required for Classes A and B only.) The effectiveness of these screens is shown in Table 8-32. Finally, the cost ranges of screening tests for Class B devices are listed in Table 8-33.

Note that Table 8-33, covering screening costs, is provided for comparative purposes only. It is intended

TABLE 8-28. FAILURE MODE DISTRIBUTION FOR TRANSISTORS AND INTEGRATED CIRCUITS

Failure Mode	TI Data in %[1]					RAC Data in %[2]	
	Transistor	SS1	MSI	LSI	MOS\LSI	TTL	CMOS
Metallization	6	10	18	26	7	**50**	35
Diffusion	10	8	12	25	13	2	9
Foreign material		5	11	13	1	6	17
Miscellaneous	6	5	12	13	21		
Oxide	31	18	20	13	33	4	16
Bonding	38	14	7	4	5	13	15
Die attach packaging	9	5	3	2	5	25	8
Misapplication		35	17	4	15		
	100	100	100	100	100	100	100

[1] Data from [4]Elements of Device Reliability by Peattie, et al, *Proceedings of the Institute of Electrical and Electronics* Engineer, Inc., February 1974. Copyright @ 1974 IEEE.

[2] Data supplied by Reliability Analysis Center, Rome Air Development Center.

TABLE 8-29. MICROCIRCUIT DEFECTS/SCREENS (Ref. 1)

Point at Which a Reliability-Influencing Variable is Introduced	Failure Mechanism	Failure Mode	Failure Detection Method
Slice preparation	Dislocations and stacking faults	Degradation of junction characteristics	Initial electrical test; operational life tests
	Nonuniform resistivity	Unpredictable component values	Initial electrical test
	Irregular surface	Improper electrical performance and/or shorts, opens, etc.	Initial electrical test; operational life tests
	Cracks, chips, scratches (general handling damage)	Opens, possible shorts in subsequent metallization	Initial electrical test; visual (precap); thermal cycling
	Contamination	Degradation of junction characteristics	Visual (precap); thermal cycling; high temperature storage: reverse bias
Passivation	Cracks and pinholes	Electrical breakdown in oxide layer between metallization and substrate; oxide diffusion mask	High temperature storage; thermal cycling; high voltage test; operating life test; visual (precap)
	Nonuniform thickness	increased leakage in the oxide layer	High temperature storage; thermal cycling; high voltage test; operating life test; visual (precap)
Masking	Scratches, nicks, blemishes in the photomask	Opens and/or shorts	Visual (precap); initial electrical test
	Misalignment	Opens and/or shorts	Visual (precap); initial electrical test
	Irregularities in photoresist patterns (line widths, spaces, pinholes)	Performance degradation caused by parameter drift, opens, or shorts	Visual (precap); initial electrical test
Etching	Improper removal of oxide	Opens and/or shorts or intermittents	Visual (precap); initial electrical test; operational life test
	Undercutting	Shorts and/or opens in metallization	Visual (precap); initial electrical test
	Spotting (etch splash)	Potential shorts	Visual (precap); thermal cycling; high temperature storage; operational life test
	Contamination (photoresist, chemical residue)	Low breakdown; increased leakage	Visual (precap); initial electrical test; thermal cycling; high temperature storage; operational life test; reverse bias

(cont’d on next page)

TABLE 8-29. (cont'd)

Point at Which a Reliability-Influencing Variable is Introduced	Failure Mechanism	Failure Mode	Failure Detection Method
Diffusions	Improper control of doping profiles	Performance degradation resulting from unstable and faulty passive and active components	High temperature storage; thermal cycling; operational life test; initial electrical test
Metallization	Scratched or smeared metallization (handling damage)	Opens, near opens, shorts, near shorts	Visual (precap); thermal cycling; operational life test
	Thin metallization to insufficient deposition or oxide steps	Opens and/or high-resistance intraconnections	Initial electrical test; operational life test; thermal cycling
	Oxide contamination-material incompatibility	Open metallization to poor adhesion	High temperature storage; thermal cycling; operational life test
	Corrosion (chemical residue)	Opens in metallization	Visual (precap); high temperature storage; thermal cycling: operational life test
	Misalignment and contaminated contact areas	High-contact resistance or opens	Visual (precap); initial electrical test; high temperature storage; thermal cycling; operational life test
	Improper alloying temperature or time	Open metallization, poor adhesion, or shorts	Initial electrical test; high temperature storage; thermal cycling; operational life test
Die separation	Improper die separation resulting in cracked or chipped dice	Opens and potential opens	Visual (precap); thermal cycling; vibration; mechanical shock; thermal shock
Die bonding	Voids between header and die	Performance degradation caused by overheating	X ray; operational life; acceleration; mechanical shock; vibration
	Overspreading and/or loose particles of eutectic solder	Shorts or intermittent shorts	Visual (precap); X ray; monitored vibration; monitored shock
	Poor die-to-header bond	Cracked or lifted die	Visual (precap); acceleration; shock; vibration
	Material mismatch	Lifted or cracked die	Thermal cycling; high temperature storage; acceleration
Wire bonding	Overbonding and underbonding	Wire weakened and breaks or is intermittent; lifted bond; open	Acceleration; shock; vibration
	Material incompatibility or contaminated bonding pad	Lifted lead bond	Thermal cycling; high temperature storage; acceleration: shock: vibration

(cont'd on next page)

TABLE 8-29. (cont'd)

Point at Which a Reliability-Influencing Variable is Introduced	Failure Mechanism	Failure Mode	Failure Detection Method
Wire bonding (cont'd)	Plague formation	Open bonds	High temperature storage; thermal cycling; acceleration; shock; vibration
	Insufficient bonding pad area or spacings	Opens or shorted bonds	Operational life test; acceleration; shock; vibration; visual (precap)
	Improper bonding procedure or control	Opens, shorts, or intermittent operation	visual (precap); initial electrical test; acceleration; shock; vibration
	Improper bond alignment	Opens and or shorts	visual (precap); initial electrical test
	Cracked or chipped die	Opens	visual (precap); high temperature storage; thermal cycling; acceleration; shock; vibration
	Excessive loops, sags, or lead length	Shorts to case, substrate, or other leads	visual (precap); X ray; acceleration; shock; vibration
	Nicks, cuts, and abrasions on leads	Broken leads causing opens or shorts	Visual (precap); acceleration; shock; vibration
	Unremoved pigtails	Shorts or intermittent shorts	Visual (precap); acceleration; shock; vibration, X ray
Final seal	Poor hermetic seal	Performance degradation; shorts or opens caused by chemical corrosion or moisture	Leak tests
	Incorrect atmosphere sealed in package	Performance degradation caused by inversion and channeling	Operational life test; reverse bias; high temperature storage; thermal cycling
	Broken or bent external leads	open circuit	Visual; lead fatigue tests
	Cracks, voids in kovar-to-glass seals	Shorts and or opens in the metallization caused by a leak	Leak test; electrical test; high temperature storage; thermal cycling; high voltage test
	Electrolytic growth of metals or metallic compounds across glass seals between leads and metal case	Intermittent shorts	Low voltage test
	Loose conducting particles in package	Intermittent shorts	Acceleration; monitored vibration; X ray; monitored shock
	Improper marking	Completely inoperative	Electrical test

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TABLE 8-30. COMPARISON OF SCREENING METHODS

Screen	Defects	Effectiveness	cost	Comments
Interval visual inspection	Lead dress Metallization Oxide Particle Die bond Wire bond Contamination Corrosion Substrate	Good Good Good Good Good Good Good Good Good	Inexpensive to moderate	This is a mandatory screen for high reliability devices. Cost will depend upon the depth of the visual inspection.
Infrared	Design (thermal)	Very good	Expensive	For use in design evaluation only.
X ray	Die bond Lead dress (gold) Particle Manufacturing (gross errors) Seal Package Contamination	Excellent Good Good Good Good Good Good	Moderate	The advantage of this screen is that the die-to-header bond can be examined, and some inspection can be performed after encapsulation. However, some materials are transparent to X rays, (i.e., Al and Si), and the cost may be as high as six times that of visual inspection, depending upon the complexity of the test system.
High temperature storage	Electrical (stability) Metallization Bulk silicon Corrosion	Good	Very inexpensive	This is a highly desirable screen.
Temperature cycling	Package Seal Die bond Wire bond Cracked substrate Thermal mismatch	Good	Very inexpensive	This screen may be one of the most effective for aluminum lead systems.
Thermal shock	Package Seal Die bond Wire bond Cracked substrate Thermal mismatch	Good	Inexpensive	This screen is similar to temperature cycling but induces higher stress levels. As a screen it is probably no better than temperature cycling.
constant acceleration	Lead dress Die bond Wire bond Cracked substrate	Good	Moderate	At 20,000 g stress levels, the effectiveness of this screen for aluminum is questionable.
Shock (unmonitored)	Lead dress	Poor	Moderate	The drop-shock test is considered inferior to constant acceleration. However, the pneupactor shock test may be more effective. Shock tests may be destructive.

(cont'd on next page)

TABLE 8-30. (cont'd)

Screen	Defects	Effectiveness	Cost	Comments
Shock (monitored)	Particles Intermittent short Intermittent open	Poor Fair Fair	Expensive	Visual or X-ray inspection is preferred for particle detection.
Vibration fatigue	Lead dress Package Die bond Wire bond Cracked substrate	Poor	Expensive	This test may be destructive. Except for work hardening, it is without merit.
Vibration variable frequency (unmonitored)	Package Die bond Wire bond Substrate	Fair	Expensive	The effectiveness of this screen for detecting particles is part dependent.
Vibration variable frequency (monitored)	Particles Lead dress Intermittent open	Fair Good Good	Very expensive	The effectiveness of this screen for detecting particles is part dependent.
Random vibration (unmonitored)	Package Die bond Wire bond Substrate	Good	Expensive	This is a better screen than vibration variable frequency (unmonitored) especially for space-launch equipment, but it is more expensive.
Random vibration (monitored)	Particles Lead dress Intermittent open	Fair Good Good	Very expensive	This is one of the most expensive screens; since it combines with only fair effectiveness for particle detection, it is not recommended except in very special situations.
Helium leak test	Package Seals	Good	Moderate	This screen is effective for detecting leaks in the range of 10^{-8} to 10^{-10} cm^3/s at one atmosphere.
Radiflo leak test	Package Seals	Good	Moderate	This screen is effective for leaks in the range of 10^{-8} to 10^{-12} cm^3/ s at one atmosphere.
Nitrogen bomb test	Package Seals	Good	Inexpensive	This test is effective for detecting leaks between the gross-and-fine-leak-detection ranges.
Gross-leak test	Package Seals	Good	Inexpensive	Effectiveness is volume dependent. Detects leaks greater than 10 cm^3/s at one atmosphere.
High-voltage test	Oxide	Good	Inexpensive	Effectiveness is fabrication dependent.
Isolation resistance	Lead dress Metallization Contamination	Fair	Inexpensive	Most effective after vibration testing.
Intermittent operation life	Metallization Bulk silicon Oxide Inversion channeling	Good	Expensive	Probably no better than ac operating life.

(cont'd on next page)

TABLE 8-30. (cont'd)

Screen	Defects	Effectiveness	cost	Comments
Intermittent operation life (cont'd)	Design Parameter drift Contamination			
ac operating life	Metallization Bulk silicon Oxide Inversion/ channeling Design Parameter Contamination	Very good	Expensive	More effective than dc operating life.
dc operating life	Essentially the same as intermittent life	Good	Expensive	No mechanisms are activated that could not be better activated by ac life tests.
High-temperature ac operating life	Same as ac operating life	Excellent	Very expensive	Temperature acts to accelerate failure mechanisms. This is probably the most expensive screen and one of the most effective.
High-temperature reverse bias	Inversion/ channeling	Poor	Expensive	Effective for small-scale integrated circuits,

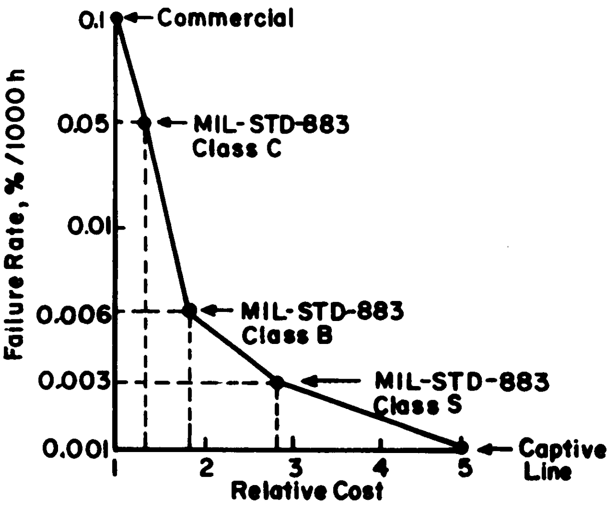

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Figure 8-15. Screening Effectiveness (Ref. 1)

TABLE 8-31. SCREENING SEQUENCE—METHOD 5004—MIL-STD-883

Screen	Reliability Classes		
	S	B	C
Internal visual	Condition A	Condition B	Condition B
Stabilization bake	24 h	24 h	24 h
Thermal shock	15 cycles and	15 cycles or	15 cycles or
Temperature cycle	10 cycles	10 cycles	10 cycles
Mechanical shock	20,000 g	no	no
Centrifuge	30,000 g	30,000 g	30,000 g
Hermeticity	yes	yes	yes
Critical electrical parameters	yes	no	no
Burn in	168+72h	168 h	no
Final electrical	yes	yes	yes
X-ray radiograph	yes	no	no
External visual	yes	yes	yes

TABLE 8-32. FALLOUT FROM MIL-STD-883 TESTS (Ref. 1)

Screen	Average Fall-out, %	Range, ‘%
Precap visual	15	2.0-45
Hermeticity	5	0.1-10
Burn in	3	0.1-20
Electrical testing	5	1.3-12
External visual	4	0.1-8

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TABLE 8-33. SCREENING TEST COSTS FOR CLASS B DEVICES (Ref. 1)

MIL-STD-883 Method	Cost, $		
	Minimum	Typical	Maximum
1. Precap visual inspection condition	0.15	0.25	3.00
2. High-temperature storage	0.01	0.05	0.10
3. Temperature cycling	0.05	0.10	0.10
4. Constant acceleration	0.05	0.10	0.25
5. Fine leak	0.05	0.10	0.25
6. Gross leak	0.05	0.10	0.20
7. Burn in	0.25	0.50	5.00
8. Final electrical	0.25	0.50	2.00
Total Class B	0.86	1.70	10.90

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to illustrate relative cost differences (up to 20 to 1) for screening tests on devices of varying complexity. For a simple integrated circuit logic gate, screening tests will be lower. For LSI devices the cost will approach the maximum indicated.

In connection with screening methods it should be pointed out that injudicious use of accelerated temperature tests can cause so-called "purple plaque" problems in all aluminum interconnection bonds. For example, if the time-temperature regression plot in MIL-STD-883 is used for the burn in test to shorten test time by subjecting devices to higher temperature, intermetallic compounds are formed and voids can form in the intermetallics. Contamination either in gold or aluminum causes enhanced diffusion between both metals. The intermetallic formation is decreased if pure metals (Au and Al) are used. These voids, known as Kirkendall voids, render the substance brittle and may cause open circuits in the wire bond to the metallization layer. This compound is purple in color and is rich in aluminum. The compounds formed range from $AuA1_2$ to Au4A1. $AuA1_2$ (purple) in itself is not a problem; the gold-rich compound Au_4A1 expands during formation, creates stresses in the silicon, and ultimately breaks the silicon. The process is exothermic and may be accelerated by high temperature.

Two methods are used to prevent the compound formation. The first is to use aluminum wire. The second is to make the contact with chromium followed by an overlay of gold or silver. In either case there is no gold to aluminum bond.

8-2.4 LIFE CYCLE COST (LCC)

The life cycle of the planned system should provide:

1. Maximum performance and reliability within cost goals
2. Minimum support costs.

In coordination with the producibility engineer, the design engineer, who embraces reliability fundamentals in design, is actually incorporating sound economic principles that will lead to the lowest cost to the owner. A design that minimizes support cost involves the application of reliability disciplines during the design phase. The producibility engineer must be ever mindful and conscious of total system cost from the inception of the design.

LCC represents all costs incurred from the conception of a system to final disposal. It should be noted that reliability and maintenance can have a significant impact on production costs, and redundant systems can add to both system weight and cost. Use of established reliability components (per appropriate military specifications) and stringent quality control during production (e.g., equipment screening tests plus extensive subassembly testing) can also increase production cost. High quality parts, which increase the design safety factors, may be costly to procure and may be costly to inspect. The cost factors associated with production test failures can be minimized if failure modes are eliminated during design and if reliability defects are uncovered early in the production cycle. The factors that would reduce production costs, as reliability requirements are increased, include rework, material review board action, scrap rate, and quality control inspection.

The most complex cost estimating relationships are found in the operating and support costs, which include

1. Initial and pipeline spares cost
2. Replacement spares cost
3. On-equipment maintenance cost
4. Off-equipment maintenance cost
5. Inventory entry and supply management cost
6. Support equipment cost
7. Cost of personnel training and training equipment
8. Cost of management and technical data.

These cost areas identify an incurred cost. From these data, times for training, spares placement, and testing are derived. All these logistic elements will now reflect the total resources necessary in military field operational support and an on-site time schedule.

A model for LCC is illustrated in Fig. 8-16. The design engineer must balance performance, reliability, and unit production goals equally against LCC. Attention is focused on a design approach from an LCC model that is composed of submodels that display reliability, maintenance, and associated cost variables. A variety of analytical approaches can be used as input in the development of the optimum LCC model. The total LCC model composed of many subsets is then exercised during trade-off studies and analyses. The cost models and cost estimating relationships range

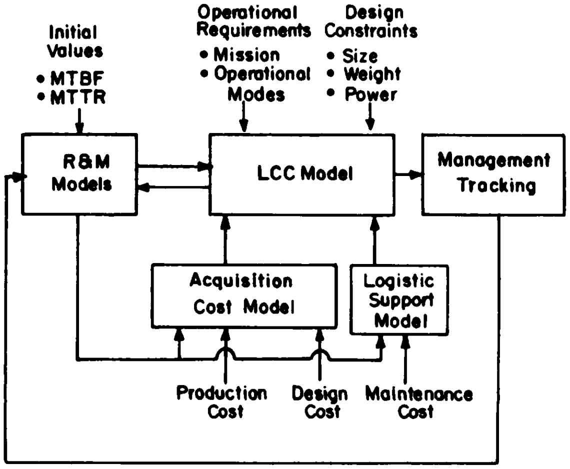

Figure 8-16. LCC Model

from simple to complex mathematical statements derived from empirical data. However simple or complex the model might become, costing so collected and developed falls into two basic areas: (1) system acquisition costs and (2) operating and support costs. There are three life cycle cost categories:

1. Research, Development, Test, and Evaluation (RDT&E) (Design and Development)
    - a. Basic engineering
    - b. Test and evaluation
    - c. Experimental tooling
    - d. System management
2. Procurement Appropriation (PA)
    - a. Fabrication
    - b. Production tooling
    - c. Quality control
    - d. Test equipment
    - e. Facilities
    - f. Initial spares
3. Operating and Support (O&S)
    - a. Planned spares
    - b. Personnel and training
    - c. Maintenance facilities
    - d. Support equipment (special and test)
    - e. Logistic factors.

LCC models have been formulated to establish relationships with the three cost categories listed. To obtain estimates for design and development, detailed engineering costs as well as statistical cost relationships (parametric sensitivity analyses) should be established and/or compiled. Obtaining this information necessitates a firm understanding of the equipment, its development and production processes, and a historical data base on similar equipment. There are a few specific approaches that should be undertaken: relating costs to measurements of technology over a given period of time and using trend line parameters developed from the historical data base of similar equipment. The technological advance sought through the new equipment and the alloted development time can be used for gross estimating purposes.

To estimate procurement costs, production cost information is required. Production costs, in general, include material, labor, overhead, profit, capitalization for production, handling, and transportation. Specific factors that comprise production costs are

1. Recurring Production Costs
    - a. Fabrication
    - b. Assembly
    - c. Test
    - d. Manufacturing support
    - e. Quality control
    - f. Engineering support
2. Nonrecurring Costs
    - a. Manufacturing engineering
    - b. System integration
    - c. Engineering changes
    - d. Quality assurance
    - e. First article tests
    - f. Test equipment
    - g. Tooling
    - h. Facilities
    - i. Documentation.

A review of O&S costs indicates that they are driven by system reliability and maintenance characteristics. For example, when considering maintenance costs, the reliability of the system and its components, in terms of unscheduled maintenance frequencies and mean time between failures (MTBF), directly impacts the frequency of repair and/or overhaul of failed components. Also, the higher the reliability, the fewer field modifications will be required to correct problems and lower the cost, including retrofit costs. Significant reliability and maintenance expenditures during development can be cost justified if improved field reliability and maintenance performance and lower- operating and support costs will result from these efforts.

8-3 MANUFACTURING PROCESSES

The manufacturing processes employed to produce the parts selected in accordance with military specifications are well-established and are rigidly controlled. In the rapidly changing technology of the electronic industry, the greatest advances have been achieved in the microelectronic world. Therefore, the emphasis of this paragraph is on LSI circuits.

8-3.1 NEW TECHNOLOGIES IN LSI CHIPS (Ref. 9)

The “name of the game” in the electronic semiconductor industry over the last two decades has been to get more capability from semiconductor technology. In the last 10 yr, for example, metal-oxide semiconductor chips have progressed from low-density shift registers, gates, and flip-flops operating at millisecond speeds to being entire memories, microprocessors, and dedicated systems consisting of thousands of electronic functions contained in a single device capable of nanosecond operations.

Fig. 8-17 shows graphically the rapid progress in LSI circuit capability. There are four new technologies: a scaled down silicon-gate metal-oxide semiconductor (HMOS); an anisotropically etched, double-diffused process (VMOS); a complimentary MOS silicon-on-sapphire process (SOS); and I^2L.

8-3.1.1 HMOS

The HMOS technology involves scaling down the dimensions and process parameters of standard silicon-gate MOS devices. The HMOS designers (Intel) predict that the present channel length of 4 µm will be reduced to 2 µm, which will yield gates with speed-power products of about 0.15 pJ. These devices will be 65,536-

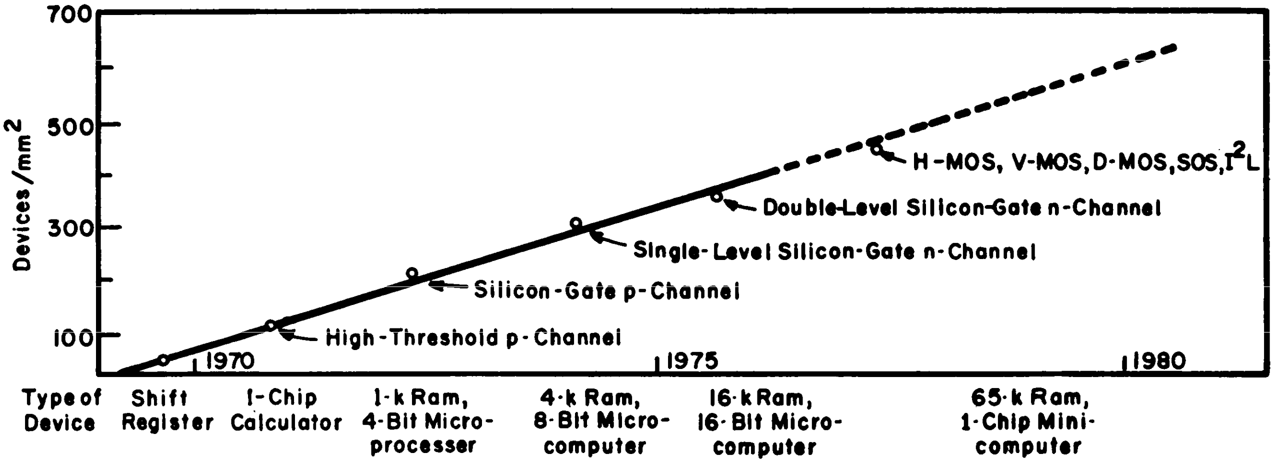

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Figure 8-17. LSI Circuits Progress (Ref. 10)

to 762,144-bit memories on chips measuring 26 mm^2 (40k square roils) in area and will operate in the 50-ns range at 500 m W, and 16- to 32-bit microcomputer chips containing 250k bits of program memory. The HMOS process is potentially the cheapest way to achieve this performance since it is a simple extension of standard silicon-gate structures. Table 8-34 shows the evolutions of the MOS device scaling through the years 1972 to 1980.

Fig. 8-18 shows the cross section of a silicon-gate, n-channel device, where L is the channel length, T_{ox} is the gate oxide thickness, X, is the junction depth, *LD is* the lateral diffusion, and C_B is the substrate doping level. The first-order scaling theory says that the characteristics of an MOS device can be maintained and the desired operation can be assured if the parameters of the

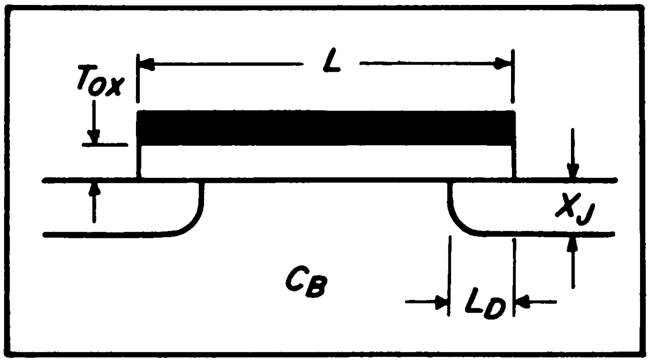

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Figure 8-18. Cross Section of a Silicon Gate (Ref. 10)

TABLE 8-34. MOS DEVICE SCALING (Ref. 10)

Device/Circuit Parameter	Enhancement Mode n-MOS 1972	Depletion Mode n-MOS 1976	HMOS 1977	MOS 1980
Channel length *L,* µm	6	6	3.5	2
Lateral diffusion *LD,* µm	1.4	1.4	0.6	0.4
Junction depth X_j, µm	2	2	0.8	0.8
Gate-oxide thickness T_{ox}, nm	120	120	70	40
Power supply voltage Vcc, V	4-15	4-8	3-7	2-4
Shortest gate delay r, ns	12-15	4	1	0.5
Gate power P_D, mW	1.5	1	1	0.4
Speed power product, pJ	18	4	1	0.2

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device are scaled as shown in Table 8-35. When S is the scaling factor and the channel length L is scaled by a factor of 1/S, then the other device dimensions—the thicknesses of the gate oxide and the lateral underdiffusion, the device width and junction depth—must also be scaled 1/S. Moreover, to maintain adequate threshold voltage and drain-source breakdown voltage, the scaling theory also states that the substrate doping concentration must be increased by S while the supply voltage and current decrease by 1/S.

TABLE 8-35. SCALING FACTORS (Ref. 10)

Device/Circuit Parameter	Scaling Factor
Device dimension T_{ox}, L, L_D, W, X_j	1/S
Substrate doping C_B	S
Supply voltage V	1/S
Supply current I	1/S
Parasitic capacitance WL/T_{ox},	1/S
Gate delay VC/I, τ	1/S
Power dissipation VI	$1/S^2$
Power-delay product	$1/S^3$

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An example of what device scaling means to the user of IC is given in Figs. 8-19 and 8-20, which chart the progress made over the years in static random-access memories. In 1972 the standard static MOS RAM was the 500-ns 2102, built with a 6-µm channel length and 1200-angstrom gate oxide thickness. Its resulting speed-power product was 18 pJ, and it occupied a silicon chip nearly 4 mm (140 roils) on a side and had a cell size of almost 0.005 mm^2 (8 square roils).

In 1974 the 2102 was redesigned around a depletion n-channel technology that shrank its die area by 15% and its access time to 200 ns. Oxide isolation and built-in substrate bias were added to this process in 1976 to create the 2115 static RAM that accessed the same 1024 bits in less than 70 ns. The impact of device scaling is even more apparent with HMOS, which fits the 2115 RAM (now called the 2115A) onto a chip slightly larger than 2.5 mm (100 mils) on a side, while improving access time typically to 25 ns.

Moreover, applied to a 4096-bit static memory design, HMOS results in a chip a little larger than the original 2102 yet typically pushes access times below 50 ns. Finally, as the MOS process evolves and scaling continues, a 16,384-bit fully static RAM will fit on a chip no larger than 5.1 mm (200 mils) on a side and will offer system designers access times in the 50-ns range.

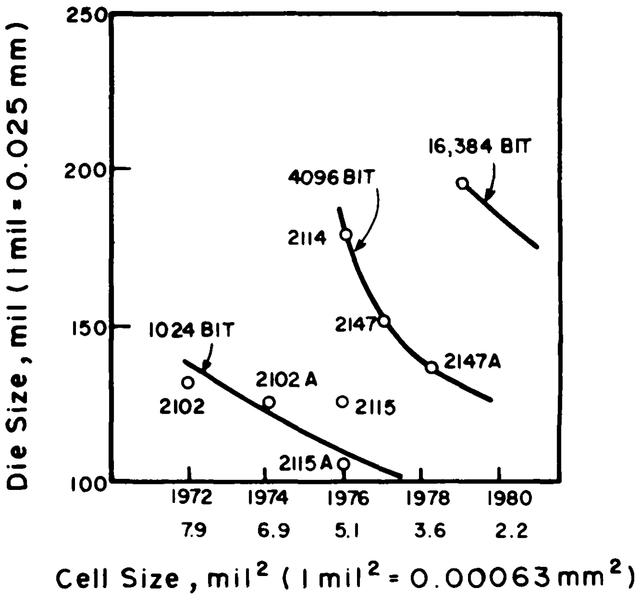

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Figure 8-19. Progress of Die Size Versus Cell Size (Ref. 10)

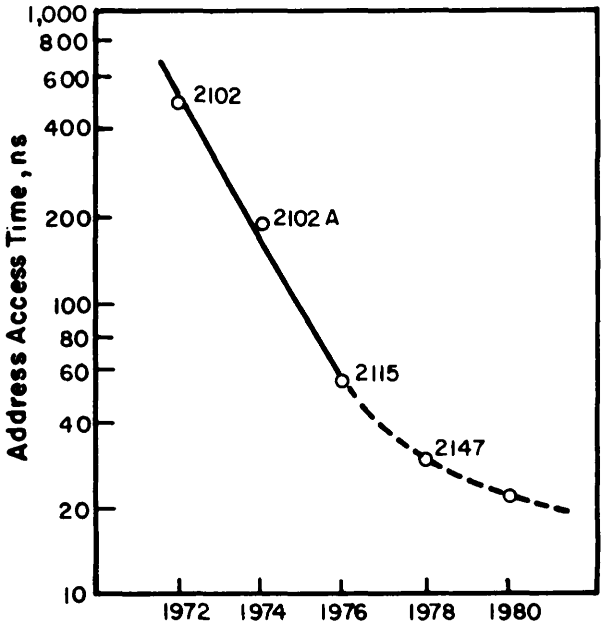

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Figure 8-20. Progress of Address Access Time (Ref. 10)

8-3.1.2 VMOS

Traditionally, MOS transistors in LSI circuits have been planar or two-dimensional. VMOS technology adds a vertical dimension by forming devices with the source beneath the gate and drain rather than alongside them. This third degree of freedom makes VMOS faster as well as denser than standard n-channel MOS and I^2L circuits.

The fabrication sequence of a VMOS transistor is shown in Fig. 8-21. The process requires seven masking operations through the metal definition—one more than typical depletion-load NMOS technology with polysilicon-to-diffusion contacts. However, two of the masks are noncritical in their alignment. In Fig. 8-21(A) the VMOS process begins with doping the surface of a heavily doped n^+ wafer with boron and then growing a pi epitaxial layer about 3 μm thick on the substrate. The next step, Fig. 8-21 (B), is to deposit silicon dioxide and then silicon nitride, followed by removal of the nitride from those areas where a boron implant is next made. In Fig. 8-21(C) two thin p layers are formed—the upper one from the boron implant and the lower one from the original boron doping. Next, a standard, local-oxidation field oxide is grown.

In Fig. 8-21(D) the remaining nitride is patterned again to open the areas to be doped n+, except for the areas to become VMOS or NMOS devices or resistors. The n^+ drain regions are formed by an arsenic ion implantation. In Fig. 8-21(E) local oxidation is performed a second time to give a thick oxide over the diffused regions. Finally, in Fig. 8-21(F) the V-grooves are etched, the gate oxide is grown, polysilicon is deposited, contacts are etched, and metal is deposited and defined. Another view of the V-groove is shown in Fig. 8-22.

Several types of devices can be formed during the VMOS process (as shown in Fig. 8-23): a VMOS transistor, an NMOS transistor, an n-channel resistor, and a resistor-aligned NMOS transistor (useful as the pass gate in a random access measuring cell). The VMOS static random access memory in Fig. 8-24 uses a conventional six-transistor cell in which the two storage elements, Q_3 and Q_4 are VMOS devices, and the pass devices are resistor-aligned n-channel MOS transistors.

To make a dynamic RAM (Fig. 8-25) with VMOS, a buried source is used in the p^+ substrate. Note the use of metal word line for low impedance and the absence of polysilicon in interconnections. The layout (B) in Fig. 8-25 shows a four-transistor cell built with 6-μm rates.

The erasable PROM (Fig. 8-26) is made by adding a polysilicon floating gate to the VMOS structure. Electrons injected from the drain through the oxide into the gate raise the threshold to prevent turn on with 5 V on the word line.

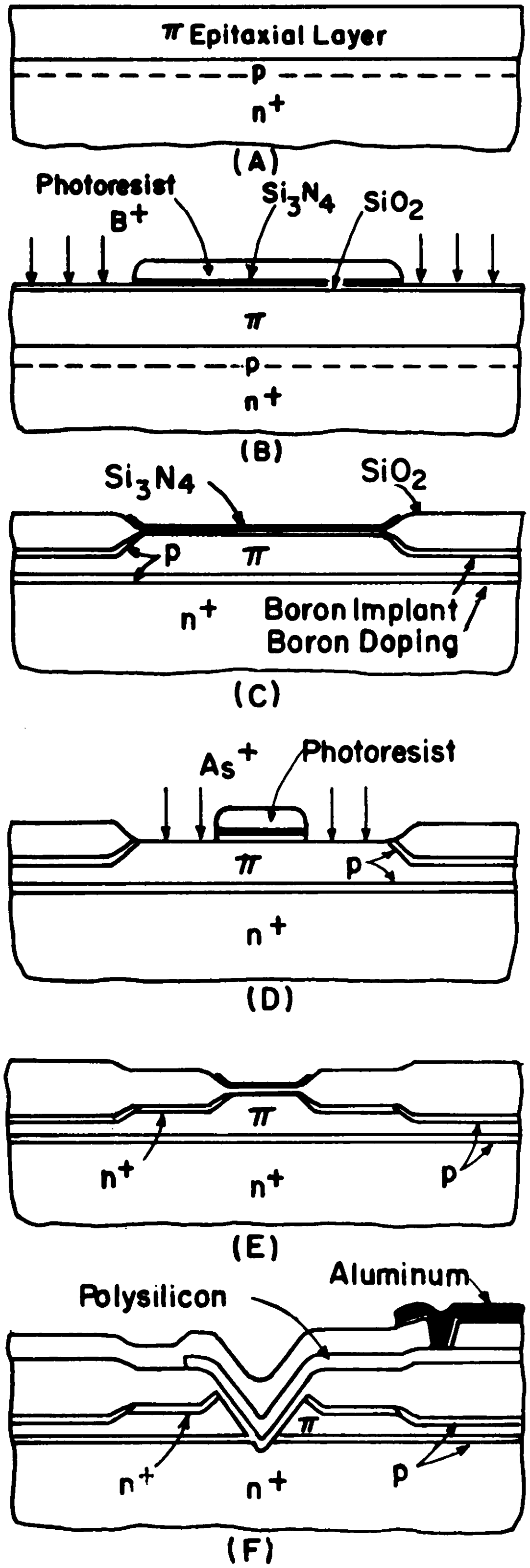

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Figure 8-21. Fabrication Sequence of VMOS Transistor (Ref. 10)

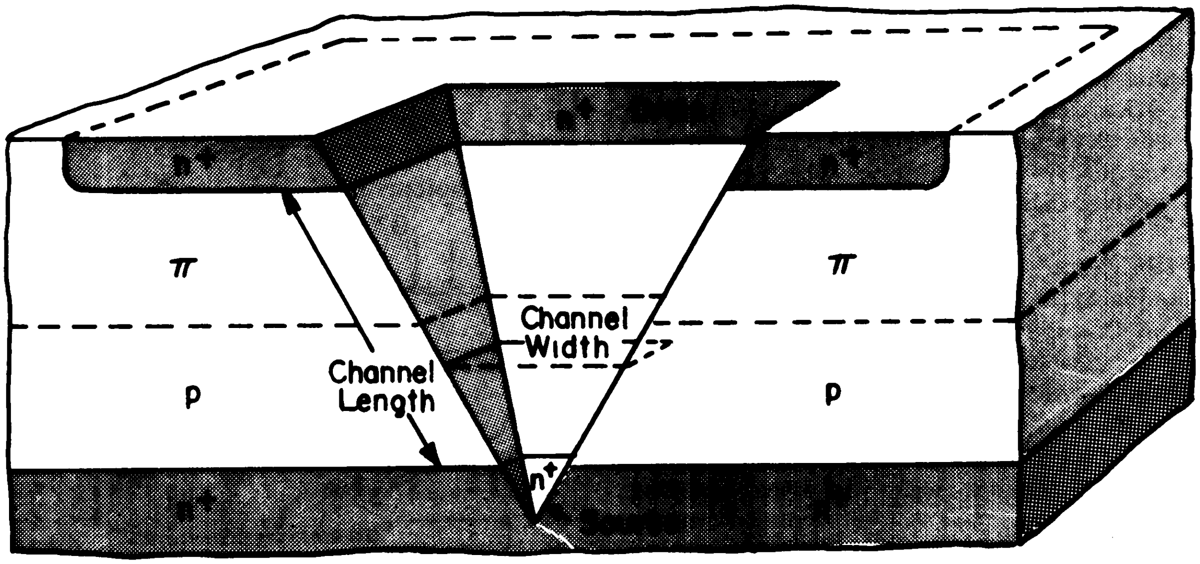

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Figure 8-22. Three-Dimensional View of the V-Groove (Ref. 10)

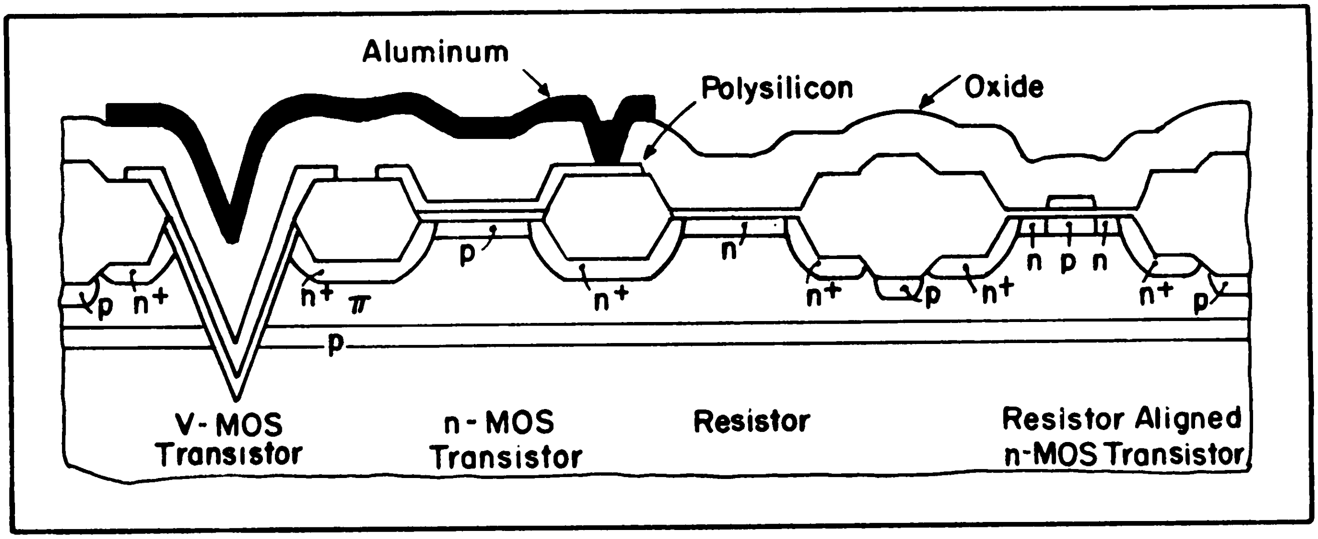

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Figure 8-23. Multiple Devices (Ref. 10)

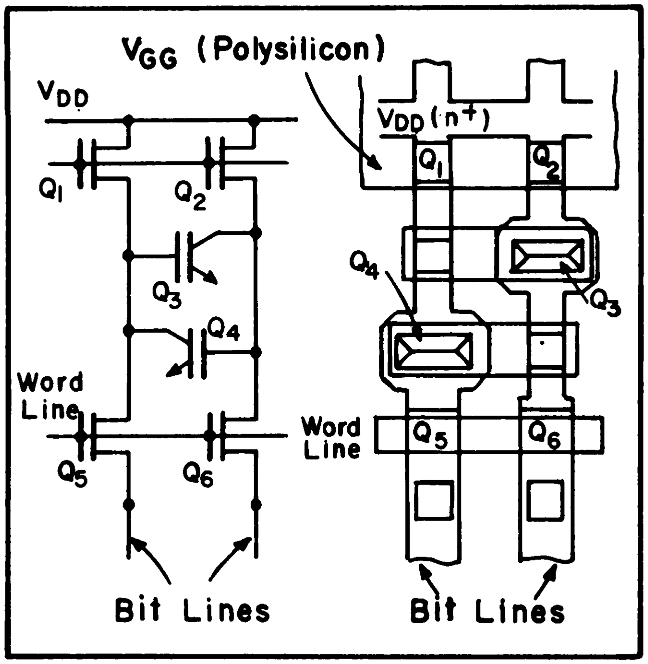

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Figure 8-24. Static RAM (Ref. 10)

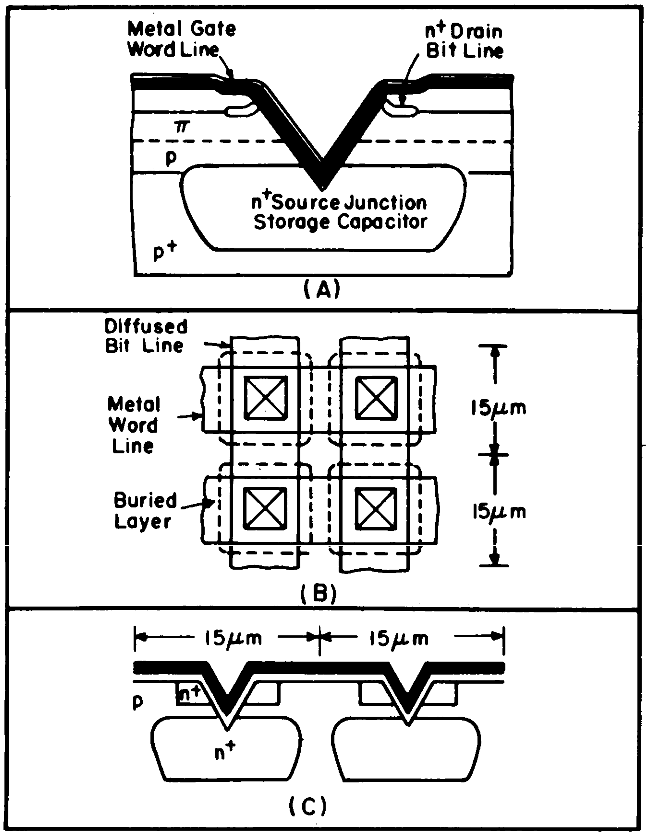

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Figure 8-25. Dynamic RAM (Ref. 10)

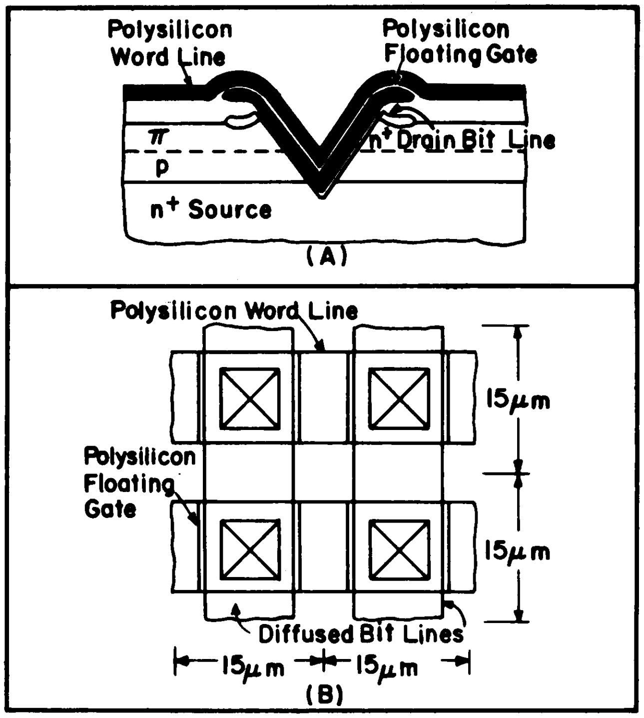

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Figure 8-26. The Erasable PROM (Ref. 10)

8-3.1.3 SOS

SOS IC technology is used extensively by RCA, which has some complementary MOS on sapphire static RAM on the market. RCA is also building an SOS microprocessor for its 1802 line as well as a host of high performance custom processors and other LSI components for the US Army. Hewlett-Packard Co. is building a wide variety of custom SOS memories, microprocessors, and peripheral circuits for its own equipment,

Complementary MOS on sapphire offers one of the best speed-power products of any technology (0.1 pJ now) especially for RAM microprocessors and other logic applications where the high speed is not of primary importance. The designers believe that the dense, low-power configuration of the technique will give its equipment a performance advantage over that built with standard n-channel MOS. The advantage far outweighs the SOS process development costs and higher substrate startup costs. For instrument and computer manufacturers, the performance and capability of the system are of primary consideration.

8-3.1.4 I^2L

The 1^2L, built with such techniques as isoplanar isolation and walled emitters, yields memory and logic circuits that are extremely dense [1290 μm^2 (2 mil^2)] and very fast (less than 5-ns delays). The I^2L devices consume very little power, less than 1 nW and cost little more than MOS circuits. For example, 1^2L 4k-bit dynamic RAM, which are compatible with T^2L logic, typically operate at 90 ns and dissipate less than 500 mW or are about two times better speed-power products than even the best 4k MOS types.

The 1^2L technology can produce microprocessors and peripheral IC, an entire 16-bit minicomputer central processing unit, or a high-speed program sequencer on a single low-power chip, which can bring bipolar performance to the computer designer at practically MOS costs. Table 8-36 depicts the 1^2L memory performance characteristics. Representing the most recent advances in isoplanar injection logic, the 1^2L dynamic bipolar memory cell shown schematically in Fig. 8-27(A) is a merged NPN-PNP structure. The cross section of the cell illustrating the unique, double-diffused PNP transistor used in the process is shown in Fig. 8-27(B). The simple surface topology required for the cells is illustrated in Fig. 8-27(C). The cell size is only 0.0004516 mm^2 for the 16,384-bit version.

The entire cell consists of a single transistor pair—NPN and PNP—merged on silicon so that it occupies little more space than a single transistor. Moreover, it needs no space-consuming capacitors to store charge. Here the logic 1‘s and O’s are stored in the shared collector-base junction of the merged transistors.

Although the storage capacitor is quite small, on the order of 0.1 pF, the relatively high doping concentrations provide both high coupling capacitance and low leakage per unit area, In addition, th NPN cell transistor provides a gain of beta = 70 during readout so that the effective coupling capacitance is about 7 pF and the signal available at the output is large enough to drive high-capacitance bit lines.

8-3.2 SEMICONDUCTOR PHOTOLITHOGRAPHY TECHNOLOGY (Refs. 11 and 12)

In the past, the IC mask-producing procedure was to involve creating master artwork on a large, flatbed plotter to scales of up to 200X. This plot was photoreduced to form a 10X reticle that was used in a step-and-repeat system (photorepeater) for making the 1 X master mask. Working masks were then produced and used in a contact printer to pattern the wafer. This technique was replaced by optical pattern generators, which directly pattern a 5 to 20X hard-surface reticle for use in the photorepeater. The resulting 1X-master mask is used to make working masks for contact and proximity printers or is used directly in a projection printer.

Optical projection lithography systems are beginning to take over tasks formerly reserved for conven-

TABLE 8-36. I^2L MEMORY PERFORMANCE CHARACTERISTICS (Ref. 10)

	4027-4	4027-3	4027-2	93481	93481A
Access time, ns	250	200	150	120	100
Cycle time, ns	375	375	320	280	240
Page access time, ns	155	125	90	75	65
Page cycle time, ns	275	215	160	75	65
	4027 (All)			93481 (All)	
Maximum power (at maximum cycle time), mW	462			450	
Maximum power (standby), mW	27			70	
Power supply, V	+12; +5; –5 (10%)			+5 (5%)	
Chip selects	1			2	
Timing inputs	2			1	
Data latch	Always			User controlled	
Input capacitance, pF	4-8 typical			2 typical	
Output drive low/high, mA	3.2/5			16/5	
Chip size, mil^2	14,500			11,700	
Refresh	64 lines; 2 ms			32 lines; 2 ms	

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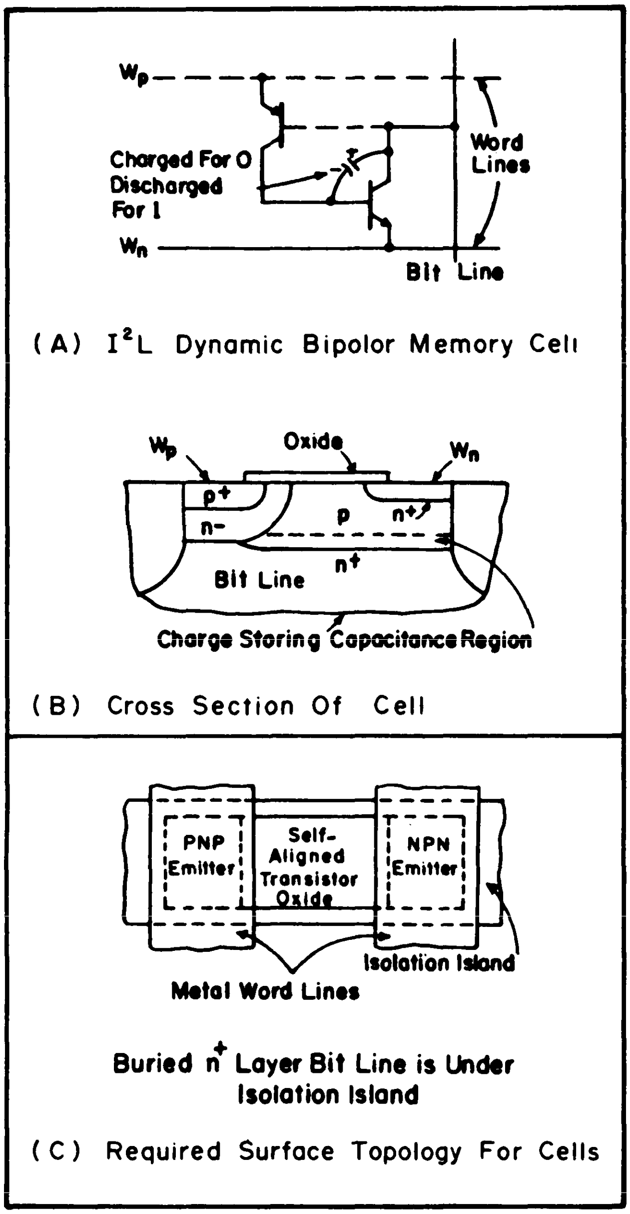

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Figure 8-27. I²L Technology (Ref. 10)

tional contact and proximity photolithographic systems. Step-and-repeat optical reduction techniques are making possible projection printing of devices with line widths from 2.5 to 3 µm on a routine production basis and down to 1.5 µm in the laboratory over a field as large as 1 cm². Advanced techniques presently under development include electron beam (E-beam) and X-ray lithography. Both X-ray lithography and the E-beam system can offer superior fine line geometry and accuracy over optical methods, which are limited by the wavelength of light. Fig. 8-28 shows the experienced and the projected trends in the silicon die area and the minimum line width.

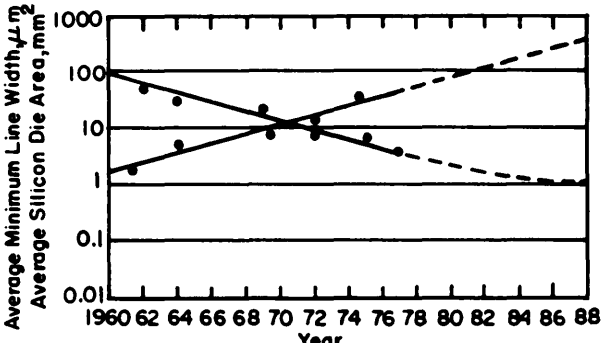

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Figure 8-28. Die Size and Line Width Trends (Ref. 12)

The X-ray lithography shows the most promise for achieving high resolving power, high throughput, and relatively inexpensive equipment. The X-ray system, however, requires the use of an E-beam-generated mask to achieve its performance capability. In effect X-ray printing, unrestricted by the limitations of ultraviolet light, offers negligible scattering through the mask material and less diffraction through slits smaller than 1 µm.

The E-beam system known for its fine line resolution capability can be used to generate a 10X reticle for step and repeat, generate a complex 1 X mark for use on all types of printers including X ray, and pattern the wafer directly without masking.

To meet the needs of future high-density IC, plasma etching has been used instead of chemical (wet) etchants. It offers several advantages over conventional wet etching—the greatest of which are much finer line resolutions (well below 1 µm) and minimization of the resist undercutting problem.

8-3.3 PLASTIC ENCAPSULATED AND POLYMER SEALED DEVICES

Plastic encapsulation (most often epoxy or, for higher powered circuits, silicon) for IC is beset with problems among professionals. However, recent application of some improved resins has somewhat reduced thermomechanical failure. It has not demonstrated a reduction in such characteristics as mechanical defects due to processing (opens/shorts\intermittents), external lead frame corrosion, or external leakage currents. Encapsulation has not shown an improvement in internal surface effects, internal metallization corrosion, or lot-to-lot variability. The military user has not observed extended 1ife of the operating part nor prolonged storage capability. Examination of the design, material, and process of plastic encapsulation devices (PED) appears to be indicative of a low-cost objective.

Chip coating and barrier coating materials used for protection against moisture and ionic contamination are silicon-based elastomers, aluminum oxide, silicon dioxide, glass, and silicon nitride. Silicon nitride is widely used because it acts as a barrier and offers a scratch-resistant surface. Fig. 8-29 shows silicon nitride as a protective coating between chip and encapsulant.

Table 8-37 shows typical IC manufacturing costs when plastic coatings are used. It can be seen that the package, materials, and labor costs area very small part of the price. The price is dominated by the yield, and the saving is between 3¢ and 25¢. Encapsulation plus automation (beam tape carrier, etc.) can save as much as 45¢ per device. The real cost saving potential is the yield improvement, which is dominated by final test losses in the more complex IC. Automated assembly can improve yield by reducing handling aberrations and damage. But the greatest cost reduction lies in the vastly improved wafer level electronic probing to insure that nearly 100% good dies are committed to assembly and final test. This would improve reliability.

In reference to the AN/GYQ-18 system, we have a direct comparison between PED and hermetics of similar quality and side by side in the same black boxes. As observed in Table 8-38, the PED failure rate was 11.6 times that of the hermetic rate.

In a commercial application, General Electric observed a comparable failure rate of PED versus hermetics as displayed in Table 8-39.

The time it takes for PED to fail caused by moisture penetration is a phenomenon that makes them look attractive on short-term environmental tests. The reported failure rates for old and new plastics have been changed to equivalent values of 61°C and 12’% relative

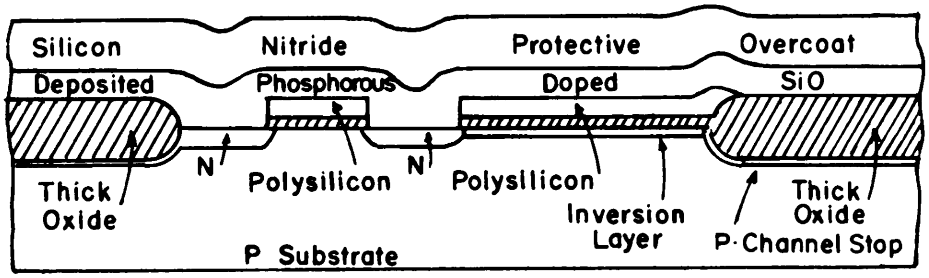

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Figure 8-29. 4k RAM, Silicon Nitride Protection (Ref. 13)

TABLE 8-37. TYPICAL IC MANUFACTURING COSTS

	Commercial 0° to 75°C TTL\SSI 14 pin plastic	Jan-Type Class B –55° to 125°C TTL/SSI 14 pin CERDIP[1]	Commercial Calculator Chip 28 pin plastic	Commercial 4k RAM 22 pin CERDIP[1]	Commercial 16k RAM 16 pin CERDIP[1]
Wafer yield	90%	90%	50%	40%	10%
Cost per “good” die	1.2¢	3¢	22¢	61¢	$3.09
Cost of package materials	2¢	4¢	3¢	25¢	20¢
Cost of package, labor	5¢	6¢	22¢	20¢	15¢
Yielded assembly cost	8¢	12¢	34¢	54¢	71¢
Cost of testing	1¢	18¢	5¢	35¢	55¢
Yielded test cost	2¢	21¢	11¢	79¢	$2.86
Total manufacturing cost	11.2¢	36¢	77¢	$1.94	$6.66
Volume purchase price	16¢	72¢	$1.54	$3.88	$13.32
Savings possible by use of plastics	0	3¢	0	25¢	20¢

[1] ceramic dual in-line package

TABLE 8-38. AN/GYQ DATA DISPLAY SYSTEM

Comparison of Hermetic- and Plastic-Encapsulated Failure Rates:

Ground benign environment, $\pi_E = 0.2$

Average cabinet temperature, $T_A = 30°C$ ($T_J = 40°C$)

Plastic and hermetic devices side by side in same hardware

307 X 10^6 device h over 22 months at four locations (Cheyenne Mt., Offutt AFB, Ft. Richie, and The Pentagon)

Observed Failure Rate:

All devices (5211 per system) – 0.051%\kh
Hermetic devices only – 0.020%\kh
Plastic devices only – 0.232%\kh

$$\text{Ratio} \quad \frac{\text{plastic failure rate}}{\text{hermetic failure rate}} = 11.6$$

T_J = junction temperature
π_E = application environment factor
T_A = average temperature

TABLE 8-39. POWER LINE CARRIER EQUIPMENT

After 10 million semiconductor device years:

1. High failure rate experienced in storage of plastic semiconductors at high humidity, which does not exist with hermetics.
2. J-FET*, MOSFET**, and CMOS are much more prone to failure due to moisture contamination and may show up to **50:1** failure rate ratio.
3. Plastic semiconductors do not lend themselves to effective screening techniques.
4. Hermetic semiconductors save about $7.30 per installed device over 20-yr useful life of equipment, and they reduce total life cycle costs about 36%.
5. The observed operating failure rate for 300,000 each of plastic and hermetic linear integrated circuit

Plastic — 0.05%/kh
Hermetic — 0.007%\kh

$$\text{Ratio} \quad \frac{\text{plastic failure rate}}{\text{hermetic failure rate}} = 7.14$$

* J-FET = J-type field effect transistors
**MOSFET = metal oxide silicon field effect transistors

humidity, and the values of Tables 8-38 and 8-39 are summarized in Table 8-40. Conclusions are drawn from the foregoing discussion and are summarized in Table 8-41.

Although current plastic encapsulated semiconductors exhibit increased moisture resistance and better temperature cycling capabilities over earlier PED, the DoD discourages plastic encapsulated semiconductor and microelectronic devices. MIL-S-19500, MIL-M-38510, and Requirements 30 and 64 of of MIL-STD-454 require that all semiconductor devices and microcircuit devices be hermetically sealed in glass, metal, metal oxide, ceramic, or combinations of these and that no

TABLE 8-40. RELIABILITY OF PLASTIC ENCAPSULATION DEVICES (PED)

Package Type	Induction Time
PED without die coat	0 to 3000 h
PED with die coat	3000 to 5000 h
Ceramic dip with die coat	>47,000 h
Package Type	**Reported Failure Rate %/kh**
“Old” plastic (pre-1972)	0.082
Epoxy/novlac	0.011
Ceramic	0.027
AN/GYQ-18:	
PED	0.232
Ceramic	0.020
GE power line integrated circuit:	
PED	0.050
Ceramic	0.007

TABLE 8-41. CONCLUSIONS OF PLASTIC ENCAPSULATION DEVICES DISCUSSION

1. PED must demonstrate they can pass some legitimate screening, quality control inspection (QCI), and qualification requirements aimed at PED problems.
2. They must be able to do so consistently.
3. They must demonstrate:
   a. acceptable failure rates
   b. a useful lifetime in storage and operation.
4. They must generate user confidence rather than confusion.
5. The economic benefits must be significant enough to outweigh the cost of proliferating a whole set of parallel stock numbers.

plastic (organic or polymeric) encapsulated or sealed devices be used without the approval of the procuring activity.

8-3.4 HYBRID MICROCIRCUITS (Ref. 12)

Hybrid microcircuits are essentially conventional electronic circuits vastly reduced in size. Circuit conductors, resistors, and some small value capacitors are film deposited onto glass or ceramic substrates. Other circuit components including diode and transistor dice chip capacitors and monolithic integrated microcircuits are then attached to the substrate, and wire bonds are used to achieve the circuit interconnections. The completed substrate is then put into a case, lead attachments are made, and the completed hybrid circuit is then sealed.

Hybrid circuits allow a consolidation of a large variety of discrete components into a single package, which reduces circuit size and weight. More functions can be included per circuit board, and this reduces the number of connectors and cables; small circuit packages allow a more flexible system partitioning. Circuit performance is enhanced because

1. Resistors are made of identical material and will have close temperature tracking.
2. Resistors can be trimmed to the proper values while the circuit is functional.
3. Reduced component lead lengths minimize stray capacitive and inductive effects.
4. The proximity of all circuit components offers a uniform environment for the circuit.
5. Risks associated with the combined performance of a large array of discrete components are reduced.

Hybrid circuit components include thick- and thin-film resistors, deposited and chip capacitors, diodes and transistors, and monolithic integrated circuits. Thick-film resistors are made by screen printing resistive inks onto the hybrid substrates. The film thickness is set during manufacture so that resistor values are obtained by varying the film length and width. Fine trimming is being done by etching, abrasion, or laser. Thin-film resistors use vapor-deposited or sputtered films of metal of controlled conductivity, which are then masked and etched to the desired resistor value. Accordingly, thin-film resistors can have improved performance characteristics but take longer and are more difficult to manufacture. They also do not have the power-handling capability of the thick-film resistors.

Current technology is producing resistors with resistance tolerances of ±0.5% for thick-film resistors and ±0.05% (±0.001% with trim) for thin-film resistors. Absolute temperature coefficients of ±200 ppm/°C for thick-film and ±20 to 50 ppm/°C for thin-film are routine. Resistance ratio tracking temperature coefficientts are even better; they approach 5 ppm/°C for thick-film and 0.2 ppm/°C for thin-film networks. Power dissipation for 2% stability thick-film resistors is 78.2 W\cm^2; thin-film resistors are considerably lower and, therefore, are primarily used for large-value (low-power), ultraprecise applications.

Capacitors can be either screen printed or purchased as chips. Screen-printed capacitors are made by printing a dielectric material over a lower conductor and then printing an upper conductor over the dielectric to form a parallel plate capacitor. Due to their large size, these capacitors become impractical above approximately 2500 pF. Accuracy of ±3% is routine. Larger value capacitors are purchased in chip form and are bonded to the microciruit substrate like the active devices. Capacitor size is related to the dielectric material (temperature coefficient), capacitance, and voltage rating required. Capacitor values to 0.1 μF and voltage ratings up to 200 V are usually compatible with size and economic consider at ions. Commonly used chip capacitors use zero temperature coefficient (NPO) and K1200-type dielectric material.

Active semiconductor devices are purchased directly from the semiconductor manufacturers in dice form, and virtually all passivated semiconductor dice are compatible with standard die mount and wire-bonding techniques. Great circuit flexibility is possible since both bipolar and MOS semiconductor devices and integrated circuits can be combined in the same hybrid circuit. Wire-bonding techniques have progressed from gold ball thermocompression bonds to gold and aluminum ultrasonic bonds which use no heat and can pierce oxides. Some active devices are beam lead chips that eliminate the chip wire bond.

The ceramic hybrid circuit substrate can be designed for dip-soldered, copper, or swaged pin terminals. By using this packaging approach, a conformal coating is applied to the hybrid circuit, and a ceramic lid is epoxied into place. For very small substrates, dual-in-line packages can be used to house the hybrid circuit.

The most rugged packages in use today are metal cans, either round or rectangular. The hybrid substrate is bonded into the can, lead attachments are made, and then a cover is put onto the hybrid circuit to seal it hermetical]}. Sometimes the can is flushed and backfilled with an inert nitrogen helium atmosphere. The covers are usually welded onto the can using are resistance, stitch, or cold weld techniques. The cover can be soldered onto the can for a repairable hybrid circuit.

Since hybrid circuits shrink package size while maintaining power dissipation, package thermal capability is an important package consideration. Cermic substrates are made that use high thermal conductivity alumina and beryllia ceramics, and substrate bonding techniques achieve very good overall thermal conductitvities that minimize package temperature rise above ambient temperatures. Thermal impedances of present packages are approximately 20 deg C rise per watt of package power dissipated. Screening and quality control procedures for hybrid circuits are well-established, and hybrid circuits screened similar to MIL-STD-883, Method 5008, Class B, are readily available.

Fig. 8-30 shows an example of a thick-film packaging technique.

Figure 8-30. Micro Networks 12-Bit Analog-to-Digital Converter

8-4 PACKAGING TO WITHSTAND ENVIRONMENT

To use fully the benefits of producibility-oriented design, consideration must be given early in the design process to the required environmental resistance of the equipment being designed. Packaging techniques employed for most military and aerospace applications are aimed at achieving high density, ruggedized, highly reliable systems.

The volume reduction in digital technology due to LSI microcircuits and the greater reliability of solid-state parts made this progress in packaging possible. The most spectacular] progress was made in avionics for which light, densely populated, highly sophisticated electronic equipment is of prime importance. In many military applications the mission-supporting electronic equipment is exposed to extreme temperature and humidity changes, altitude changes, and severe vibration. The structutal and thermal aspects must be taken into consideration during design stages to avoid compromise of the operability and reliability of the equipmtmt.

The environmental resistance, both the intrinsic and that provided by specifically directed design features, will singularly determine the ability of the equipment to withstand the deleterious stresses imposed by the environment in which the equipment will be operated. The initial requirement for determining the required environmental resistance is the identification and detailed description of the environments in which the equipment must operate. The next step is the determination of the performance of the components and materials that comprise the equipment when exposed to the degrading stresses of the environments so identified. When such performance is inadequate or marginal with regard to the equipment reliability goals, corrective measures, such as derating, redundancy, protection from adverse environments, or selection of more resistant materials and components, are necessary to fulfill the reliability requirements of the equipment.

8-4.1 ENVIRONMENTAL FACTORS

Since reliability is strongly dependent upon the operating conditions encountered during the entire life of the equipment, it is important that such conditions are accurately identified at the beginning of the design process. Environmental factors that exert a strong influence on equipment reliability are listed in Table 8-42.

High temperatures impose a particularly severe stress on most electronic components because they can cause catastrophic failure, such as melting of solder joints and burnout of solid-state devices and can also accelerate progressive deterioration of component performance due primarily to chemical degradation effects. It is often shown that excessive temperature is the primary cause of limited reliability in military electronic equipment. In present day electronic systems design, great emphasis is placed on small size and high component part densities. This generally requires a cooling system to provide a path of low thermal resistance from heat-producing elements to an ultimate heat sink of reasonably low temperature.

Solid-state components are generally rated in terms of maximum junction temperatures, and the thermal resistances from this point to either the case or to free air are usually specified. The specification of maximum ambient temperature for which a component is suitable is generally not a sufficient method for component selection with densely packaged parts since the surface temperatures of a particular component can be greatly influenced by heat radiation or heat conduction effects from other nearby parts. These effects can lead to overheating above specific maximum safe temperatures even though the ambient temperature rating appears not to be exceeded. It is preferable, therefore, to specify thermal environment ratings, such as equipment surface temperatures, thermal resistance paths associated with conduction, convection and radiation effects, and cooling provisions, such as air temperature, pressure, and velocity. In this manner, the true thermal

TABLE 8-42. ENVIRONMENTAL STRESSES, EFFECTS, AND RELIABILITY IMPROVEMENT TECHNIQUES IN ELECTRONIC EQUIPMENT (Ref. 1)

Environmental Stress	Effects	Reliability Improvement Techniques
High temperature	Parameters of resistance, inductance, capacitance, power factor, dielectric constant, etc., will vary; insulation may soften; moving parts may jam due to expansion; finishes may blister; devices suffer thermal aging; oxidation and other chemical reactions are enhanced; viscosity reduction and evaporation of lubricants are problems; structural overloads may occur due to physical expansions.	Heat dissipation devices, cooling systems, thermal insulation, heat-withstanding materials.
Low temperature	Plastics and rubber lose flexibility and become brittle; electrical constants vary; ice formation occurs when moisture is present; lubricants gel and increase viscosity; high heat losses; finishes may crack; structures may be overloaded due to physical contraction.	Heating devices, thermal insulation, cold-withstanding materials.
Thermal shock	Materials may be instantaneously overstressed, which causes cracks and mechanical failure; electrical properties may be permanently altered; crazing; delamination; ruptured seals.	Combination of techniques for high and low temperatures.
Shock	Mechanical structures may be overloaded, which causes weakening or collapse; items may be ripped from their mounts; mechanical functions may be impaired.	Strengthened members, reduced inertia and moments, shock absorbing mounts.
Vibration	Mechanical strength may deteriorate due to fatigue or overstress; electrical signals may be mechanically and erroneously modulated; materials and structures may be cracked, displaced, or shaken loose from mounts; mechanical functions may be impaired; finishes may be scored by other surfaces; wear may be increased.	Stiffening, control of resonance.
Humidity	Penetrates porous substances and causes leakage paths between electrical conductors; causes oxidation which leads to corrosion; moisture causes swelling in materials such as gaskets; excessive loss of humidity causes embrittlement and granulation.	Hermetic sealing, moisture-resistant material, dehumidifiers, protective coatings.

Salt atmosphere and spray	Salt combined with water is a good conductor, which can lower insulation resistance; causes galvanic corrosion of metals; chemical corrosion of metals is accelerated.	Nonmetal protective covers, reduced use of dissimilar metals in contact, hermetic sealing, dehumidifiers.
Electromagnetic radiation	Causes spurious and erroneous signals from electrical and electronic equipment and components; may cause complete disruption of normal electrical and electronic equipment, such as communication and measuring systems.	Shielding, material selection, part type selection.
Nuclear/cosmic radiation	Causes heating and thermal aging; can alter chemical, physical, and electrical properties of materials; can produce gases and secondary radiation; can cause oxidation and discoloration of surfaces; damages electrical and electronic components especially semiconductors.	Shielding, component selection, nuclear hardening.
Sand and dust	Finely finished surfaces are scratched and abraded; friction between surfaces may be increased; lubricants can be contaminated; clogging of orifices, etc.; materials may be worn, cracked, or chipped; abrasion, contaminates insulations, corona paths.	Air filtering, hermetic sealing.
Low pressure (high altitude)	Structures, such as containers and tanks, are overstressed and can be exploded or fractured; seals may leak; air bubbles in materials may explode causing damage; internal heating may increase due to lack of cooling medium; insulations may suffer arcing and breakdown; ozone may be formed; outgasing is more likely.	Increased mechanical strength of containers, pressurization, alternate liquids (low volatility), improved insulation, improved heat transfer methods.

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state of the temperature-sensitive internal elements can be determined.

Low temperatures experienced by electronic equipment can also cause reliability problems. These problems are usually associated with mechanical elements of the system and include mechanical stresses produced by differences in the coefficients of expansion (contraction) of metallic and nonmetallic materials, embrittlement of nonmetallic components, mechanical forces caused by freezing of entrapped moisture, stiffening of liquid constituents, etc. Typical examples include cracking of seams, binding of mechanical linkages, and excessive viscosity of lubricants.

Additional stresses are produced when electronic equipment is exposed to sudden changes of temperature or rapidly changing temperature cycling conditions. These conditions generate large internal mechanical stresses in structural elements particularly when dissimilar materials are involved. Effects of the thermal, shock-induced stresses include cracking of seams, delamination, loss of hermeticity, leakage of fill gases, separation of encapsulating components from components and enclosure surface leading to the creation of voids, and distortion of support members.

A thermal shock test is generally specified to determine the integrity of solder joints since such a test will create large internal forces due to the effect of differential expansion. Such a test has also been found to be instrumental in creating segregation effects in solder alloys—a condition that leads to the formulation of lead-rich zones susceptible to cracking effects.

Electronic equipment is often subjected to both environmental shock and vibration during normal use and testing. Such environments can cause physical damage to components and structural members when the deflections produced cause mechanical stresses that exceed the allowable working stress of the constituent parts.

The natural frequencies of parts and subsystems comprising the equipment are important parameters if they are within the vibration frequency range and must be considered in the design process because a resonant condition will greatly amplify the maximum deformation and may increase stresses beyond the safe limit. The vibration environment can be particularly severe for electrical connectors since it may cause relative motion between members of the connector. This motion in combination with other environmental stresses can produce fretting corrosion, which generates wear debris and causes large variations in contact resistance.

Humidity and salt air environments can cause degradation of equipment performance because they promote corrosion effects in metallic components and can foster the creation of galvanic cells, particularly when dissimilar metals are in contact. Another deleterious effect of humidity and salt air atmospheres is the formation of surface films on nonmetallic parts that causes leakage paths and degrades the insulation and dielectric properties of these materials. Absorption of moisture by insulating materials can also cause a significant increase in volume conductivy and dissipation factor of materials so affected.

Electromagnetic and nuclear radiation can cause disruption of performance levels and, in some cases, permanent damage to exposed equipment. It is important, therefore, that such effects be considered in determining the required environmental resistance for electronic equipment that must achieve a specified reliability goal.

Electromagnetic radiation often produces interference and noise effects within electronic circuitry, which can impair the functional performance of the system. Sources of these effects include corona discharges, lightning discharges, and sparking and arcing phenomena. These may be associated with high voltage transmission lines, ignition systems, brush-type motors, and even the equipment itself. Geneally, the reduction of interference effects requires incorporation of filtering and shielding features or the speciification of less susceptible components and circuitry.

Electromagnetic interference may be controlled through the use of conventional filters, compatible lossy filter(s), and common mode filters. Shielding offers major wide-band protection from the power supply interference when it and the suspect circuit cannot be separated far enough to attenuate the radiation sufficiently. With careful design and construction, high values of abatement are obtainable. Double shielding can be even more effective if necessary. Relays are frequently used for switching power circuits. Since relays are generally remote, the transient interference will be carried on the interconnecting wiring and will couple into the nearby susceptible circuits. A variety of circuits made up of resistors, capacitors, and inductors can be used with or without linear elements to reduce or eliminate the interference waveform. In brush-type motors radio frequency can often be troublesome. However, when diagnosed, each can be suitably reduced.

In selecting interference circuitry to provide for the construction of shielding, etc., it is usually necessary to make trade-offs between interference reduction and other considerations, such as allowable rise or decay of the load current, ease of installation of the circuits, physical size of the interference reduction components, ease of installation of the circuits, and the adaptability of the power supply. DARCOM-P 706-410, Electro*magnetic Compatibility (EMC)* Handbook, treats these in considerable detail.

Nuclear radiation can cause permanent damage by alteration of the atomic or molecular structure of dielectric and semiconductor materials. High-energy radiation can also cause ionization effects that degrade the insulation levels of dielectric materials. The mitigation of nuclear radiation effects typically involves the use of materials and components possessing a higher degree of intrinsic radiation resistance and the incorporation of shielding and hardening techniques.

In addition to the aforementioned stress factors, other environmental factors may require consideration in the design to assure that equipment will withstand the total environmental stress. These additional factors include sand and dust, fungus, acoustic noise, electric fields, magnetic fields, and the presence of reactive liquids and gases. Each of these stress factors, if present, requires determination of the impact of it on the operational and reliability characteristics of the materials and components comprising the equipment being designed. It also requires the identification of material, component, and packaging techniques that afford the necessary protection against such degrading factors.

In the process of identifying environmental stress that precedes the selection of environmental resistance techniques, it is essential that stresses associated with all life cycle intervals of the equipment be considered. This includes not only the operational and maintenance environments, but also the preoperational environments when stresses imposed on the parts during manufacturing assembly, inspection, testing, storage, shipping, and installation may have significant impact on the eventual reliability y of the equipment. Stresses imposed during the preoperational phase are often overlooked, but they may represent a particularly harsh environment that the equipment must withstand. Often the shock and humidity environments to which commercial and military systems are exposed during shipping and installation are more severe than those it will encounter under normal operating conditions. It is also probable that some of the environmental resistance features incorporated into system design pertain to conditions encountered in the preoperational phase and not necessarily to conditions that the equipment experiences after being put into operation.

8-4.2 ENVIRONMENTAL RESISTANCE PROVISIONS

After identification of all environmental stress factors that will be encountered by a particular electronic system, a determination is made of the components and elements of the system that will be adversely affected and of the effects of this degradation on the apportioned reliability goals. Generally, such a determination will not only identify elements of the proposed design that are totally unsuitable, but equally important, it will identify trade-off situations for which incorporation of specific protective features will significantly enhance the achievable reliability.

In these cases the solution is the specification of components with greater inherent resistance to the identified environmental stresses and the selection of particular protection techniques for reducing these stresses to levels that produce acceptable reliability characteristics. Technical information in the form of a data package covering all specifications and the delineation of engineering requirements must be developed for an early design review to achieve full assurance of proposed system compliance.

8-4.2.1 Thermal Protection

Since excessive temperature is a primary cause of operational and reliability y degradation, each proposed system must be designed so that the thermal performance of it is consistent with the required equipment reliability. The preferred method for evaluating the thermal performance of electronic equipment is the part stress analysis method, which determines the maximum safe temperatures for constituent parts. A reduction in the operating temperature of components is a primary method for achieving improved reliability levels. This is generally made possible by reducing heat input to minimally achievable levels and by providing heat sinks or coolants for heat-producing elements to an ultimate heat sink of reasonably low temperature. The thermal design is often as important as the circuit design in obtaining the necessary performance and reliability characteristics of electronic equipment.

The failure rates of electronic system components vary significantly with temperature. Table 8-43 illustrates the reliability improvement potential associated with the operation of circuit elements at reduced temperatures. Consideration of LCC will generally indicate that the cost of designing and implementing adequate thermal performance into equipment is fully recovered by savings in maintenance costs early in the operational life of the equipment. A suitable thermal design will also minimize temperature excursions of components when environmental temperatures or power dissipation vary, resulting in further reliability benefits.

The part stress analysis method for evaluating system thermal performance is based on a determination of the maximum allowable temperature for each component that is consistent with equipment reliability and the failure rate allocated to that component. Once these maximum allowable temperatures are assigned and the power dissipated by each component is ascertained, a heat flow network can be established from each component to available heat sinks or coolants for analysis of the thermal performance of the system. For situations in which surface temperatures must be related to maximum allowable internal temperatures,

TABLE 8-43. RELIABILITY IMPROVEMENT POTENTIAL AT REDUCED TEMPERATURES (Ref. 1)

Part Description	Base Failure Rates,[1] per 10^6 h		ΔT deg C	Decrease in Failure Rate Due to Low T
	Reduced Temp, °C	High Temp, °C		
PNP silicon transistors	0.0080 at 40°	0.0630 at 160°	120	8:1
NPN silicon transistors	0.0054 at 40°	0.0330 at 160°	120	6:1
Glass and porcelain capacitors	0.0009 at 40°	0.0290 at 125°	85	32:1
Transformers and coils	0.0010 at 40°	0.0267 at 85°	45	27:1
Resistors, composition carbon	0.0002 at 40°	0.0063 at 90°	50	31:1

[1] Taken from MIL-HDBK-217 at a 10% stress level.

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such as junction temperatures of semiconductor devices, a knowledge of the internal thermal resistance of these components is required to calculate the corresponding surface temperatures for the particular operating conditions of the component.

A step-by-step procedure for evaluating thermal performance of proposed designs includes these activities:

1. Establish the maximum and minimum environmental temperatures of anticipated heat sinks and coolants.
2. Characterize the available cooling techniques, such as forced air convection, liquid, or vaporization cooling.
3. Develop a heat flow network using electrical analog techniques for the conditions of maximum allowable component temperatures and maximum environmental heat sink or coolant temperatures; determine the thermal resistance requirements from parts to heat sinks. Further specifics of heat flow techniques and characteristics are described in MIL-HDBK-251, *Reliability/Design Thermal Applications.*
4. Select packaging approaches and component placements that will fulfill the thermal resistance requirements in terms of the available and permissible cooling techniques.
5. Determine the suitability of simple cooling techniques, such as free or forced air cooling, for satisfaction of the heat concentration and thermal resistance requirements of the proposed design. If the techniques are insufficient, proceed to higher level cooling techniques until an optimum cooling method is identified.
6. Evaluate the penalties associated with the selected cooling method, and perform trade-off analyses to identify alternative approaches and refinements if possible.

Further specifics of the part stress thermal analysis and design techniques are described in Navelex Publication 0967-437-7010, July 1973.

Although each proposed system design requires a thermal performance analysis based on the specific characteristics of it, there are a number of standard general approaches associated with specific components that are beneficial in obtaining suitable thermal performance. Guidelines to achieve reliable design through temperature reduction of specific components are itemized in Table 8-44.

8-4.2.2 Mechanical Protection

Protection against environments in which mechanical damage can occur is generally achievable by use of suitable packaging, mounting, and structural techniques. The reliability impact of mechanical protection techniques is generally singular in that these measures do or do not afford the required protection against the stresses identified with mechanical abuse. In most cases trade-off situations between the level of protection and reliability improvements are not as pronounced as in the case of thermal protection. The one exception may be the case of fatigue damage in which the level of protection would have a significant impact on reliability if, in fact, fatigue were a primary failure mechanism in the normal life of the equipment.

8-4.2.3 Shock and Vibration Protection

The environmental resistance required to protect against specified shock and vibration stresses is generally determined by an analysis that evaluates the deflection and mechanical stresses produced by these envi-

TABLE 8-44. DESIGN GUIDELINES TO REDUCE COMPONENT OVERHEATING (Ref. 1)

1. *Semiconductor devices:*
   a. Minimize thermal contact resistance between the device and its mounting by using large area and smooth contacting surfaces and by specifying thermal gaskets or compounds as required.
   b. Locate away from high temperature parts.
   c. Use heat sinks with fins positioned vertically and parallel to air or coolant flow. To improve radiation characteristics, all devices other than glass housed devices should be painted black.
2. *Capacitors:*
   a. Locate away from heat sources.
   b. Insulate thermally from other heat sources.
3. *Resistors:*
   a. Locate for favorable convection cooling.
   b. Provide mechanical clamping or encapsulating material for improved heat transfer to heat sinks.
   c. Use short leads whenever possible.
4. *Transformers and inductors:*
   a. Provide heat conduction paths for transfer of heat from these devices.
   b. Locate favorably for convection cooling.
   c. Provide cooling fins where appropriate.
5. *Printed wiring boards:*
   a. Specify larger area conductors where practicable.
   b. Segregate heat producing elements from heat sensitive components.
   c. Use intermediate metal core layers in multilayered systems, and provide good conduction paths from these layers to support members and intermediate heat sinks.
   d, Use protective coatings and encapsulents for improving heat transfer to lower temperature supports and heat sinks.

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ronmental factors. This generally involves the determination of natural frequencies and the evaluation of the mechanical stresses within components and materials produced by the shock and vibration environment. If the mechanical stresses so produced are below the allowable safe working stress of the materials involved, no direct protection is required. If, on the other hand, the stresses exceed the safe levels, corrective measures, such as stiffening, reduction of inertia and bending moment effects, and incorporation of further support members, are indicated. If such approaches do not reduce the stresses below the safe levels, further reduction is usually possible by the use of shock absorbing mounts.

8-4.2.4 Humidity, Salt Air, Sand, and Dust Protection

It is often mandatory to provide protection of the elements of the system against dust, dirt, contamination, humidity, salt spray, and other environments that cause mechanical abuse. This type of protection does significantly improve the operational and reliability levels of the equipment.

Possible methods of protection against these environmental stresses include hermetic sealing, desiccants, and protective coatings. Hermetic sealing is often required when components such as solid-state devices must be operated in a controlled atmosphere. When selecting hermetic seals, consideration must be given to the effects of them on the thermal performance of the system and the resistance of them to cracking during thermal shock conditions.

There are many insulating compounds that are suitable coating materials for electronic component assemblies. Among these are epoxies, silicones, polyurethane, and polystyrenes. Generally, these are selected in accordance with MIL-I-46058 for military applications. Technical considerations for selection of suitable protective coatings are insulation resistance under the expected humidity and temperature conditions, dissipation factor, dielectric constant, mechanical flexibility, resistance to cracking during thermal shock, ease of removal for repair work, ease of application, and their ability to prevent the migration of corrosion products.

8-4.2.5 Radiation Protection

Radiation protection generally is the employment of specific preventive measures, such as shielding and filtering techniques that are effective in the frequency range of concern.

Nuclear radiation protection generally consists of the use of specific components having an intrinsic hardness and of the incorporation of shielding features that impart the required level of hardness to the system. Again, the provision of nuclear protection schemes is usually a go/no-go proposition because few trade-off situations are apparent.

8-4.3 GENERAL PACKAGING CONSIDERATIONS

The selection of a suitable packaging method for electronic equipment requires consideration of many trade-off factors in addition to the environmental protection factors already described. Factors that influence the choice of a packaging method include cost, size, producibility, maintainability, repairability, and reliability. In many cases, the system requirements are conflicting, and the selection process becomes one of identifying the packaging approach that offers the best compromise.

In military electronic systems, size, weight, and reliability are prime considerations, and the choice of packaging methods must reflect the priority of these factors. System packaging approaches are usually concentrated on microelectronic packaging systems because of size reduction and reliability benefits associated with semiconductor IC devices. Semiconductor IC'S offer reliability improvements because of their inherent properties and also because of the reduced number of interconnections that are needed. Further advantages arise from the highly controlled fabrication processes and techniques used in the manufacture of such devices. Table 8-45 illustrates a general ranking of trade-offs associated with electronic packaging techniques. For particular systems these ranking factors will vary depending upon the specific requirements of the system. However, the general order or ranking is believed to be appropriate for a large population of systems. Some pictorial examples of various packaging techniques are shown in Figs. 8-31 through 8-34.

8-5 ASSEMBLY AND PACKAGING CONSIDERATIONS

New packaging techniques emerge continuously to accommodate the complexity and miniaturization of electronic systems, The main thrust in producibility consideration is in the areas of printed circuit boards, cabling, solderless wire connections, flexible etched circuits, and part or component insertion techniques.

8-5.1 PC BOARDS: TRENDS (Ref. 16)

Standard FR-4* laminates now represent the bulk of the PCB business, and they will continue to do so for a long period of time. However, other newly developed materials are growing in popularity, and their share of the market has increased with time as shown in Fig. 8-35. For additional information concerning the manufacture of printed circuits, refer to MIL-STD-275 and MIL-STD-1569.

The PCB industry will use composite and polyester mat laminates at a faster rate than epoxy-glass cloth and paper-base materials. These newer laminates will capture a market share from both older materials. Composites and polyester mat will supplant epoxy-glass cloth laminates in some applications in which punching is more economical than drilling because they punch more uniformly and reduce tool wear. Similarly, composites and polyester mat will replace paper-base laminates in those applications needing improved strength.

The same technical expertise that went into fabricating highly reliable boards for aerospace applications is now going into consumer products such as hand-held calculators and wrist chronographs that provide the time of day and display solutions to difficult mathematical problems. The reinforced laminates have been filling the needs of a growing market for printed circuits with materials and technology developed over the past 25 yr. Today's users of laminated materials are concerned mainly with cost and reliability.

In spite of inflation, changes in material construction and process technology have successfully held epoxy-glass laminate pricing at relatively the same level. One major saving in laminating 1.57-mm (0.062 -in.) stock has resulted from the use of six plies of thicker glass cloth in place of nine plies of thinner cloth. This construction reduces the number of yards of cloth processed and the number of pieces handled; however-, fewer plies of thicker glass cloth layers present problems for some users.

For those who have problems processing thick-ply laminates, the large fibers can interfere with drilling clean holes and can increase epoxy smear. These fibers may reduce hole-plating integrity and cause dielectric leakage by absorbing and storing chemicals used during processing. The larger the fibers, the worse the problems. Yet a good number of thick-ply laminate users can process the material into circuit boards with relatively few problems.

Customers can also save costs by reducing laminate thickness. For example, the industry standard today is 1.4 mm (0.055 in.) instead of the 1.57 mm (0.062 in.) of the past. When designers begin to call for circuit boards only thick enough to support the electronic components used, they will reduce laminate thickness even more. Customers are using 1.19- and 0.81-mm (0.047- and 0.032-in.) laminates whenever these thicknesses can satisfy the mechanical strength required. In the future, the introduction of new cloth styles will reduce the number of plies even farther.

By punching holes rather than drilling them, users can reduce production costs substantially. But punching is feasible only for high volume boards; for a run of 10,000 boards per yr, the $15,000 to $20,000 cost of a piercing and blanking die represents too much of an investment.

A breakthrough in reduced cost of processing has made multilayered printed boards more attractive to

---

* FR-4 = Sheet of continuous-filament-type glass cloth with epoxy resin binder.

TABLE 8-45. PACKAGING TRADE-OFFS (Ref. 1)

Type of Packaging	Characteristics					
	Size	cost	Throwaway cost	Reliability	Maintenance Repair	Logistics/ Repair Parts
Soldered modules on boards	P	F	G	P	F	F
Welded modules on boards	P	P	F	P	F	F
Hybrid modules (with integrated circuits)	F	P	F	F	F	F
Hybrid compartmentalized	F	P	F	F	F	F
Etched circuits	F	P	F	F	F	F
Pluggable flat-pack modules	F	F	G	P	G	F
Flat-pack integrated circuits printed wiring board	G	G	G	F	G	G
Welded flat-pack IC stack	G	P	P	F	P	F
Thin-film circuits	G	G	F	F	P	F
IC chips	G	G	P	G	P	P
Large-scale integration	G	G	P	G	P	P
MOS devices	G	G	P	G	P	P

G = good; F = fair; P = poor

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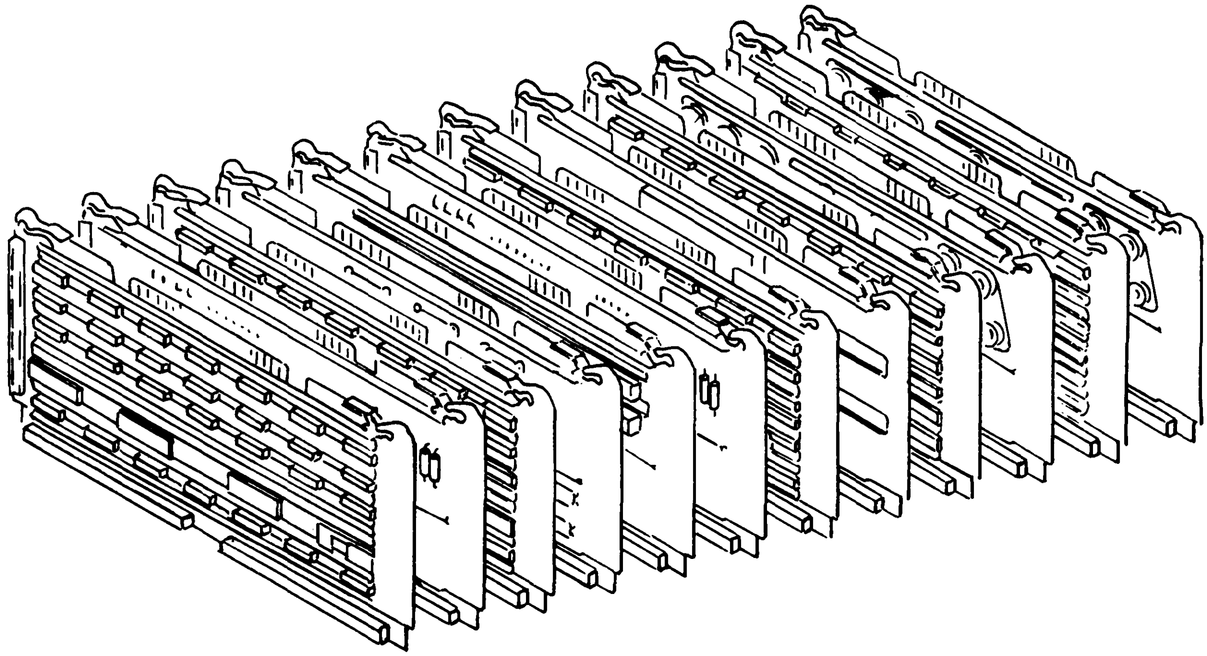

Figure 8-31. Typical PCB Network (Ref. 14)

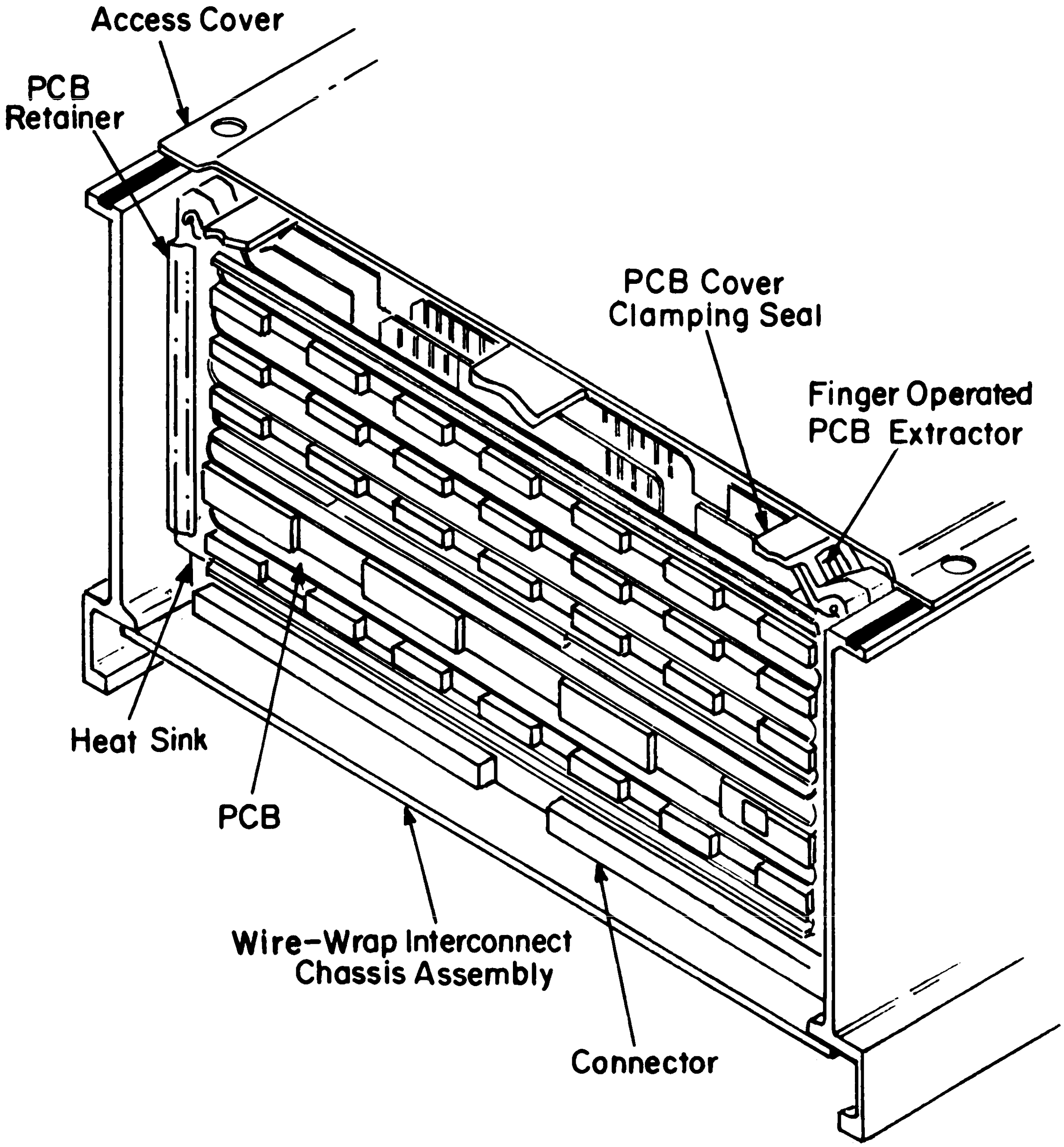

Figure 8-32. Packaging Example of a Multiple PCB Network (Ref. 14)

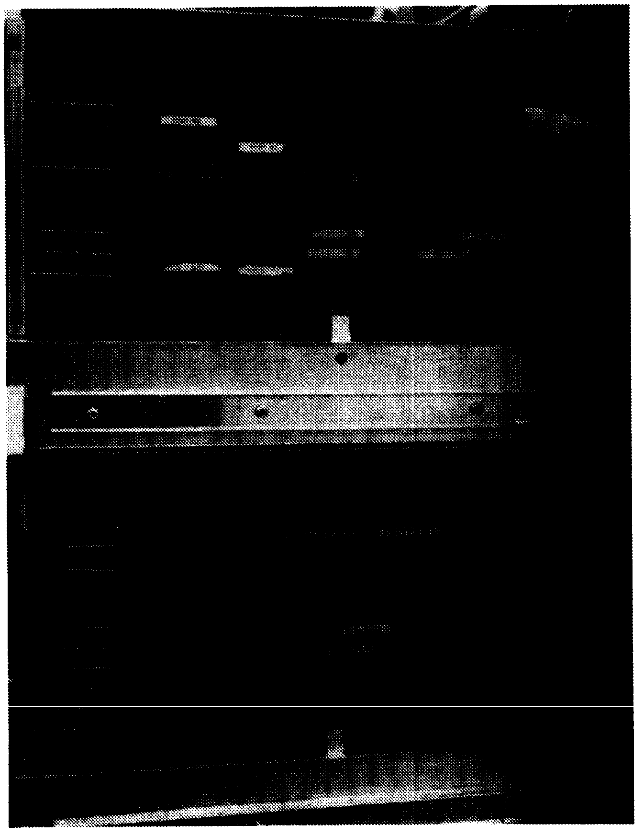

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Figure 8-33. Packaging Example of a Digital System (Ref. 10)

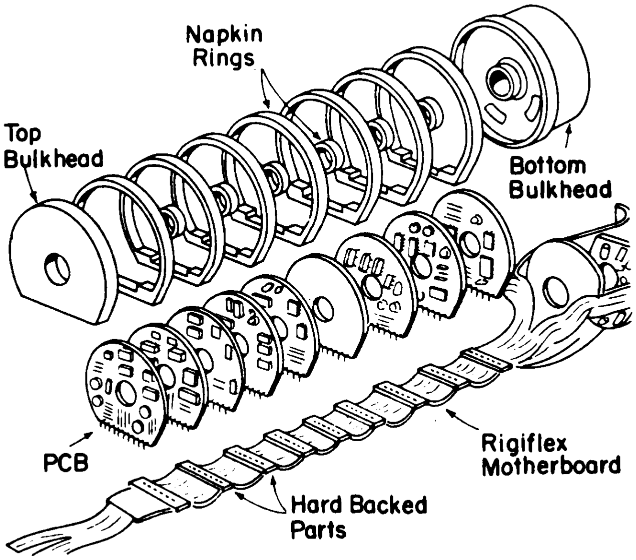

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Figure 8-34. Packaging Example of Copperhead Projectile Built to Absorb 9000g When Fired From 155-mm Howitzer (Ref. 15)

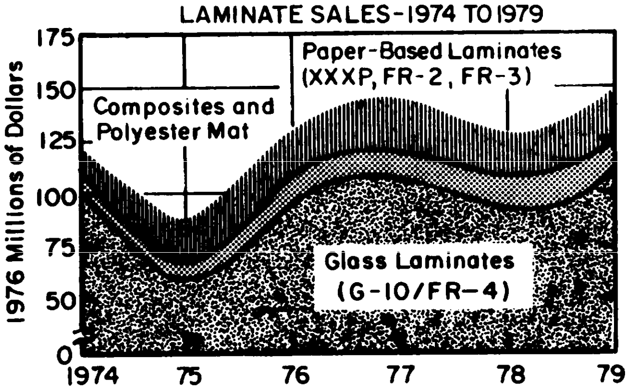

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Figure 8-35. Present Trends in PCB Materials (Ref. 16)

use in commercial and industrial applications. This breakthrough is attributable to the process called mass lamination. The name is given to large-scale multilayered production that occurs in the order indicated in Fig. 8-36. The first step consists of printing and etching a thin laminate or core material into a double-sided board. Next, the etched core is placed on the center of a laminated package (usually five packages per press opening) and clad with prepreg and copper to a predetermined overall thickness. The sheet size approximates 610 x 914 mm (24 x 36 in.). Since these sheets

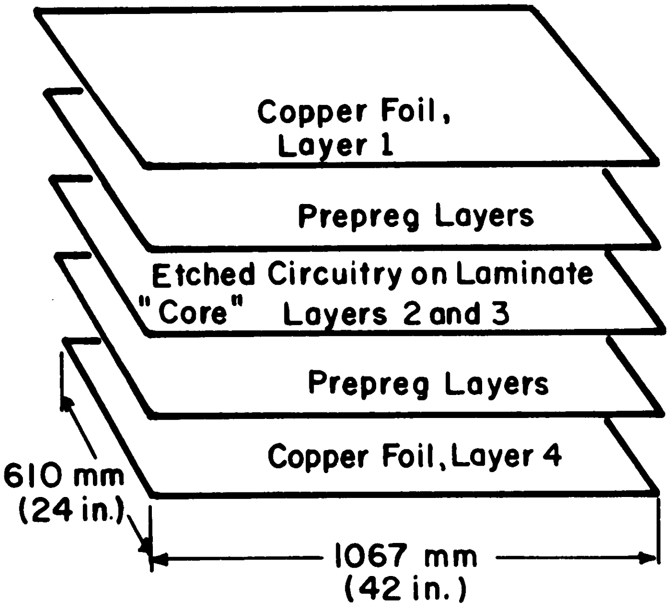

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Figure 8-36. Multilayered PCB Manufacturing Process (Ref. 16)

contain 12 or more layers, this type of processing is relatively inexpensive.

8-5.2 FLAT CABLE (Ref. 14)

To overcome the complexity and miniaturization of electronic systems, flat cable is ideally suited as a replacement for bulky conventional cable harnesses. Preformed shapes are available for use as jumpers (Fig. 8-37), hinges (Fig. 8-38), or as expandable roll-up jumpers (Fig. 8-39). Flat cable is available for use with many different connector housings including transitions from flat to round connectors as in (Fig. 8-40). The leads of flat cable can be terminated in individual pins. Terminations can be made by crimping, soldering, or welding. The cable can be made of insulated round wires that can be bonded to each other or woven together by using synthetic, metallic, or natural fibers. Flat conductors insulated with Mylar, Teflon, or other inert materials are also available. Various thicknesses and widths are available, and if required, the cable can be shielded.

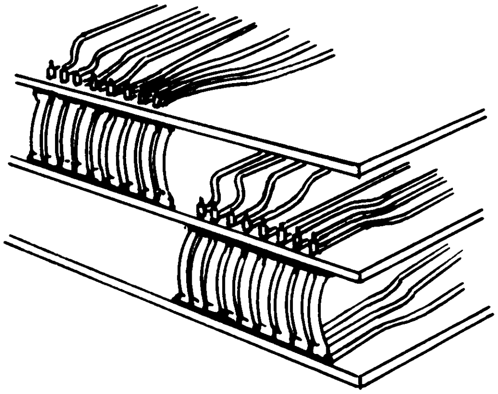

Figure 8-37. Flat Cable Used as a Jumper (Ref. 14)

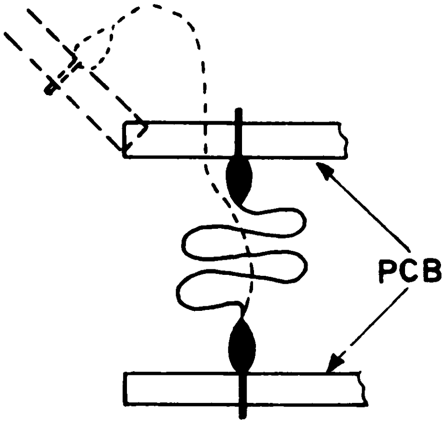

Figure 8-38. Flat Cable Used as a Hinge (Ref. 14)

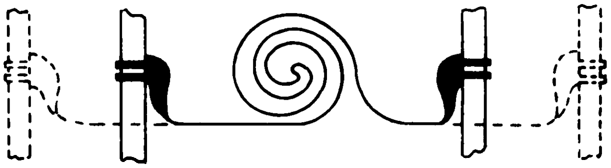

Figure 8-39. Flat Cable Used as Expandable Roll-Up Jumper (Ref. 14)

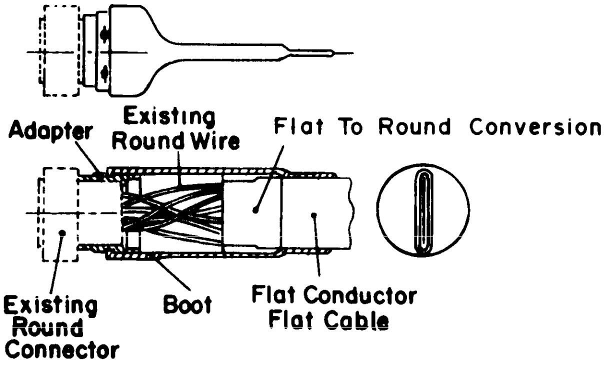

Figure 8-40. Flat to Round Connector (Ref. 14)

Flat cables are very useful in areas having restricted room or access. They can be solder assembled in the open and plugged onto a circuit board to eliminate the possibility of damaging components or other wiring during the soldering operation. The reliability of flat cables increases with the use of thinner wire and insulation because less flexure and bending stress will be experienced. Flat wire cables can be used in restricted areas where a conventional harness will not fit. In case of damage, individual wires can be replaced by bonding, reweaving, or splicing new wires into place. With flat cable it is possible to optimize economies in space, weight, and cost even when the total design requires the use of custom-made cables.

8-5.3 SOLDERING

The American Welding Society defines soldering as: ... a joining process which produces coalescence of materials by heating them to a suitable temperature and by using a filler metal having a liquidus not exceeding 450°C (840°F) and below the solidus of the base materials.", The filler metal is distributed between the closely fitted surfaces of the joint by capillary attraction.

Soldering is a major means of making electrical connections in all phases of electronic packaging including

1. PCB
2. Module
3. Terminal board

4. Interconnecting wires
5. Thin- and thick-film circuits
6. Hybrid circuits
7. Connectors and cables.

Some of these subassemblies can be soldered by use of a. soldering iron, others by means of more sophisticated processes, e.g., wave soldering or cascade soldering automatic equipment. MIL-HDBK-217, *Reliability Prediction of Electronic Equipment,* lists the failure rates that follow for the soldering connections:

Connection	Failure Rate Failures/10^6h
Hand solder connection	0.00440
Wave solder connection	0.00044
Reflow lap solder connection	0.00012

8-5.3.1 Hand Soldering

Hand soldering is done with a soldering iron. In electronic assemblies, especially in assemblies of high component density, it is important to safeguard the part from being overheated. For this reason the soldering should be accomplished using only the amount of heat necessary to provide the optimum solder connection.

There are several types of soldering irons available that are geared specifically for the particular type of operation. They are

1. Instrument irons for light soldering tasks
2. Industrial irons for production operations
3. Heavy-duty industrial irons for high-speed production soldering operations
4. Temperature-controlled irons for soldering of temperature-sensitive devices (e.g., semiconductors); power supplied to the soldering element is controlled by a thermal sensor located at the tip.
5. Pencil irons, same as instrument irons except they operate at low voltage, usually below 12 Vac
6. Soldering guns for intermittent operation like repair of electronic equipment.

8-5.3.2 Wave Soldering

The wave soldering process involves passing the PCB over a liquid solder wave that is generated by a pumping mechanism. The wave is approximately 25 mm (1 in.) high and can vary considerably in width depending on application. The wave provides heat to the areas to be soldered as well as solder to the parts to be joined.

Since the entire PC surface is exposed sequentially to the heat of the solder as it passes over the wave, the thermal stress on the board and the cooling effect on the solder are considerably reduced. The fluid motion of the molten solder minimizes the chance that solder oxidation will come in contact with the board, which reduces bridging and icicling; both of which were quite common in dip soldering. Blowholes, however, cannot be eliminated since the board passes over the solder wave in a horizontal position.

8-5.3.3 Cascade Soldering (Reflow Lap Soldering)

An improvement over the wave soldering method is accomplished in a process called cascade soldering. Here a solder waterfall is constructed by pumping the molten solder to the top of the steplike structure (cascade) and letting it flow to the lower level.

Due to the nature of the cascade the PCB passes over the steps of the solder at a slight angle, which permits the escape of the trapped air and eliminates the probability of the formation of blowholes. The soldering operation of the PCB can be conveyorized as shown in the simplified diagram, Fig. 8-41.

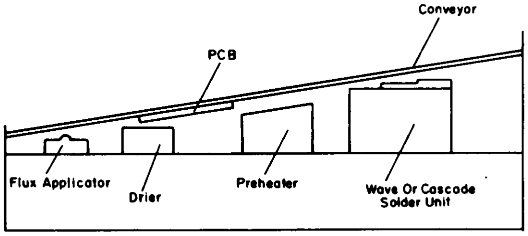

Figure 8-41. Cascade Soldering

8-5.3.4 Fluxes and Fluxing Methods

A soldering flux is usually a liquid or solid substance that, when heated, promotes the wetting of the surfaces to be joined by solder. Flux tends to remove metal oxides, prevent reoxidation, and lift other impurities from the areas to be soldered.

Fluxes are subdivided into three categories that depend on their ingredients:

1. Noncorrosive
2. Intermediate
3. Corrosive.

Noncorrosive flux is most common in the electronics industry because flux residue is noncorrosive and nonconductive. Resin is the main ingredient in the noncorrosive flux. Its characteristics are such that the active component of resin is inactive when solid, active when melted (127°C to 315°C), and again inactive when cooled.

Resin fluxes are manufactured in three types, namely, nonactivated (R), mildly activated (RMA), and activated (RA). Nonactivated resin flux contains no additives and is covered by specifications MIL-F-14256 and Federal Specification QQ-S-571. Mildly activated resin flux contains additives that improve the fluxing action of the resin but leave noncorrosive and nonconductive residues. MIL-F-14256 and QQ-S-571 specifications cover this flux also. Activated resin flux contains complex organic compounds as additives in an amount varying from 0.2% to 5%. The use of the activated resin flux is not permitted in electronic equipment because the problem of harmful flux residues cannot be easily solved.

Because of harmful flux residues, use of intermediate and corrosive fluxes has minimal, if any, application in the electronics industry.

8-5.4 SOLDERLESS WRAP ELECTRICAL CONNECTIONS (Refs. 14 and 17)

A wire-wrap connection consists of a helix of continuous solid wire wrapped tightly around a rectangular or square post as shown in Fig. 8-42. The wrapping provides a gastight joint that will have greater flexibility, density, serviceability, and reliability than solder or crimp terminations.

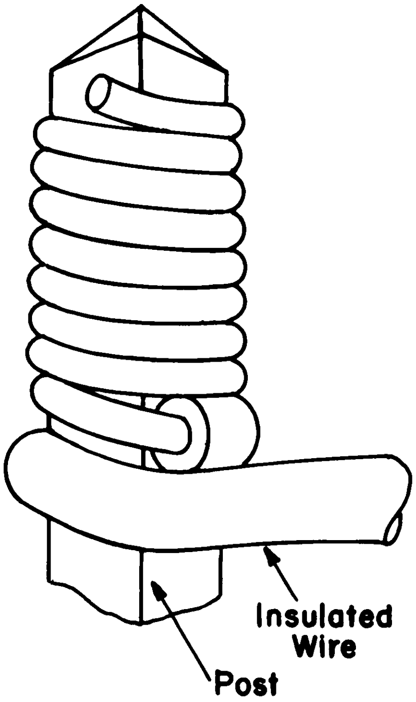

Figure 8-42. Typical Wire-Wrap Connection (Ref. 14)

A gastight area is defined as that area between the wrap post and wire, which, due to the quality of the wrap, will exclude gas fumes. This wrapped connection—except for the first and last turns—shall, for each turn, exhibit a gastight area on at least 75% of the corners in contact with the uninsulated wire. The procedures for obtaining a gastight joint are covered by MIL-STD-1130.

Maintainability is increased because the unit can be repaired easily, and the wrap posts can be replaced without removing or damaging adjacent contacts. If circuit design changes are required, the wire(s) can be removed and new ones wrapped in their places. It is ideal for systems having a high number of interconnections because it eliminates requirements for multilayered circuit boards. The unit is easily repairable because all connections are visible as shown in Fig. 8-43. Reliability is high because the connections are resistant to corrosive atmosphere, severe shock, and vibration.

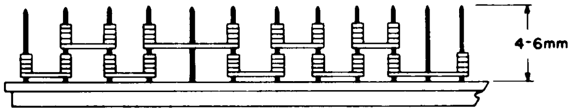

Figure 8-43. Example of a Multiple Wire-Wrap Board (Ref. 14)

MIL-HDBK-217 shows the failure rate for wire-wrap connections as 0.0000037 failures per 10^6 h. For this same period of time, hand soldered connections (wires to terminals) experienced 0.00044 failures, and reflow lap solder to printed wiring boards experienced 0.00012 failures. Wrap posts are available for use in a standard glass epoxy board or are insulated and used in a metal chassis. The interconnection can be made using number 26 American Wire Gage (AWG) to number 30 AWG solid insulated wire.

8-5.5 STITCH WIRING (Refs. 14 and 17)

Stitch wiring combines the flexibility of a point-to-point wiring system with the low profile and high packaging density of multilayered boards. There are at present two approaches to this type of assembly as shown on Figs. 8-44 and 8-45.

The first method (Fig. 8-44) uses a stainless steel terminal as a welding surface and can have either wires

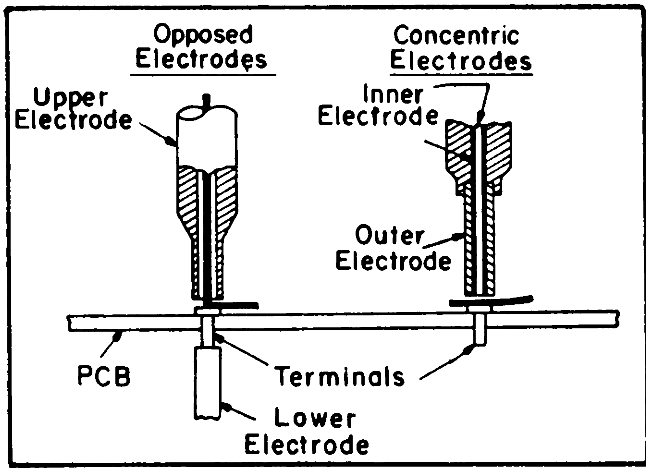

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Figure 8-44. Stitch Wire With Terminals (Ref. 17)

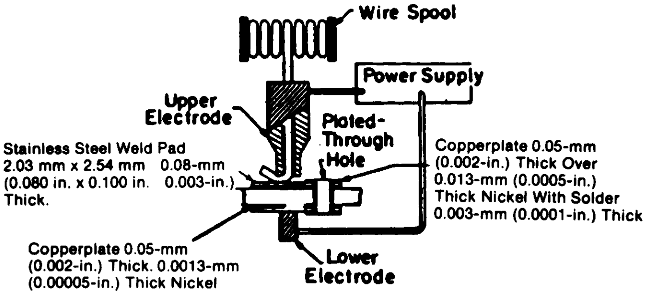

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Figure 8-45. Stitch Wire With Pads (Ref. 17)

or components welded and/or soldered to them. It is a two-sided, copper-clad wiring board. Holes are drilled at pad locations, but they are not plated through. Stainless steel terminals plated with a nickel and gold alloy are pressed into these holes and, where required, are soldered to the pads on both sides of the board. Components are soldered or welded to one side of these terminals, and wires are welded to the other side.

The second method (Fig. 8-45) uses an epoxy glass board clad on both sides with stainless steel. The double-clad stainless is etched to form a pattern of rectangular pads. Holes are drilled and plated through with a copperplate area on both sides to join the top and bottom pads, and components are inserted into these holes and soldered. The interconnecting wires are then welded to the stainless steel pad areas on either side of the board.

The termination in either case is a resistance welded joint between a Teflon-coated nickel wire conductor and the stainless steel pad or terminal. The wire passes through the center of the upper, hollow, cylindrical electrode (Figs. 8-44 and 8-45), and when this electrode is lowered, the wire insulation is mechanically displaced, which permits metal-to-metal contact between the upper electrode, wire conductor, and the stainless steel pad or terminal. After contact is made, a current pulse is passed through the wire and pad and forms a resistance welded connection. (See Fig. 8-46.)

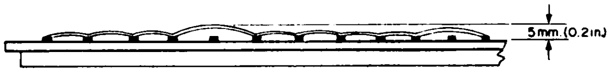

Figure 8-46. Example of a Stitch-Wired Board (Ref. 14)

Stitch wiring has been used on several airborne, space, and computer applications and is one solution to high density circuitry. The use of a two-sided board with stitch wiring on both sides can attain the same density as that of a six- to eight-layer printed wiring board. Stitch wiring is a relatively new process, and the failure rates for this process are not yet included in MIL-HDBK-217. As covered by MIL-HDBK-217, resistance welding, based on welded module construction, had a failure rate of 0.0019 failures per 10^6 h. The cost of a stitch-wired board is approximately five times as great as the cost for a conventional, two-sided circuit board. This type of construction is only recommended for use in very tight packages in which component density would require the use of multilayered printed wiring boards.

8-5.6 FLEXIBLE, ETCHED CIRCUITS (Ref. 14)

Like flat cable, flexible, etched circuits (Fig. 8-47) save space and weight; drastically reduce assembly, checkout, and rework time; and eliminate human errors in comparison to point-to-point discrete wiring. The present availability of copper and film dielectrics in a variety of materials offers unlimited design capabilities relative to circuit board layout with resulting savings in weight, size, volume, and cost.

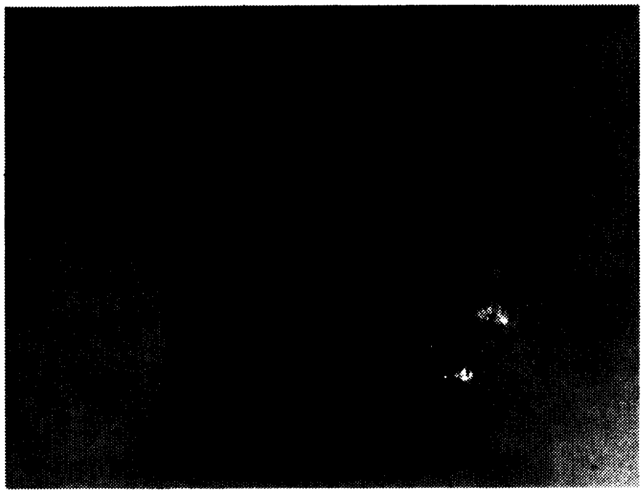

Figure 8-47. Examples of Flexible Circuits

Usually produced as custom designs for specific applications, flexible, etched circuitry is not restricted to the use of parallel conductors. It can be just as complex as any of the rigid boards but have the added advantage of being able to go around corners and, therefore, be useful in tight, irregular shapes. Etched circuitry can be used for interconnections between connectors, wiring boards, submodules, and if properly supported, individual components.

8-5.7 COMPONENT INSERTION EQUIPMENT (Ref. 10)

A PCB assembly consists of component lead preparation, component insertion, and the soldering operation. This subparagraph concerns itself primarily with component insertion decisions. The first decision to be made is to choose between manual or automatic insertion methods. This decision depends mostly on lot size, type of components, and labor and equipment costs. Table 8-46 shows the relation of assembly method to types of components to be mounted on the PCB.

TABLE 8-46. COMPONENT MIX VERSUS ASSEMBLY METHODS (Ref. 18)

Type of Components	Assembly Methods
Mostly discrete components (50 to 500 total count) Up to 20 IC (DIP)	Single operator, bench, and trays Single operator, component locator Group operation, progressive line Single operator, automatic axial lead insertion
Mixed discrete and IC 50 to 200 discrete 20 to 100 IC (DIP)	Single operator, component locator Single operator, bench, and trays Single operator, semiautomatic DIP insertion
Mostly IC (DIP) 20 to 200 IC (DIP) O to 50 discrete	Single operator with templates and DIP dispenser Single operator, component locator Semiautomatic DIP inserter Fully automatic DIP inserter

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Table 8-47 shows a simplified categorization of component insertion equipment, which lists insertion rate (parts per hour), positioning technique, additional features, and the price range. Table 8-47 can be used in the decision making process and/or preliminary production cost estimates. Figs. 8-48 and 8-49 show manual and semiautomatic insertion systems.

Fully automated insertion systems are available and can be considered. These are complex systems that can be built in a variety of ways and can be considered as extensions of the semiautomated systems. Hence no sketch is included. Several automated systems are discussed.

8-5.7.1 Manual Insertion and Semiautomatic Systems

Assembly directors offer an efficient method of circuit board assembly at low cost. The latest version by Ragen Precision Industries provides a degree of automation in seven different assembly applications: PCB component insertion, cordwood assembly, point-to-point soldering, harness lay-in wiring, mechanical assemblies, point-to-point wire wrapping, and component interconnection.

The Ragen system delivers, sequentially or via random access, parts, components, or wires to the operator or directs the operator to the correct part by lighting bins mounted on the system console. Simultaneously, an overhead projector flashes an arrow or dot, depending upon the application, that indicates the exact insertion location, assembly, or interconnection site. The system is run by standard numerical control (NC) tape punched to an Electronic Industries Association (EIA) code.

The Manix (Henry Mann, Inc.) system is driven by a cassette-loaded filmstrip read electronically by the projector. The system provides rotary delivery of various parts, individually in any sequence, to an illuminated aperture, while a projected light image indicates where the component is to be placed. Peripheral information or instructions can also be projected during each sequence. Paced production is possible by programming the exact insertion time for each component.

An assembly director offered by Heller Industries employs fiber optics to project color-coded lighting from under the PCB. The fibers illuminate the proper holes for each sequenced insertion for a group of identical components. When the set of illuminated holes is filled with the proper component, the operator depresses a foot switch to deliver the next component bin and also to illuminate a new set of holes. The programming supplies consist of precut lengths of plastic, monofilament light guide, color-coding dye, and light-sequencing heads, together with a representative PCB with holes drilled at a 1.27-mm (0.050 -in.) diameter.

For DIP, Heller supplies a microprocessor-controlled sequencing dispenser. The system allows storage of a variety of DIP in predetermined tubes and distribution of the DIP in a predetermined sequence for manual insertion. The system consists of a data entry keyboard, LED program information display, and one or more controlled ramps, each of which contains 20 DIP storage tubes.

Systems featuring manual board handling with automated component insertion have been pioneered by Amistar. Edwin Booth, Amistar's manager of marketing, reveals that market studies show the existence of three general areas: hand insertion, fully automatic, and a gray area somewhere in-between, i.e., semiautomatic. Booth adds, "Semiautomatic DIP and axial

TABLE 8-47. TYPES OF COMPONENT INSERTION EQUIPMENT (Ref. 18)

Type of Handling PCB and Parts	Insertion Rate, Parts/h	Positioning	Additional Features	Price Range
PCB manual Parts manual	1000	Light image projected on PCB	Leads cut and clinched	$5,000-$15,000
PCB manual Parts automatic	1500	Light image projected on PCB; sequencing by tape or memory	Leads bent to hold DIP in place	$10,000-$15,000
PCB positioning by pantograph Parts automatic	2000	Sequencing controlled by tape or minicomputer	Leads bent to hold parts n place	Axial inserters $10,000-$15,000 DIP inserters $25,000
PCB automatic Parts automatic DIP variable center distance (VCD)	4000	Minicomputer	Leads bent to hold parts in place	$50,000-$70,000

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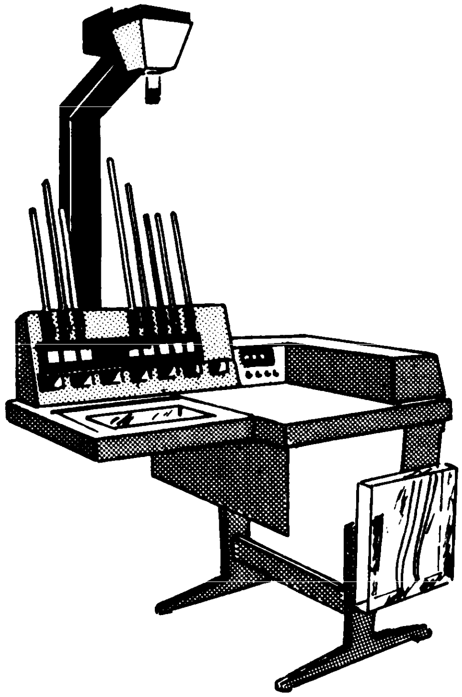

Figure 8-48. Manual Insertion System

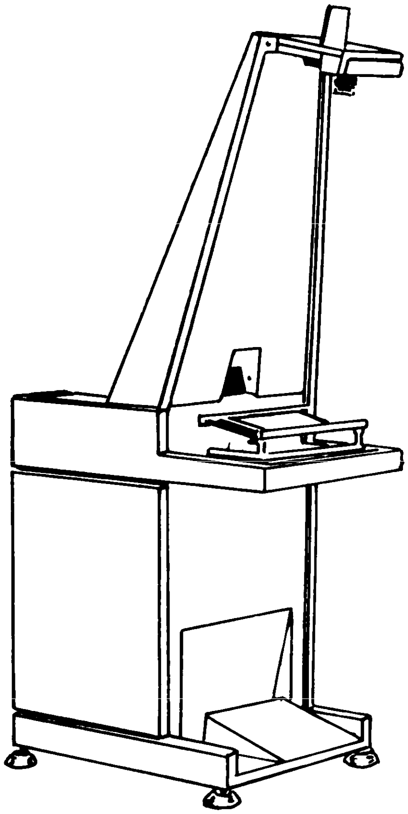

Figure 8-49. Semiautomatic Insertion System

inserters bring automation to the short- to medium-run assembler. We see the size of this market as being equal to the hand insertion and fully automatic markets combined.”.

Amistar’s DIP inserter incorporates a sensing device for insuring proper location of the board before insertion. The insertion head also straightens bent DIP leads before each cycle. The axial inserter of the firm sequentially inserts axial-lead components from preloaded cartridges. The system forms the component into a staple shape, inserts it into the hand-held PCB, and then clinches the leads.

The DIP insertion machine by Universal is a semiautomatic machine that can be conveniently mounted on a workbench or tabletop. Two versions of the machine are presently available: A 16-magazine model handles 7.62 mm (0.300 in.) wide DIP’s with up to 20 leads, and a 12-magazine model handles 15.24 mm (0.600 in,) wide DIP’s with up to 40 leads. The magazines are mounted above an inclined track onto which the DIP’s are dispensed. The DIP’s are gravity fed to the spreader assembly and are transferred to the insertion head. They are then inserted, and the leads are cut and clinched.

Universal’s manual assembly machine has an adjustable tabletop and board holder, board positioning system, 25-position image projector, 4-digit decimal display of pattern step number and parts bin number, 60-or 80-station sequential rotary parts bin, and an adjustable clinch-angle setting. The automatically controlled functions include moving the board to the insert position, controlling a projector assembly that displays an image indicating the insert position on the circuit board, positioning the rotary parts bin, and controlling the orientation and cycling of the cut-and-clinch assembly.

Contact Systems claims that for boards with a mixture of discrete axial components and DIP’s, the trend is away from paced lines and toward a wider use of assembly directors. Contact also claims that assembly directors are more efficient than progressive lines in small-quantity PC assembly. Also PC assembly has traditionally been the entry level shop job, i.e., the quality work ethic may not have been developed yet. The cost of assembly errors is skyrocketing because of higher component cost and technician test time. Assembly directors provide on-line quality control not possible with paced lines.

SPi Products offers a semiautomatic DIP inserter with a 25-stick storage magazine, which allows random selection via a small tape reader. The system is designed for situations in which the customer is doing hand insertion and is ready to upgrade to a mechanized insertion system.

8-5.7.2 Fully Automatic Systems

Component locating systems with hand insertion are most effective when the user is inserting large population of axial lead devices in comparison with the number of DIP’s. However, when the volurne of DIP’s being inserted approaches approximately 250,000 per year, the user should begin to consider seriously switching to automated DIP insertion and using a semiautomatic system. Pantograph insertion systems begin to be justifiable in the range of 2.50,000 to 500,000 DIP’s per year, and fully automatic DIP insertion systems are justifiable at insertion volume of 1,000,000 DIP’s per year and up.

SPi’s fully automatic DIP inserter has a servpositioned table with NC or computer control. The magazine consists of a lightweight metal assembly that can accommodate 50 sticks of different types of DIP’s. Each stick in the magazine has its own escapement and can be individually removed. SPi uses gravity feed and vacuum forces to provide a “soft” handling system for transporting the DIP to the insertion head. All three manufacturers of fully automatic DIP insertion equipment condition the leads prior to insertion. In the SPi system, pneumatic anvils position the leads for proper registration.

Universal Instruments’ newest DIP inserter can insert DIP’s with lead spans of 7.62, 10.16, and 15.24 cm (0,300, 0.400, and 0.600 in.) by substituting or resetting the tooling in the insertion head, magazine, and cut-and-clinch assemblies. The machine is available with options to accommodate 8, 12, 16, 24, 32, or 48 sticks.

Universal dual-head VCD axial-lead inserter offers a 457 x 457-mm (18 x 18-in.) insertable area under each head. An insertion head is availably for the insertion of disc capacitors, which have been properly prepared and taped in axial-lead configuration. Insertion heads are also available for inserting components in stand-up hairpin orientation. The firm’s Satellite Controller provides a pattern program library, management information, full on-line editing, and a dynamic diagnostic display. A single controller can drive and monitor up to eight different insertion machines or sequencers with each performing a different operation. The system is available as a single machine controller with add-on capability for future expansion.

The industry’s fully automatic class of insertion equipment has been significantly improving over the past few years. Production rates of up to 17,000 components per hour for dual-head and axial-lead machines and 4000 components per hour for DIP inserters have been achieved.

Development of the on-line component testing option for sequencing machines allows the testing of axial-lead components while the sequencer is opera t-ing. The testing mechanism tests at the same speed—about 19,000 components per hour—as the running speed of the sequencer.

8-6 DESIGN TO MINIMIZE RELIABILITY DEGRADATION DURING PRODUCTION AND USE

The reliability estimate, i.e., MTBF, computed when using MIL-HDBK-217 prediction techniques, does reflect the reliability potential of a system or component item during its useful life period. This estimate depicts the inherent (or potential) reliability of the design as defined by its engineering documentation, basic stress/strength design factors, and gross application factors. However, the estimate does not represent operational reliability unless design failures have been eliminated, manufacturing and quality defects have been minimized, and operating and maintenance procedures have been optimized. Therefore, to insure high field reliability, special efforts to minimize reliability degradation must be applied during system design and development, production, and operation and maintenance. Lack of effort in these areas can result in system reliability as low as 10% of its inherent reliability.

Furthermore, experience has indicated that the degree of degradation is directly related to the degree of inspectability and maintainability built into the system. The purpose of this subparagraph is to provide information and guidelines to design for ease of inspection and maintenance, thus providing the means to minimize production and use degradation. However, no degree of inspection and/or maintenance can correct poor design.

8-6.1 CONTRIBUTIONS TO RELIABILITY DEGRADATION

Those factors that contribute to unreliability and that can be controlled during production and use are discussed herein. The specific objectives of this subparagraph are to

1. Provide insight into basic fabrication and assembly processes that can be planned and traded off during design to minimize degradation effects
2. Establish the conceptual framework for viewing operator maintenance procedures as contributors to operational unreliability
3. Estimate the advantage of additional process controls, tests, or better inspection.

The key to minimizing and controlling reliability degradation is to estimate the defects introduced by production and maintenance. Two types of defects must be considered—quality defects and reliability defects. Quality defects are defined as those defects that can be located by conventional inspection; reliability defects are those defects that require some stress applied over a time interval to develop into a detectable defect.

As an example of the two types of defects, consider a resistor with the leads bent close to its body. If the stress imposed during bending causes the body to chip, this is a quality defect. However, had the stress been sufficiently low as not to chip the body, the defect would go unnoticed by conventional inspection. Temperature cycling can produce small stress cracks in the body that would allow moisture and other gases to contaminate the resistive element causing resistance changes. This is a reliability defect R(t). This defect is also a design defect if the design specifications require a tight bend to fit the component properly in a board, If the improper bend is due to poor workmanship, the defect is classified as an induced defect.

Table 8-48 shows some of the processes involved in the manufacturing of an electronic assembly and identifies some of the associated defects and resultant failure modes.

The operation and maintenance of equipment in normal field usage also induce defects. It has been shown that operators in the field will stress systems beyond the predicted levels through neglect, unfamiliarity with the equipment, lack of adequate test equipment, carelessness, or mission demands, Also maintenance, scheduled and unscheduled, may degrade reliability. During unscheduled maintenance good parts may be replaced in an effort to locate the faulty parts. In many cases the good parts may be written up as defective rather than being reinstalled. These parts often are returned to depot for repair or are discarded, which indicates a failure rate higher than is actually occurring. The possibility also exists that these reworked parts—which eventually become repair parts—are not returned to the same level of reliability as that realized when they were initially procured. Scheduled maintenance also may introduce defects into satisfactory assemblies. These defects are due to foreign objects left in an assembly, bolts either not tightened sufficiently or overtightened, dirt injection, parts replaced improperly, and use of improper lubricant.

These induced defects and operational stresses, along with the influence of the environment, are factors that must be controlled and accounted for in the analysis of reliability. In general, the environmental factor considered in handbook prediction techniques accounts for the added stress provided by operation within that environment. However, the environmental stresses imposed during maintenance may be other than those anticipated during prediction. For instance, a subassembly removed for repair in a desert area may be placed in direct sunlight while awaiting transfer. Component temperatures may exceed those experienced during an extended period of normal operation; therefore, component life expectancy is reduced. Mechanical stresses imposed on components during removal,

TABLE 8-48. PRODUCTION PROCESS AND ASSOCIATED DEFECTS (Ref. 1)

General Process	Induced Defects	Failure Mode				
		Intermittent	Short Circuit	Open Circuit	Value Change	Noise
Wire stripping	Nicked lead			x		
	Broken strands		x			
	Short leads	x		x		X
	Long leads		x			
Soldering	Excessive heat			x	x	x
	Insufficient heat	x		x		x
	Excessive solder		x			x
	Insufficient solder	x		x		x
Lead cutting	Dull tools (shock)	x		x	x	x
Crimping	Wrong tool	x		x	X	X
	Wrong terminal		x			
	Low force			x		
	Excessive force	x		x		
Wire wrapping	Broken wire			x		
	Loose connection	x		x		x
Lead bending	Stress on case	X	x		x	x
Wire dress	Vibration sensitivity	x	x	x		x
	Residual stress	x	x	x		x

repair, and reinsertion may exceed the stresses for a given environment. Therefore, all maintenance procedures should be evaluated and controlled to minimize maintenance induced defects.

Reliability degradation control involves concepts related to inspection—frequency of, type, location, and efficiency. A key facet of reliability degradation control is the determination of the efficiency of inspections—incoming, production, final, and field inspections. It should be recognized that no inspection procedure is perfect. The possibility or the probability of an error in an inspection procedure is a function of a number of factors; some of which are

1. Probability that all component functions are exercised by the test performed
2. Reliability and calibration of test fixture and equipment
3. Probability of inspector error
4. Complexity of item inspected
5. Inspection instructions, criteria, etc.
6. Sampling plan,

The efficiency of an inspection can be expressed as a probability of detecting a defect, and it will have a numerical value between 0 and 1, i.e., a perfect or error-free inspection would have an associated numerical value of 1. Inspection efficiency may also be expressed as a percentage.

The factors that influence inspection efficiency can be expressed as probabilities, which are the tools for calculating the detection of a defect. As an example, assume there are four independent factors that influence a particular inspection. Further assume that the probability of detecting each factor is 0.9, The probability of inspection (i.e., inspecting efficiency assuming that each inspection is independent of the others) is $(0,9)^4$ or about 0.66. Thus even though the probability of detecting each factor is relatively high, the collective probability, or the inspection efficiency, is relatively low. This illustrates one of the difficulties of obtaining a perfect inspection.

As previously discussed, conventional inspections are designed to remove quality defects; however, since inspections are not perfect, all quality defects will not be removed. Fig. 8-50 is an example of how inspections can be used to reduce the number of quality defects in a component.

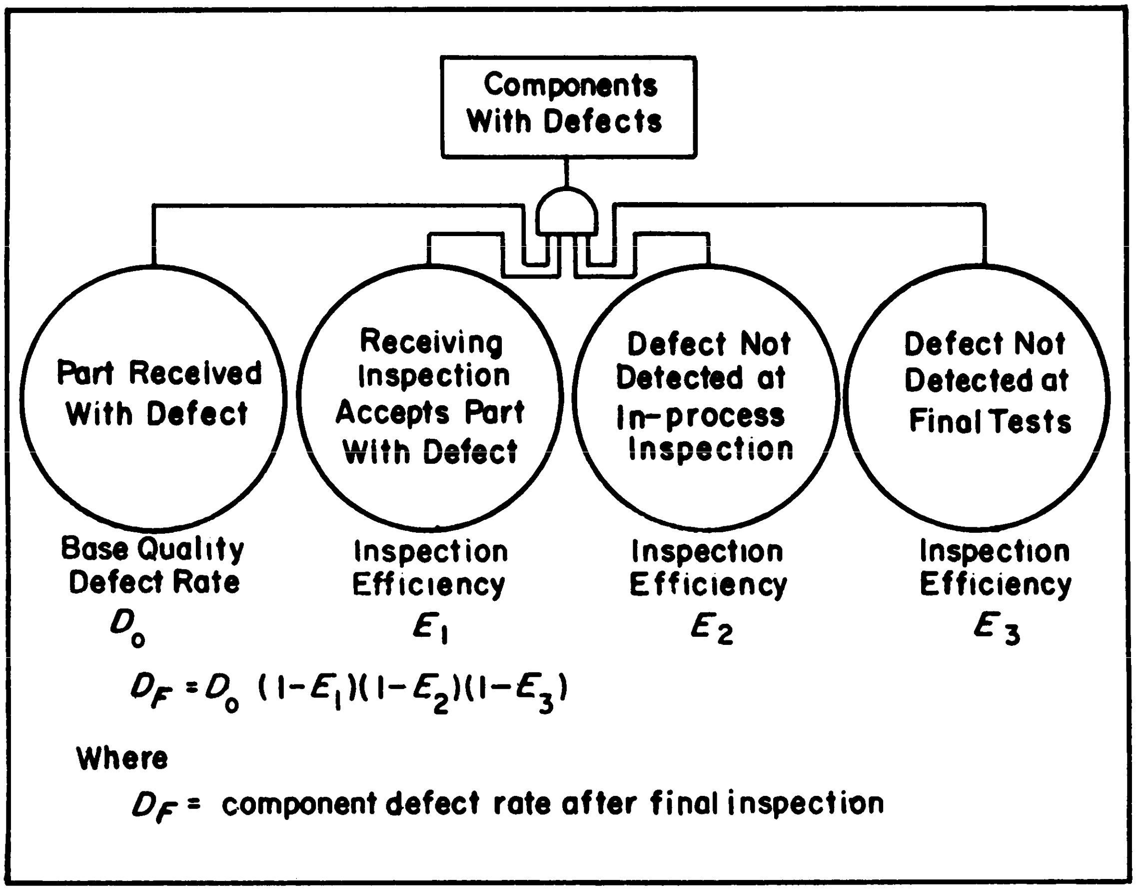

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Figure 8-50. Fault Tree Diagram for Quality Defects (Ref. 1)

Even though an individual inspection is not perfect, a sequence of inspections can insure a small number of outgoing defects. This can be seen from the fault tree diagram (Fig. 8-50), which shows that for an outgoing component to contain a defect, the occurrence of all four of the following events is required:

1. Part received with a defect
2. Receiving inspection accepts part with a defect
3. Defect not detected at in-process inspection
4. Defect not detected at final test station.

Note also that if any of the inspections of the example were perfect, ($E_i = 1$), there would be no outgoing components with defects.

A burn in or screen testis included in the inspection of many electronic equipments. This type of test is designed to convert reliability defects that will cause premature failures in the field into failures in the assembly plant. This results in a lowered infant mortality rate of the system immediately after production. The screen efficiency S is the probability of converting a reliability defect into an observable failure. The number of reliability defects converted and detected is the product of the number of incoming reliability defects, the screen efficiency, and the inspection efficiency. If the screen efficiency is 0.9 and the inspection efficiency is 0.9, the probability of converting and detecting a reliability defect is 0.81 efficient. Thus even with the use of a screen, not all of the induced reliability defects will be detected and removed.

To assess and control the reliability of a system as it leaves production or a field maintenance activity, values for inherent quality and reliability defect rates, induced quality and reliability defect rates, and inspection/screening efficiencies must be determined by a process and inspection analysis. The process and inspection analysis involves (1) a determination of the induced defects (quality and latent reliability) associated with each of the more significant steps required in the fabrication of the system as planned—based on an analysis of planned inspection criteria and historical rejection rates derived from similar processes, (2) an assessment of a total outgoing (from production) defect rate based on the derived process-induced defects and supplied inspection reject rates, and (3) a calculation, based on the ratio of the inherent reliability to the outgoing reliability.

Values for process- or maintenance-induced defect rates can be derived from an evaluation of reject statistics, determined from an evaluation of stresses applied by the manufacturing processes, or they can be based on experience factors of similar systems and processes. The values derived or obtained for reject rates, induced defect rates, and inspection and screen efficiencies can be combined in a process and inspection analysis flowchart, which is used to derive a final outgoing defect rate. The total defect rate or outgoing reliability numeric stemming from a process analysis can then be used to determine manufacturing reliability degradation factors.

8-6.2 DESIGN FOR EASE OF INSPECTION AND EASE OF MAINTENANCE

As previously indicated, achieving high reliability is directly related to the degree of effectiveness of the special features designed and built into a system that would make it easy to produce (i.e., assemble and test) and maintain. These features must be designed with the objective of aiding the production inspector or maintenance technician in recognizing and diagnosing failures or weak areas and in making a repair as early and as rapidly as possible. Furthermore, the incorporation of these special features into a system—in addition to improving reliability, producibility, and maintainability—will result in a reduction of manufacturing and field support cost.

To effectively design for ease of inspection and for ease of maintenance, the designer must be completely aware of basic problems and marginal or difficult areas related to assembly and maintenance. He must be aware of possible equipment failure modes associated with these problem areas, and he must be completely familiar with the production and maintenance environment. The designer must recognize that production problems are potential maintenance problems, e.g., if assembly is difficult under factory conditions, it would be virtually impossible under field conditions.

Achieving ease of inspection and maintenance requires designing special features into the system for (1) identifying failure and/or potential (or marginal) failures and (2) facilitating fault diagnosis (e.g., access to failed units and removal and replacement of failed units). Table 8-49 presents a simplified list of activities and development guidelines that will aid in assuring implementation of these features. Although implementing these features involves essentially all aspects of equipment development, concepts relative to hardware partitioning (i.e., packaging, modularity, etc.), fault diagnosis, and detection of incipient failures are considered key elements.

8-6,2.1 Hardware Partitioning

Hardware partitioning is the process of dividing the system into physically and functionally distinct units to facilitate handling during manufacture, fault isolation, removal, and replacement. Partitioning enables equipment units, assemblies, and subassemblies to be designed as discrete items or modules.

Modularization affects both maintainability and producibility as indicated in Fig. 8-51. Modularization is achieved through functional design, which encompasses the packaging of components and subassemblies performing related functions in self-contained units, thus facilitating testing, fault isolation, and maintenance.

The application of modular design allows the isolation of faults to a unit that may be removed from the equipment on-site and thrown away or shipped to a depot for repair. The equipment may be immediately put back into operation by replacement of a module with another, minimizing on-line maintenance action. Localization of functions into modules eliminates long paths and crossovers, as illustrated in Fig. 8-52. This further enhances ease of maintenance by simplifying

TABLE 8-49. EASE OF MAINTENANCE GUIDELINES (Ref. 1)

Failure diagnosis, identification, and replacement are facilitated by:

1. Using modular design techniques
2. Using special built-in circuits for fault detection and indication error warning lights, etc.
3. Designing for replacement at higher levels
4. Using increased skill level technicians
5. Increasing depth of penetration of localization features
6. Employing test indications that are less time-consuming and/or less difficult to interpret
7. Designing for minimum diagnostic strategies
8. Making accessible and obvious both the purpose of the test points and their relationship to the item tested
9. Improving quality of technical manuals or maintenance aids
10. Designing access for ease of entry
11. Reducing number of access barriers
12. Reducing need for isolation access by bringing test point, controls, and displays out to accessible locations
13. Reducing number of interconnections per replaceable item
14. Using plug-in elements
15. Reducing requirements for special tools

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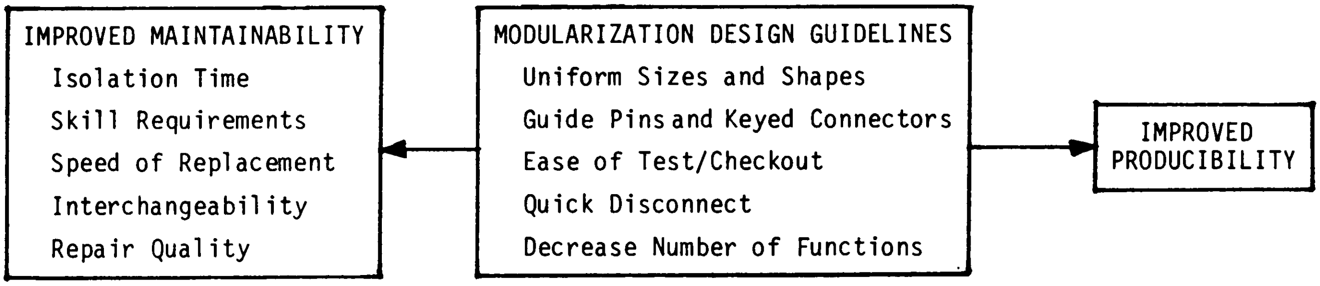

Figure 8-51. Modularization Design

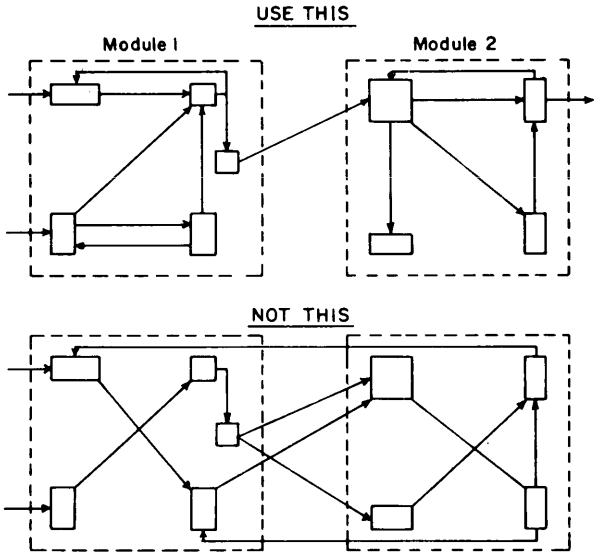

Figure 8-52. Design for Functional Modularization

the tracing of signal paths when locating and isolating a failure.

An example of modularization currently used in airborne system design is the line replaceable unit (LRU). The LRU concept allows the rapid removal and replacement of large equipment modules or subsystems on the flight line for maintenance at a repair station. The application of this concept allows reduction of system downtime, reduces skill requirements of on-line maintenance personnel, and provides for consistent quality of repair.

If the cost of a new module is less than the cost of repair, there is a strong likelihood of adopting a throwaway maintenance concept for the module. The logistics of module replacement are directly related to the initial design decisions on size and complexity of modules. Repair of equipment can be accomplished by replacement of a module after fault isolation is accomplished by portable or built-in test equipment (BITE). The repair of a module generally requires jigs, fixtures, power supplies, etc. This equipment for the repair of modules is usually located at the production plant to enable reworking of these modules. However, it is generally too expensive for field application.

Along with the training and technical manuals required for field repair of a module, there are the cost factors that must be considered. Based on costs and logistics, a design trade-off must be made in the concept formulation stage whether to design small, inexpensive modules, which will be designated throwaway, or to design larger, costlier modules for possible economy of equipment repair. To assist in minimizing the cost of throwaway modules, component parts should be selected that have approximately the same wear-out rate. It is crucial that these decisions be made early in the conceptual phase where changes least affect program costs. Equipment that implements the throwaway concept of modular design possesses several advantages. Throwaway modules allow savings in repair time, tools, facilities, and manpower. They also allow improved standardization and interchangeability of modules and assemblies. Throwaway modules also impose several penalties; they increase supply burdens because modules must always be on hand. Similarly, redesign or retrofit of manufactured units becomes difficult because the modules cannot be readily modified.

If a module can be cost-effectively thrown away, there is no need to troubleshoot or repair that module. For more expensive modules, it may be possible to provide a plug-in connection allowing salvage of the expensive parts (more than 30% of module cost), while the remainder of the module is discarded and replaced. Care should be taken in the design of a module so that it will not have to be replaced because of a single failure-prone component.

8-6.2.2 Fault Diagnosis and Isolation

It must be emphasized that the ease of maintenance of a system depends on those design features that impact the ability to diagnose failure rapidly and accurately. Repair cannot begin until the failure is identified, located, and isolated. Consideration of fault diagnostics during equipment design can significantly increase ease of maintenance by reducing diagnostic time and, therefore, equipment downtime. Design factors contributing to rapid fault diagnosis are maintainability considerations, built-in test (BIT) provisions, and maintenance support.

Special provisions must be designed into the system that will provide the means to assess the condition of internal LRU, assemblies, or modules for the purpose of locating failures. Such provisions can have a wide range of complexity, depending on the needs and constraints of the specific system. Some systems may simply provide test points to interface with external support equipment. Other systems may incorporate BITE or a sophisticated BIT, either of which operates under computer control and provides complete indication of failure.

BIT provisions obviously influence inspection and maintenance cost. From the maintenance viewpoint, maximizing fault isolation is the most desirable approach; however, a number of difficulties arise. BIT provisions add cost to equipment development. Thus the extent of the provisions must be determined through trade-off studies concerning maintenance needs and total cost of ownership. The trade-off between acquisition costs (AC) and potential maintenance savings must be evaluated to determine the impact. Other factors, such as short downtime requirement, criticality of the item, or personnel requirements, may influence the decision.

Incorporating test points into the system involves considering number, type, location, and arrangement. The physical location of the test points has a marked effect on the quality of inspection and maintenance. Generally, test points should be located near the signal source since the nature of a signal may be such that it does not travel well without being altered in the process of transmission. This consideration is particularly pertinent in those cases in which the waveshape of the signal is critical and will tend to change in transmission to a test point. The designer should keep in mind that the technician needs only an indication that reflects an out-of-tolerance condition of the true signal. If these indications are documented during engineering tests, they will provide adequate malfunction indicators for field use.

Particular care should be taken to make test points accessible. Ideally, internal test points should be clustered around the portion of the unit that will be most accessible when installed. There should be only one adjustment control associated with each test point; it should be easily and reliably operated and should not be too sensitive.

Test points should be grouped or arrayed on a central panel to facilitate checking and troubleshooting, and they should also be grouped to make sequential checking convenient. The specification of test points in an electronic system depends on the operational and tactical demands placed on the system design and on the special needs of a particular service. The number and type of test points should be compatible with the test instrumentation (built-in or otherwise) available at the place of system use or at the maintenance or repair activity.

The functional location of test points is determined from the manufacturing inspection requirements and the maintenance procedures, as well as which signals must be available to the technician and where they must be available. Those signals must be made available that indicate the technician needs to inspect and maintain the system. Their location must be planned into the system for maximum effectiveness.

A test point (which maybe nothing more than a bare wire) should be provided at the input and output for each line replaceable unit. One convenient way to provide these test points is to mount components on one side of a board and wiring on the other side with electrical connection through the board. The advantage of having test points alone on a flat surface rather than among the parts is that full identifying information for each test point can be stamped on the surface and not be obscured by the parts.

It should not be necessary to remove any assembly from a major component to inspect or troubleshoot that assembly. This may require special test points on the major components or assemblies, but test equipment and bench mock-up access to the output and input of each line replaceable unit should be provided through the normal interconnecting plugs wherever possible. Design guidelines for test points in electronic equipment are listed in Table 8-50.

The decision to include BITE or BIT must be based on a trade-off between basic maintenance factors and other system parameters and constraints. BIT capabilities have three uses:

1. Warning that subsystem has become inoperative
2. Generate failure signals so that the system can be configured to operate in an alternative available mode
3. Fault isolation to a replaceable element.

The difficulties of applying BITE or BIT are

1. Changes in hardware (modifications or additions to the system) require BIT hardware and/or software modifications.
2. Information transfer between systems with BIT is greater than between those without BIT.
3. System BIT normally is designed by system integrators who are not as familiar with the system as the original designers.
4. Centralized BIT requires increased data input and more elaborate logic.

In general, BIT performs fault isolation by applying a signal to a circuit and measuring its response by primary measurements, such as voltage levels, distortion, and noise. Meters or go/no-go test equipment are

TABLE 8-50. DESIGN GUIDELINES FOR TEST POINTS (Ref. 1)

1. Test points should be provided for the input and output of each line-replaceable or -repairable assembly, circuit, item or unit; these points should be immediately available.
2. Ground points should be provided as necessary, particularly when a painted surface would otherwise prevent good electrical contact.
3. Voltage dividers should be incorporated at test points for voltage in excess of 300 V.
4. Test points and their associated labels and controls should face the technician for best visibility; consider use of color coded test points for ease of location.
5. Combine test points, where feasible, into clusters for multipronged connectors, particularly where similar clusters occur frequently.
6. Arrange test points in test panels or other surfaces according to the following criteria, listed in order of priority:
    a. Type of test equipment to be employed at each point
    b. Type of connector used and the clearance it requires
    c. Function to which each point is related
    d. Test routines in which each point will be used
    e. Order in which each will be used.
7. Label each test point with the tolerance limits of the signal and a number, letter, or other symbol keyed to the maintenance instructions.
8. Locate routine test points so that they can be used without removal of cabinet cover or chassis.
9. Label each test point with the In-tolerance signal.

built into the circuit so that a minimum of external test equipment is required to test the performance of the circuit. Checkout is normally performed manually by applying a stimulus and observing the response of the circuit by BITE. The output can be fed to a computer that determines whether all measured parameters are within limits. The computer can also generate the necessary test signals. BITE, in addition to reducing the mean time to repair (MTTR) a failure, also lowers the skill level needed to maintain equipment because fault isolation is performed by a computer, and the technician must only replace the component identified by the computer.

To determine BITE sophistication, it is necessary to define the requirements for MTTR, number of parameters tested, criticality of malfunction, and level of maintenance personnel. For instance, aircraft operating under battlefield conditions pose severe restraints on the time permitted for a system check. In a combat situation aircraft are recycled as rapidly as possible because of the limited time between missions and shortened preflight checkout. Therefore, the MTTR should be minimal, e.g., 1 h or less. Due to the complexity of the avionic equipment, many parameters should be tested to insure mission success. Even with skilled technicians, the time required to remove panels to expose test points is prohibitive. Therefore, some form of BITE is necessary, and the more complete the testing performed, the higher the likelihood of finding critical malfunctions. If the aircraft were to have a computer on board, the computer could cycle the avionics through a complete test while returning from a mission when the computer burden is low. All necessary parameters could be printed out for a semiskilled technician to evaluate for conformance to specification, or the computer could perform this function as well as identify any defective avionic modules.

An example with opposing requirements is a central communication network having redundant equipment. In this case, a few voltage current and/or power meters located at the output of large subassemblies in the BITE network would allow an operator to isolate a malfunctioning subassembly quickly. The backup unit would be switched on, and once the defective subassembly is disconnected, the defective component can be identified and repaired at a less demanding pace. The degree of BITE used in this example would depend upon the skill level of the technician.

A very important consideration when implementing BITE is the manner in which it affects the circuit. Ideally, it should look like an open circuit at all times under all failure modes in the control circuit. In this way, the BIT provision will not decrease circuit reliability. Since this is not always possible or practical, the loading effects should be evaluated in the operation of a circuit, and circuit operation should be studied to determine whether there is another location in the circuit where a similar measurement might provide as much and possibly more information with less loading. A failure mode and effect study should be performed on the BITE to determine the impact of various failures on the operation of the circuit under test. Those failure modes causing lowered performance of the circuit under test should be eliminated by a different test technique.

The system to be maintained should be fully described by the designer. Schematic diagrams of new or unusual circuits should be provided. Equipment to be tested should be broken down into functional block diagrams, and engineering sketches and diagrams should be provided to identify modules and test points. Modules and test points should be labeled or coded to facilitate identification from documentation. The testing procedure should be documented in a clear, concise manner, and expected signal levels and waveforms adequately indicated.

The designer should also prepare a technical description of proposed test or support equipment that must be available to maintain the equipment. If the test or support equipment is Government furnished, the nomenclature of the equipment should be identified. However, if the test or support equipment for maintaining the equipment is commercial, the designer should list the name of the supplier and catalog number of the commercially available equipment. A statement should be furnished, and preferred and alternative devices should be indicated if there is more than one suitable test or support equipment available. Also whether or not the proposed test is built into the equipment should be stated.

8-7 TESTS AND PARTS EQUIPMENT USED ON THE PRODUCTION LINE

Parts, boards, and assembly testing are discussed in this paragraph.

8-7.1 DISCRETE COMPONENT TESTING

Testing of discrete components is fairly well standardized, e.g., testing of resistors, capacitors, inductors, relays, switches, transistors, diodes, and similar devices. There are some relatively new digital, logic controlled bridges and computer controlled testing procedures. The measurement of temperature compensated capacitors can be of interest, and several digitally controlled bridges have been designed for this application.

8-7.1.1 In-Process Semiconductor Device Testing (Ref. 18)

Table 8-51 contains a list of most of the tests performed during the fabrication of a typical IC logic device.

TABLE 8-51. TESTS PERFORMED DURING FABRICATION OF TYPICAL BIPOLAR SEQUENCE OF LOGIC CIRCUITS (Ref. 19)

Previous Processing Step	Test Description	Purpose of Test	Type of Instrument
First oxide layer	C/V plot at room temperature and 300°C	Contaminants in oxide	C/V plotter
Buried layer diffusion	Sheet resistance measurement	Dopant level	Four-point probe or contactless probe
Expitaxial deposition	Monitor color of film against standard	Determine thickness	Fluorescent light and magnifier
	Measure resistivity	Dopant level	Four-point probe or contactless probe
	Visual inspection under infrared or etch and inspect under regular light	Dislocation count	Infrared microscope or dark field microscope
Isolation diffusion	Sheet resistance measurement	Dopant level	Four-point probe or ccntactless probe
Etching window in boron glass	Placing a contact in two adjacent windows	Reverse breakdown voltage across collector-to-substrate junction	Two-point probe

(cont'd on next page) _

TABLE 8-51. (cont'd)

Previous Processing Step	Test Description	Purpose of Test	Type of Instrument
Base deposition	Sheet resistance measurement	Dopant level after initial deposition	Four-point probe or contactless probe
Base redistribution	Sheet resistance measurement	Dopant level after redistribution processing	Four-point probe or contactless probe
	Cutting bevel or groove, staining and counting interference fringes	Base depth	Lapping machine and fixture for bevel or Signatone Model S-1100 groove cutter staining liquid, interferometer
Emitter photoresist	Placing a contact in two adjacent windows in the photoresist	Reverse breakdown and current leakage across collector-to-base junction (prior to emitter diffusion	Two-point probe
Emitter deposition and opening of window in phosphorus glass	Sheet resistance measurement	Initial dopant level	Four-point probe or contactless probe
Emitter redistribution	Sheet resistance measurement	Final emitter dopant level	Four-point probe or contactless Probe
Contact photoresist pattern	Placing a contact in two adjacent windows in the photoresist	Reverse breakdown voltage and current leakage across emitter-to-base junction (prior to back etching)	Two-point probe
	Sheet resistance measurement	Dopant level in base	Four-point probe or contactless probe
Aluminum deposition	Thickness measurement	Metallization thickness	Contact thickness gage or plating thickness gage (noncontact)
Aluminum pattern etch and heat-treat	Etch aluminum away to expose silicon interface and visually inspect surface	Quality of ohmic contact between aluminum and silicon	Etchant and microscope
Glassivation and water bake	Operating tester	Determining electrical parameters of control devices (diodes, transistors, resistors, etc.) fabricated on the water	Probe card, probe station and tester
	Operating equipment	Determining how well metallization goes over oxide	Scanning electron microscope

Note: To calculate sheet resistivity, film or layer thickness must be known or determined separately.

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8-7.1.2 Elevated Temperature IC Testing (Ref. 19)

Semiconductor manufacturers use elevated temperature testing (ETT) to ascertain that their products meet data sheet specifications and the increasing demand for higher reliability. In his screening of 4k RAM devices, one manufacturer realized that the RAM refresh cycle is very temperature sensitive. He sought, but was notable to find, an existing formula that could relate the RAM room temperature operation to the 70°C allowable maximum. He found that he could use ETT for RAM devices, and other LSI devices in which the elevated temperature created problems in timing and racing, and high current leakage. ETT helped cull weak devices and failures. He is currently trying to justify 100% ETT of other components, e.g., microprocessors.

For many devices the 16-deg C temperature tolerance associated with a hot rail tester is too great. A tighter control of temperature can be obtained with equipment using a hot chamber system inclosing the rail and test station. The hot chamber devices can maintain the temperature of the device at ± 3 deg C.

An ETT test of 1000 devices that had previously passed an ambient inspection test showed a 5% failure rate. Of these 50 failed devices, half were found to be defective at an ambient temperature retest. It is believed that in some applications an ETT could screen samples sufficiently so that a burn in test might not be necessary. A 100% ETT is more easily justified than burn in tests if this lower level of screening is acceptable.

ETT handlers with heaters that raise the temperature of the semiconductor device by conduction cannot produce close tolerance temperature limits in parts to be tested. Hot rail handlers do not maintain as close a control of temperature as hot chamber handlers. Hot chamber systems usually are designed with a large storage space for soaking up heat. If the user can tolerate the greater temperature range of the hot rail testers, he can economically justify the hot rail tester rather than the hot chamber machine. This is especially true if the volume is low and the test cycle is long. However, for a test cycle greater than 5s, the heat loss at the contactor precludes the use of the hot rail handler.

8-7.2 IN-CIRCUIT BOARD TESTER (Ref. 20)

State of the art in-circuit test systems verify the performance of devices on populated PCB and check for such manufacturing and assembly errors as shorts, opens, and incorrectly or improperly oriented components. However, they do not test the functional validity of the boards.

An in-circuit board tester (ICBT) uses guarding to set apart analog devices and a pulse technique that drives logic through the truth tables independent of the states of input and output of these IC’S. Guarding depends on an operational amplifier measuring technique. Common instruments, such as digital voltmeters, generally cannot measure components soldered to the board because of parallel paths. The key technique involves measuring desired impedance and canceling out the effects of any parallel impedance. An operational amplifier guards against the effects of parallel impedance.

To test each logic device independent of the state constraints placed on its input by its neighbors requires superimposing the desired input state over the existing state. The time period must be short enough to prevent thermal damage to the input of the device under test or the output of adjacent devices.

8-7.2.1 Testing of Microprocessors and PCB Assemblies (Ref. 21)

The use of microprocessors is expanding into new and different applications. The microprocessor chip must be mounted onto a physical structure so that it can be used, and this structure is usually a PCB. After every stage of assembly of the microprocessor/PCB subsystem, testing should be considered, and if a failure occurs, the fault must be corrected.

Usually there are two test method philosophies being followed in microprocessor/PCB production testing: (1) test the microprocessor/PCB as a single unit and (2) test the microprocessor/PCB assembly as a two-step sequence. The first method requires operating the PCB at the normal operating frequency or operating the board more slowly and single-stepping the microprocessor. In the second method, the PCB is tested, the microprocessor is inserted, and the assembly is retested at normal operating speed. Both methods use software for test pattern generation and diagnostic fault location. Hardware, such as “bed-of-nails” or a probe system, is needed as a test aid to access internal board points for fault location.

8-7.2.2 LSI Schmoo Tests (Ref. 22)

Pattern sensitivity has not been eliminated in the 4k RAM. It appears in system operation under a particular combination of voltage, temperatures, and timing. A full 100% pattern test of the 4k devices is much too expensive, and it is recommended that a set of six smaller patterns be run at 70°C.

8-7.2.3 Infrared Thermal Imaging (Ref. 23)

“Thermal imaging, while expensive, frequently is worth the cost—particularly where thoroughness, accuracy, and speed of testing are important. Thermal imaging eliminates the problems associated with the use of thermocoupler and the uncertainties that accompany a theoretical analysis. The process provides a detailed thermal map, in real time. Hot spots and malfunctioning components are detected with great accuracy. Thermography serves as a design tool as well as a quality control device for checking out the final design before it goes into production. ” Reprinted from EDN, February 20, 1977, by CAHNERS PUBLISHING COMPANY.

8-7.2.4 Circuit Analyses for PCB Testing (Ref. 24)

In testing of loading PCB, bare PCB, and backplanes, the biggest problem is associated with fixturing for automatic continuity testing. More and more engineers and managers involved in testing and decision making in connection with testing are using fixturing that employs purely mechanical methods, such as the bed-of-nails approach.

The two basic fixtures most commonly used today are the vacuum fixtures and the air-pressure-operated fixtures. Vacuum fixtures are used primarily for testing

1. Loaded boards that require top access and that do not have holes that create leaks (this problem is sometimes resolved by using a vacuum lid)
2. Bare PCB where the number of test points is relatively small compared to the size of the board and where test points are distributed fairly evenly throughout the board
3. Backplanes that are not severely warped, and the number of test points is relatively small where the test points do not create an unbalanced load condition.

Pressure fixtures are used for testing loaded boards of all types, bare PCB of all types, and backplanes of all types. Dedicated fixtures (vacuum or pressure) have a fixed pattern and are used for testing one type of board only. Universal fixtures (vacuum or pressure) have a standard pattern (grid or other) and are used to test boards of identical patterns by using masks to access test points selectively. Fixtures with removable probe heads (vacuum or pressure) can accommodate different contact test point patterns to test boards of various configurations.

Pressure-type fixtures, although more costly, are usually better engineered and constructed and have a much larger test point capacity than do vacuum fixtures. Also they do not have the leakage problem and present fewer maintenance problems than do vacuum fixtures. Pressure fixtures use shop air that is usually readily available at the customer’s plant.

8-7.2.5 Basic Types of Analyzers

Along with the decision of which fixture should be employed comes the question of which circuit analyzer best suits the overall testing objective. The two basic types of circuit analyzers used for PCB testing are low potential and high potential. The solid-state, low potential analyzer, although fairly new, is by far the most widely used and accepted today. It will accomplish 90% of total board testing required in the industry, and the cost is not prohibitive. Due to the lower power requirements of the CMOS and lower power Schottky logic used in most low potential analyzers, system blower assemblies and related devices are not required for cooling.

8-7.2.6 Digital Testing Oscilloscope (Ref. 25)

Troubleshooting current digital products is a major expense. Even with the use of automated testers, many manufacturers are being forced to spend more on testing and fault diagnosis than on assembly. The problem is that fault isolation, whether done in the factory or in the field, generally defies automation. But that is not all—the unpredictability of troubleshooting time, a shortage of field engineers, and rising training expenses and wages for technicians are problems as well.

The digital testing oscilloscope (DTO) simplifies troubleshooting at the end of the production line, in the repair depot, and in the field. It is also a powerful new engineering tool for design, documentation, and field changes.

The DTO-1 is the first oscilloscope-like instrument designed to test and troubleshoot digital systems. It performs automatic tests as well as manual troubleshooting procedures not only on digital but also on related analog circuitry. (An analog troubleshooting capability is important in digital testing since many faults have analog origins. Replacing a microprocessor that drops bits, for example, is no solution if the problem is a short between adjacent printed circuit traces.) The DTO-1 is used with a single probe, much as an oscilloscope is, and has oscilloscope-like controls. It combines the capabilities of three instruments: a go/no-go comparison tester, a time-domain logic analyzer, and a storage oscilloscope.

As a go/no-go comparison tester, the DTO-1 automatically compares logic waveforms from a known good system with waveforms acquired from a system or board being tested. The reference waveforms and other test data are stored on miniature tape cartridges during test programming by an integral tape unit for playback during test operation. A microprocessor compares the waveforms, displays both logic traces on the cathode-ray tube, and lights up pass or fail light-emitting diodes on the probe.

As a logic analyzer, it can display up to eight traces simultaneously in the familiar timing-diagram format. Logic analyzer capabilities include pretrigger recording, posttriggering, combinational and internal triggering, and detection of glitches, such as high-frequency noise spikes. The traces are acquired one at a time and stored in memory for later display.

As a storage oscilloscope, it can display digitized analog waveforms on the same time base used on display logic traces. Any number of analog waveforms can be stored in memory and superimposed on the upper part of the cathode-ray tube (CRT) display at the same time that up to three logic traces are displayed on the lower part. The combined displays help the troubleshooter determine whether a fault is caused by an analog or a digital malfunction and provide information needed to correct either type.

The DTO- 1 is virtually self-programming and uses no software language to program tests. Instead it records the reference logic traces and control settings acquired from a known good board or system on tape. When the operator plays back the tape, the instrument automatically sets itself up to perform a go/no-go test.

As a design instrument, the DTO- 1 is more versatile than conventional logic analyzers and oscilloscopes. It is an ideal before-and-after tool because it can record reference patterns before a design change and play them back later to display the effects of the change. Its performance is high enough even for some emitter-coupled-logic designs—its maximum sampling rate of 100 MHz allows it, in practice, to handle input signals with frequencies up to about 20 MHz.

8-7.3 SELECTIVE AUTOMATION

To expedite troubleshooting and reduce training costs, the digital testing oscilloscope selectively automates test routines. Since an operator's skills are not required to troubleshoot the good functions of a system, the DTO-1 automates those tests that determine which parts of a system operate properly. When a bad function is located, the DTO-1 acts as a general purpose instrument to isolate the causes of either digital or analog faults.

At the beginning of a test sequence, a microprocessor within the instrument determines, from a single test, the frequency difference between the system under test and the reference traces and automatically corrects for this difference throughout the sequence. Then the operator simply uses the smart data probe to check the specified points in the system. As he does so, the microprocessor sets up the instrument for each test and makes goino-go decisions.

The probe has pasw/fail lights and two push buttons for automated testing, which frees the operator from having to look at the display or to reach the control panel. The operator merely looks to see whether the lights are green (pass) or red (fail), and if the green luminous electronic diode (LED) lights up, he goes to the next test point. When the red LED lights up, the operator looks at the CRT display for clues to the cause of the problem. The display shows a system-under-test and reference logic-trace pair and up to six previous traces that had passed the tests. The main clue is an underlining of the system-under-test trace where it disagrees with the reference trace.

The operator then either goes to a manual mode for combined digital and analog troubleshooting or runs a previously programmed fault-isolation sequence. In the manual modes, the DTO-1 operates as a single-probe logic analyzer with oscilloscope-like controls, as a storage oscilloscope, or as a combination of the two. For instance, the faulty trace, still underlined, can be visually compared with a variety of traces and waveforms, such as the actual analog waveform of the trace, associated timing signals, power supply levels, and comparator outputs. Acquired with the same probe, these are displayed above the system and reference trace pair on the same time base. Such combination displays usually lead to the cause of the fault. If an analog signal is bad, the technician spends no further time checking digital functions. If the fault is digital, he can check out basic digital devices as he would with an oscilloscope (or an analyzer), or he can go to a recorded fault-isolated subroutine to check out complex devices and obtain additional clues.

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CHAPTER 9
PRODUCIBILITY CONSIDERATIONS FOR OTHER ITEMS

Previous chapters of this handbook have been dedicated to the producibility considerations of a single type of component. This chapter encompasses several items of a more specialized nature: propellants and explosives, *optics, ceramics, and textiles. Because of the specialized nature and availability of other sources of material relating to the producibility of these items, only an overview is given in this chapter. These discussions include material characteristics and constraints and manufacturing process characteristics and constraints. References are used to guide the reader to additional information and data relative to the less common materials and component types.*

9-1 PROPELLANTS AND EXPLOSIVES

This paragraph provides a general understanding of the producibility aspects of the commonly used propellants and explosives. Propellants and explosives are generally categorized under a scientific discipline identified as energetic. In this paragraph propellants and explosives are treated as two separate and discrete items.

9-1.1 PROPELLANTS

A propellant is a chemical or a mixture of chemicals that, when ignited, burns in the substantial absence of atmospheric oxygen at a controlled rate and evolves gas capable of performing a function. The more commonly used propellant ingredients discussed in this paragraph are nitrocellulose, nitroglycerin, and nitroguanadine. Higher energy systems are discussed in Ref. 1.

9-1.1.1 Material Selection Process

The devices in which propellants are commonly used fall into the general classification of heat engines. For example, guns that comprise moving pistons or vented vessels acquiring momentum by discharge of gas are devices that convert heat energy into mechanical enerrgy. The propellant gas is then the medium that actuates heat engines. In solid propellant heat engines the medium is generated in place by burning the propellant within the engine. A solid propellant for a heat engine must generate gas of specified properties at a specified rate. Both of these problems, the properties of the gas and the gas generation rate, are critical in the propellant selection process. The properties of the gas are determined by the composition of the propellant. The rate of gas generation is determined by the linear rate of burning. The overall problem of selecting a propellant formulation and geometry to meet a given end-item performance specification is an exercise in interior ballistics. One of the best references on this subject is Ref. 2. In addition to satisfying the propellant properties, the designer must also be concerned with the physical properties of the propellant and the operational environment including compatibility with adjacent materials. There is an excellent discussion of these factors in Ref. 3.

9-1.1.1.1 Mechanical Properties

The mechanical properties of propellants must enable them to withstand the mechanical loads imposed on them during shipping, handling, and firing. To a great extent these same mechanical properties have a significant effect on the producibility of a propellant. The important mechanical properties are briefly discussed:

1. *Ultimate Tensile Strength.* Tensile strength is important for rocket grains supported at the head end of rockets during acceleration. Tensile strength is even more important in rocket-assisted artillery projectiles that experience very high g forces at launch. It is also useful as a quality control measure to assure consistency in successive lots of a given propellant. Tensile strength ranges from about 69 MPa (10,000 psi) for straight polymer monopropellants to below 345 kPa (50 psi) for some case-bonded propellants. Specifying tensile strength greater than actually required will impose producibility constraints on the formulation, the manufacturing process, and the loading process.
2. *Stress Relaxation.* It is advantageous in a case-bonded propellant for the stresses produced by distortion resulting from fabrication to be relaxed as the grain becomes accommodated to its new environment so that residual stresses will not lead to cracking in areas of stress concentration. The property of relaxation under tension may be determined by measuring the tensile stress at fixed elongation as a function of time.
3. *Compressive Strength.* Firing imparts compressive stresses on rocket-assist grains at the base of rocket-assisted projectiles as well as on cartridge-type rocket grains supported on traps or otherwise at the nozzle end. The magnitude of such stresses and, therefore, the compressive strength needed to withstand them can be computed for any instance from the designed acceleration of the rocket. Compressive strengths of propellants are usually of the same order of magnitude as ultimate tensile strength, and for design purposes the tensile strength of the propellant is frequently used with suitable safety factors. However, caution should be exercised in applying these safety factors. Too small a safety factor can result in system failure, whereas too large a safety factor can result in a reduction in producibility.

4. Shear Properties. Case-bonded grains are stressed in shear during acceleration, which results in the possible separation of the propellant grain from the case wall to which it was bonded during fabrication. The weight of the propellant must be supported by the shear strength at the bond between the propellant and the case.

9-1.1.1.2 Propellant Classes and Characteristics

Propellants are generally classed into three different types: single base, double base, and triple base propellants. Single base propellants contain only one ingredient, e.g., nitrocellulose (NC). Double base propellants contain two ingredients, e.g., NC and nitroglycerin (NG). Triple base propellants contain three ingredients, e.g., NC, NG, and nitroguanidine (NQ).

The physical and ballistic parameters of several explosive propellant ingredients are shown in Table 9-1. Propellants are generally classed as being crystalline, plastic, or composite.

Plastic single base propellants are thermoplastic, translucent (unless pigmented), and resemble generally inert thermoplastics. Many of the physical properties are determined by the polymer content; this is probably best expressed in terms of the concentration (weight fraction multiplied by specific gravity) of polymer in the propellant. Fig. 9-1 presents data on the ultimate strength and deformation at rupture, typical of these propellants.

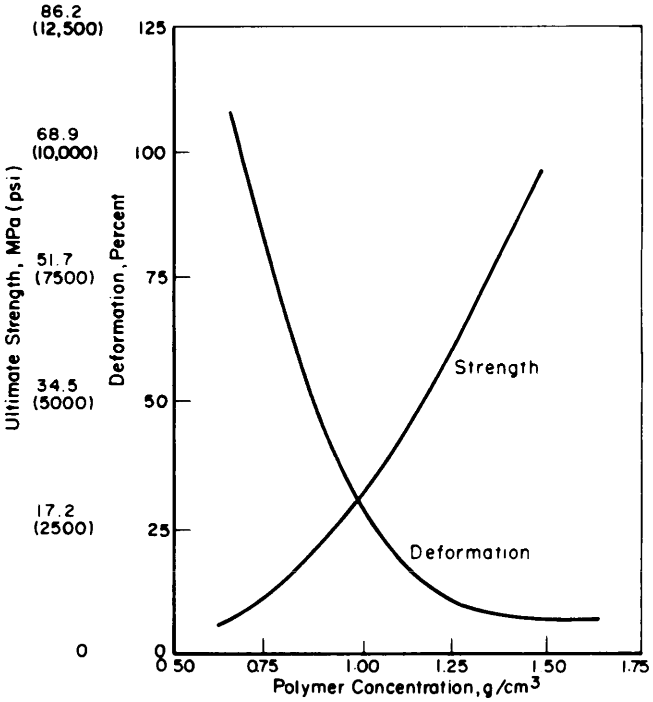

Figure 9-1. Physical Properties vs Polymer Concentration

Crystalline monopropellants have limited feasibility as propellants; the limitations are due to the difficulty in getting crystals of the size and shape required for many applications and to the fact that pure chemicals

TABLE 9-1. PHYSICAL AND BALLISTIC PARAMETERS OF SEVERAL PROPELLANT INGREDIENTS

	Density, g\cm³	Melting Point, °C	Q cal/g	M
Nitroguanidine	1.715	246		184
RDX, cyclotrimethylene-trinitramine	1.820	202	1360	222
HMX, cyclotetramethylene-tetranitramine	1.920	276	1321	296
PETN, pentaerythritol tetranitrate	1.770	140	1531	316
Ammonium nitrate	1.720	170	354	80
Ammonium perchlorate	1.950	Decomposes	335	117.5
Nitroglycerin	1.596	13.2	1600	227
Nitrocellulose (13.45%N)	1.650-1.700	Decomposes	965	$(286)_n$

Q = heat of explosion, M = molecular weight

do not yield a continuous spectrum of thermochemical properties. The force or characteristic velocity of a given crystalline monopropellant, although within the range of desirable values for propellants, is seldom optimum for a specific use. Composite propellants generally overcome these deficiencies by accepting an available particle size distribution or grist of the crystalline monopropellant and by dispersing it in a plastic monopropellant. Such composites generally assume the properties of the crystalline component. The function of the plastic is to act as a necessary diluent to permit attaining the desired geometry with acceptable physical properties and as a modifier to adjust the thermochemical properties. The physical and safe handling properties of these composites differ considerably from those of the plastic monopropellants. The composites are opaque, chalky white in color unless glazed, and generally exhibit lower physical strength.

9-1.1.1.3 Propellant Ingredient Descriptions

A brief description of several propellant ingredients follows:

1. *Nitroguanidine. The* gas volume of nitroguanidine is quite high, and the fraction of nitrogen in the gas is unusually high for propellant gas. The burning temperature of nitroguanidine is some 150 K lower than that of a smokeless powder of the same force level, which indicates that nitroguanidine should cause less gun barrel erosion than a comparable servicc gun propellant. The higher content of nitrogen in the gas should result in less tendency to flash than other service gun propellants at the same flame temperature, and this offers an even more pronounced advantage at the same level of force. The usual crystal form of nitroguanidine is needle-like, resulting in quite low gravimetric density and small web thickness. The principal uses of nitroguanidine are as a burster charge ingredient and a constituent of triple base propellants.

2. *Nitrocellulose.* Nitrocellulose as used commercially and as a propellant is less than completely nitrated. Nitrocellulose is, therefore, the product of a partial nitration of cellulose and is generally characterized by its nitrogen content. Significant commercial grades of nitrocellulose are those used for lacquers at 12% nitrogen, those used for dynamite at 12% nitrogen, and those used for plastics at 11% nitrogen. The grades of significance to propellants are 13.4.5% nitrogen and 12.6% nitrogen. The higher the nitrogen content, the higher the calorific value. The principal uses of nitrocellulosc are as a blasting explosive, smokeless powder, gun cotton, and the sole explosive constituent in single base propellant.

3. Ammonium *Nitrate. As a* monopropellant, ammonium nitrate produces a working gas containing free oxygen. For this reason, although its force and specific impulse are somewhat modest, when compounded into composites with any incompletely oxidized binders, ammonium nitrate behaves in part as an oxidant. Ammonium nitrate has commercial applications; it is widely used as a fertilizer ingredient and as a constituent of commercial high explosives.

4. *Ammonium Perchlorate.* As a monopropellant, ammonium perchlorate is even more oxidizing than ammonium nitrate. Like ammonium nitrate, ammonium perchlorate is hydroscopic. The presence of hydrogen chloride in the products of combustion makes ammonium perchlorate unattractive for use in combustion chambers that are used repetitively, such as guns. For these reasons ammonium perchlorate has not been used as a monopropellant charge. It is, however, widely used as an oxidizing filler in composite propellants for rockets.

5. RDX. The force and specific impulse are quite attractive although the flame temperatures are higher than desirable for gun applications. RDX has been fired in sporting and small arms successfully, and the ballistics have compared favorably with those of smokeless powder. As expected, the quickness was found to depend on the crystal size; finer crystals are quicker than coarser. The high burning temperatures may be tempered by formulating to a composite with a binder of lower burning temperature.

6. HMX. The ballistic parameters are similar to those of RDX. It is somewhat more dense than RDX and has a somewhat higher melting point. Like RDX, HMX can be compounded into composites.

9-1.1.1.4 Applications of Plastic Propellants

Plastic propellants hate been used in guns, rocket motors, and gas generators. A brief description of selected applications follows:

1. *Gun Propellants.* With the exception of sotne signaling guns in which the smoke puff is at least as important as any other effect, all guns use propellants based on nitrocellulose. This is more commonly known as a single base propellant.

2. *Propellants for Rockets.* Design specifications for rockets have usually required propellant burning rates between 6.4 and 12.7 mm/s (0.25 and 0.5 in./s) in suitable geometries. For short-range applications, short burning times and high accelerations may be more important than high burnout velocity, and propellants with burning rates higher than 12.7 mm/s (0.5 in./s) are used. With heavy payloads, the propellant impulse is frequently sacrificed to take advantage of a lower flame temperature and the associated ability to use cheaper materials in the weapon parts. Plastic propellants are used in shoulder-fired rockets commonly known as bazookas. High burning rate is attained by using potassium perchlorate as a constituent to satisfy

the requirement that burning be completed before the rocket leaves the launching tube.

3. *Propellants for Gas Generators*. Contrasted with rocket motors, gas generators usually require a smaller mass flow of propellant gas for longer times, therefore lower burning rates. However, for specialized applications a rocket motor may be best fitted with a gas generator-type propellant and vice versa. Other requirements for gas generator use may be cool flame temperature or high performance, depending on the application. Typical of double base gas generator propellant compositions is X-13, used in the SIDE WINDER gas generator.

9-1.1.2 Manufacturing Processes

The basic processes for formulating nitrocellulose, nitroguanidine, and nitroglycerin are provided in succeeding paragraphs. However, the production processes for these products are undergoing modernization at the Army ammunition plants. The important processes used for nitrocellulose system propellants at this time are solvent extrusion, rolling of sheets, solventless extrusion, cast double base, and slurry casting; all of which are described.

No one manufacturing process will produce the whole spectrum of plastic propellants. As in the case of commercial, inert thermoplastics, a wide variety of manufacturing processes has been developed to make different propellant grains. Nearly every fabrication process used by the commercial plastics industry has been used for propellants; in fact, some processes used for propellants have not yet been used by the plastics industry. For any given process the difference between use for propellants and use for inert plastics is that the consequences of a fire during propellant processing are severe, and extraordinary precautions must be taken to prevent fires and to control them if they do occur. In the design of facilities the most striking feature of propellant manufacturing processes has been the requirement to handle the material in batches of limited size, separated from other operations by distances such that the loss of a batch and its containing equipment will not entail propagation to neighboring operations.

9-1.1.2.1 Nitrocellulose

The flow sheet of the basic process is shown in Fig. 9-2. Cellulose in the form of cotton linters is dried on a moving belt in a tunnel drier to a moisture content well below 1%. Alternatively, sheeted wood cellulose may be dried in the drier and then shredded. The dried cellulose and mixed nitrating acid are introduced concurrently into the nitrator in which the cellulose is converted to nitrocellulose. At the end of the nitration cycle, about 25 to .30 min, the nitrator is discharged by gravity to the centrifugal wringer in which the spent acid is removed. Part of the spent acid is sent back to the process for reuse after being filtered and upgraded with fresh acid. The remainder of the acid is reworked to remove the water picked up from the nitration from the system. The wrung nitrocellulose, wet with spent acid, is quickly drowned and transferred to the boiling tubs. There, for a period of several hours depending on the degree of nitration of the nitrocellulose, it is boiled in the weak acid resulting from the dilution of the spent acid not removed in the wringing operation. This boiling treatment serves to hydrolyze any sulfate ester formed during the nitration. Next the nitrocellulose is pulped, e.g., in one or more Jordan engines similar to those used in the papermaking industry, and finally it is “poached” or boiled in a slightly alkaline solution to neutralize and remove any residual acid. Thorough washing completes the purification cycle. To accumulate lots of sufficient size or to produce a mixed nitration grade, such as military blend, poacher batches are blended in blending tubs. The finished nitrocellulose is centrifugally wrung to a water content of about 25 to 30% for transfer to propellant operations.

9-1.1.2.2 Nitroguanidine

Dry guanidine nitrate is added in small quantities to sulfuric acid at 10°C or below, As soon as all crystals

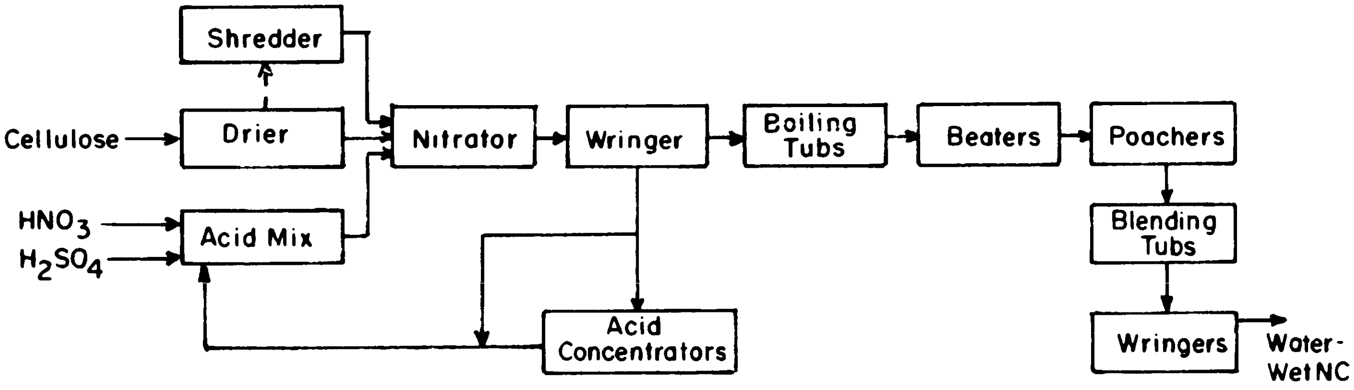

Figure 9-2. Nitrocellulose Manufacture

have disappeared, the resultant milky solution is poured into ice water and allowed to stand until crystallization is complete. The product is filtered, rinsed with water, and recrystallized from boiling water.

9-1.1.2.3 Nitroglycerin

Glycerin is usually nitrated at 25°C or below by adding it very slowly to a well agitated mixture of nitric and sufuric acids, e.g., 40/59 .5/0.5 nitric acid/sulfuric acid/water, using an acid/glycerin ratio of approximately 6:1. Agitation of the reaction mixture is accomplished with compressed air. A rapid temperature rise or appearance of red fumes automatically requires the immediate dumping of the charge into a drowning vessel filled with water. After all the glycerin has been added to the nitrator, agitation and cooling are continued until the temperature drops to about 15°C, and the charge is then run into a separator where the nitroglycerin rises to the top and is run off to the neutralizer. The nitroglycerin is washed first with water, then with sodium carbonate, and finally with water. The resultant nitroglycerin, when washed with water, produces washings that do not color phenolphthalein and is itself neutral to litmus paper.

9-1.1.2.4 Solvent Extrusion

Solvent extrusion is used sometimes for propellants with lower nitrocellulose concentration to reduce the calorific value of the mix. Because the residual solvent content increases with polymer content and with the web thickness, the solvent extrusion process can be used only on grains with fairly thin webs. It is widely used for gun propellants, including small arms and sporting guns. The flow sheet of the solvent extrusion process is shown in Fig. 9-3. The essential operations of the solvent extrusion process are mixing, forming, solvent removal, and finishing.

A number of auxiliary operations (designated by dotted lines in Fig. 9-3), designed to save operation time and improve the quality of the product, have been added to these operations. In the actual extrusion stage of the process, the cylindrical surfaces of the grain are formed by extrusion through a die, using either horizontal or vertical hydraulic presses. The die dimensions must be able to yield a green (solvent-wet) strand of cross section such that on subsequent drying the final dimensions will be as designed.

The shrinkage of propellant is almost entirely in the cross section, and the volumes of propellant and solvent are approximately additive; therefore, the desired green dimensions are readily calculated. The charge for the finishing press is prepared by compacting in a blocking press, which is a hydraulic press working against a closed end. A similar blocking operation, known as preblocking, precedes the macaroni operation, if used. Extruded strands are cut to length, usually while still containing solvent. The equipment for this varies with the grain length. The cutting knives are mounted on a rotating disk, and the strand is fed into the machine by feed rolls synchronized with the cutting head.

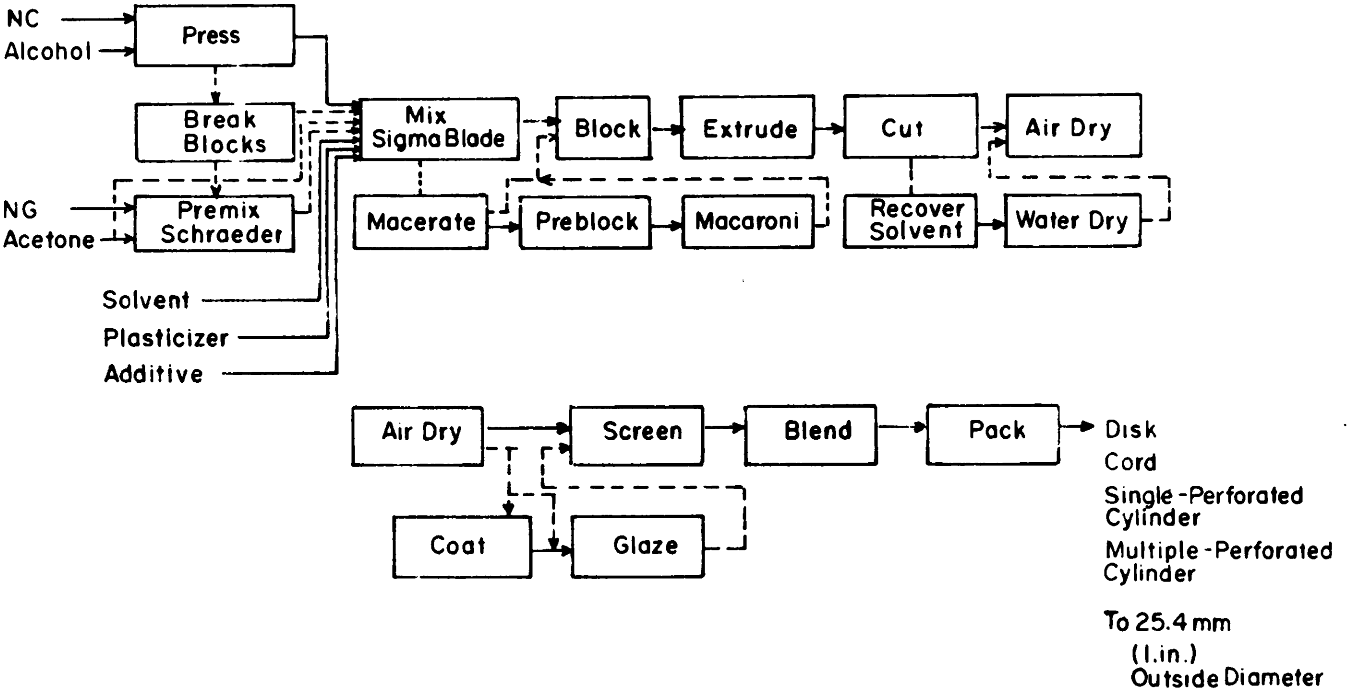

Figure 9-3. Solvent Extrusion Process

9-1.1.2.5 Rolled Sheet

If the propellant is to be used in the form of sheets, strips, cubes, or some other form of rectangular geometry, it may be suitably made by a rolled sheet process. This process is used more extensively abroad than in the United States. Strip propellant is made by slitting the sheet with equipment in which rotating knives bear on the sheet as it passes over a feed roller. Cubes maybe formed by cutting packages of strips with a guillotine or by feeding sheet stock through a dicer in which slitting and chopping are done in one operation. Individual shapes, such as disks, may be punched from the sheets with a die.

9-1.1.2.6 Solventless Extrusion

Propellants with a nitrocellulose concentration below 1g/cm^3, particularly at webs over 10.2 mm (0.4 in.), and in cross sections up to about 178 mm (7 in.) in diameter may be made by the solventless extrusion process. The upper size limit has been set by the ability of a die in a 381-mm (15-in.) press to form a perfectly consolidated grain. As with most extrusion processes, the products have cylindrical geometry. In the case of solventless extrusion, the word “cylindrical” may be very broadly construed (Fig. 9-4). Since no volatiles are present during the extrusion, the die has nearly the same shape and dimensions as the strand, and cross-sectional details, including sharp angles, can be reproduced with fidelity.

9-1.1.2.7 Cast Double Base

The cast double base process is used to form propellants in any geometry and in sizes from about 25 mm (1 in.) in diameter up to unlimited size. The process uses an intermediate casting powder, which may be made either by solvent extrusion (short cylinders about 0.76 mm (0.03 in.) in diameter by 0.76 mm (0.03 in.) long) or by the ball powder process (spheres of similar dimension) and casting solvent, which is a mixture of plasticizers. The bulk density of the casting powders is about 1g/cm^3, and the finished propellant occupies the same volume as its casting powder. This results in a maximum nitrocellulose concentration in the cast propellant of about 1 g/cm^3. Cast double base propellants are, therefore, possible in the same range of compositions as solventless extruded propellants. As a result of blending giant lots of casting powder and carefully controlling the composition of casting solvent, large lots of cast grains can be prepared with an excellent within-lot uniformity. The flow sheet of the process is shown in Fig. 9-5.

9-1.1.2.8 Slurry Casting

Slurry casting is used when the total volume of the liquid ingredients exceeds about 30% of the volume of the composition and it becomes possible to suspend the solids, including the polymer, in the mixed liquids and pour the resulting slurry directly into the mold.

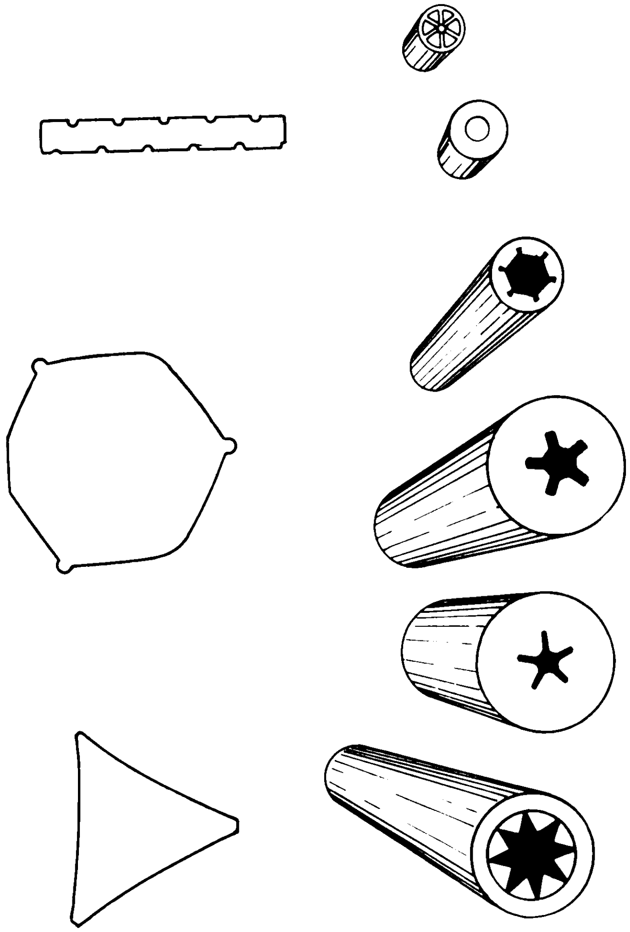

Figure 9-4. Solventless Extruded Shapes

9-1.1.3 Inert Simulants to Reproduce Physical Properties

To represent the physical properties of a propellant by the use of an inert simulant, one needs something more closely akin to the propellant than a wooden mock-up. Most modern propellants are plastics, and a plastic dummy will look, feel, and handle more like its live counterpart; however, this is not always the best possible simulant. For a detailed discussion the reader is referred to Ref. 3.

9-1.1.4 Inert Simulants to Reproduce Manufacturing Properties

To assist in the development of new manufacturing equipment, to check extruders and other types of processing machinery after maintenance or prolonged inactivity, and to displace live propellant preparatory to disassembly of processing machinery after maintenance or prolonged inactivity, it is necessary to have a

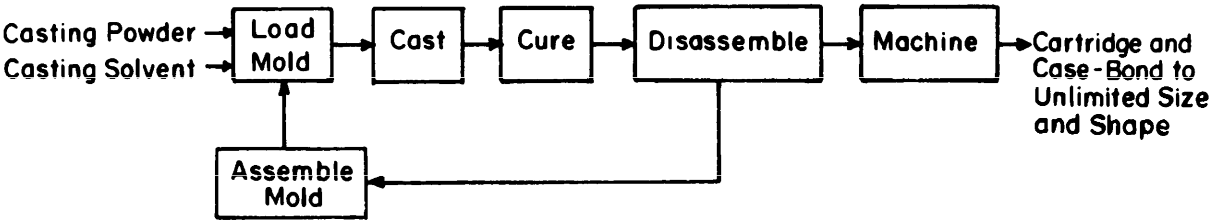

Figure 9-5. Cast Double Base Process

dummy formulation that behaves like live propellant in process. Generally, this requires matching mechanical properties over a wide range of conditions and environments. For a detailed discussion the reader is referred to Ref. 3.

9-1.2 EXPLOSIVES

No attempt is made to coVerall existing explosives or related literature. Only the explosives of military interest and those in more common use today are included in this chapter. The explosives discussed are

1. Black Powder- 10.4% sulfur, 15.6% charcoal, and 74% potassium nitrate
2. Composition B—60% RDX, 40% TNT, wax added 1 %
3. Composition C-4—91% RDX, 9% plasticizer
4. PB-RDX—90'% RDX, 8.5% polystyrene, 1.5% dioctvlphthalate
5. Trinitrotoluene (TNT)
6. Dynamite
7. Tritonal—80% TNT, 20% aluminum
8. Octol—70% HMX, 30% TNT.

Note that of the eight explosives Composition B and TNT are used much more than the others.

9-1.2.1 Material Selection Factors

9-1.2.1.1 Physical Properties

A few of the more pertinent physical properties of selected explosives are given in Table 9-2. An explanation of the table terms is given in subsequent paragraphs. The information in this table was obtained from Refs. 1 and 4. The full complement of explosives and additional physical characteristics are also available in these two references.

1. *TNT Equivalency.* A sample of the explosive to be tested (about 10 g) is exploded in a cavity, or borehole, 25.4 mm (1 in.) in diameter and 127.0 mm (5 in.) deep, in a lead cylinder 203.2 mm (8 in.) in diameter and 203.2 mm (8 in.) in height. The borehole is made in the center of the upper face of the cylinder, which is cast from desilverized lead of the best quality. Although these tests have been made under a variety of conditions, where possible the data have been taken from or related to those of Naoum (Ref. 5). Here a Number 8 blasting cap was used for initiation of the explosive sample. The weight of the explosive sample used was adjusted to give, with the initiator, a total expansion of 250 to 300 cm^3 because within this range expansion and sample weight were linearly related under the conditions of Naoum's test. Thus expansions for equivalent weights were readily calculated, and the test value was expressed in percent of the expansion of an equivalent weight of TNT.

2. *Impact Sensitivity.* A sample of explosive is subjected to the action of a 2-kg falling weight. A 20-mg sample of explosive is always used when testing solid explosives. The impact test value is the minimum height in centimeters at which at least one of 10 trials results in explosion. The explosive is held between two flat, parallel, hardened (C 63 ± 2) steel surfaces. The impact impulse is transmitted to the sample by the upper flat surface.

3. Storage *Method.* Storage for bulk explosives requires care and attention, and a riety of regulations are involved. For this reason, storage should be considered as a factor affecting producibility. Ammunition and bulk explosives are divided into quantity distance classes, Class 1 through Class 12. For further information on this subject see Ref. 6.

4. *Friction Pendulum Test.* A 7-g sample of explosive, 50 to 100 mesh, is exposed to the action of a steel or fiber shoe swinging as a pendulum at the end of a long steel rod. The behavior of the sample is described qualitatively to indicate its reaction to this experience, i.e., the most energetic reaction is explosion and, in decreasing order of severity of reactions, snaps, cracks, and unaffected.

9-1.2.1.2 Material Availability

The military is the prime supplier and user of this class of material. Consequently, availability is largely a factor of the military production base. There are, however, several industrial producers of industrial explosives such as dynamite. Inquiries should be made through proper channels to determine status and avail-

TABLE 9-2. PHYSICAL PROPERTIES OF SELECTED EXPLOSIVES

Explosive	1* TNT Equivalency	2* Impact Sensitivity	Density g/cm^3	3* Storage Method	4* Friction Pendulum Test Steel Shoe	4* Friction Pendulum Test Fiber Shoe	Compressive Strength MPa (psi)
Black Powder	10	32	Variable	Dry	Snaps	Unaffected	**
Composition B	130	75	1.65	Dry	Unaffected	Unaffected	11.10—17.79 (1610–2580)
Composition C-4	117	100+	1.64-1.66	Dry	Unaffected	Unaffected	l#
PB-RDX	**	28	0.81 Unpressed 1.62 Pressed	Dry	Unaffected	Unaffected	16.55 (2400)
TNT	100	95 to 100	1.65	Dry	Unaffected	Unaffected	96.53 (14,000)
Dynamite	Hybrid explosive with variation based on mixtures						
Tritonal	125	85	1.72	Dry	Unaffected	Unaffected	16.13 (2340)
Octol 70/30	**	18	1.80	Dry	Unaffected	Unaffected	10.41 (1510)

* Notes 1 through 4 are discussed in par. 9-1.2.1.1.

**Data not available.

ability of any explosive before commitment to a new design.

9-1.2.2 Applications

The principal uses of the discussed explosives are shown in Table 9-3. For additional information on this subject, see Refs. 1 and 4.

9-1.2.3 Manufacturing Processes

9-1.2.3.1 Black Powder

The proper mix of ingredients—sulfur and charcoal—are combined in a tumbling barrel and mixed for a short period. The mixture is transerred to a wheel mill, and the final ingredient-potaissium nitrate-is added with very strict controls of moisture content (3 to 4%). The final mill cake is then pressed at 41.4 MPa (6000 psi) between aluminum plates. The cakes are broken up between rubber or wooden rolls, and particle sizes are selected as desired. The material is then dried in hot air ovens. The particles can be glazed with graphite if desired. The material is loaded into an explosive container either in loose, granulated, or pressed form.

9-1.2.3.2 Composition B

Water-wet RDX is added slowly with stirring to molten TNT melted in a steam-jacketed kettle at a temperature of 100°C. Some water is pound off, and heating and stirring are continued until all moisture is evaporated. Wax is then added, and when thoroughly mixed. the composition is cooled to a satisfactory pouring temperature. It is cast directly into ammunition components or into the form of chips when Composition B is to be stored. The fact that it can be reheated to a liquid for casting when desired enhances its producibility and contributes greatly to its desirability as an explosive.

9-1.2.3.3 Composition C-4

Composition C-4 is prepared by hand kneading and rolling or blending in a Schrader Bowl mixer, RDX of 44-micron size or less with polyisotritylene plasticizer previously made up in ether. The thoroughly blended explosive is dried in air at 60°C and loosely packed by hand tamping to its maximum density.

9-1.2.3.4 PB-RDX

PB-RDX is a mixture of RDX coated and surrounded by a homogeneous mixture of polystyrene and dioc-

TABLE 9-3. APPLICATIONS OF SELECTED EXPLOSIVES

	Time Ring Fuzes	Igniter Powder	High Explosive Projectile	General Purpose Bombs	Shaped Charges	Grenades	Depth Charges	Demolition Charges	Demolition Ingredient	High-Strength Explosive
Black powder	x	x								
Composition B			x		x	x				
Composition C-4								x		
PB-RDX										x
TNT			x	x		x	x	x		
Dynamite									x	
Tritonal				x						
Octol 70/30			x	x						

tylphthalate. The specified percentage of RDX must consist of a mixture of 75% Type B, Class A RDX and 25% Type B, Class E RDX. The granulation of the unpressed composition shall be as shown in Table 9-4. Two methods have been reported for the preparation of PB-RDX (Reference: Los Alamos Scientific Laboratory, Contract W-7405-Eng 36 with the US Atomic Energy Commission, Report LA-1448.) The earlier method employed a Baker-Perkins-type mixer to blend the components. This procedure produced an end-item with good pressing characteristics. However, the molding composition was nonuniform in granulation and tended to be dusty. The slurry method of PB-RDX preparation yielded a product that was uniform, free-flowing, and dustless. In addition, PB-RDX granulated by the slurry method exhibited satisfactory drying, handling, and pressing characteristics.

TABLE 9-4. GRANULATION OF UNPRESSED COMPOSITION FOR PB-RDX

Through US Standard Sieve Number	Minimum %	Maximum %
6	100	—
12	60	—
20	—	2
35	—	0

9-1.2.3.5 TNT

In older processes TNT was slowly and laboriously nitrated in three stages using successively stronger acids. Today, however, a single-stage nitration is possible in a short time (less than 1 h) and produces TNT at a cost of a little less than 13¢/kg. In England a two-stage, continuous process was developed during World War II; in the first countercurrent stage, toluene was nitrated to mononitrotoluene (MNT); in the second stage, also countercurrent, MNT was nitrated to TNT. Because of the general suitability of TNT for melt-loading and its extensive use in binary and ternary explosive mixtures, TNT is considered the most important military explosive known today. TNT is either cast or pressed into the explosive device.

9-1.2.3.6 Dynamite

Dynamite is a commercial hybrid high explosive mixture containing nitroglycerin and/or nitroglycol and/or ammonium nitrate. Other materials such as fuels, oxidizers, and an inert base may be added to obtain specific desired levels of brissance, sensitivity, force, or detonation speed. It may be packed in cylindrical paper cartridges or in bags, is set off by a detonator, and is used for general blasting purposes.

9-1.2.3.7 Tritonal

Tritonal is prepared by adding TNT and aluminum separately to a steam-jacketed melt kettle equipped with a stirrer. Heating of the kettle and mixing of the ingredients are continued until all the TNT is melted. When the viscosity of the mixture is considered satisfactory (at about 85°C), the tritonal is poured into projectiles or bombs in the same way as TNT.

9-1.2.3.8 Octol 70/30

Water-wet HMX is added slowly to molten TNT in a steam-jacketed kettle at a temperature of 100°C. The mixture is heated and stirred until all moisture is driven off. The composition is cooled to a satisfactory pouring temperature and cast directly into ammunition components, or it is prepared in the form of chips and stored for later use.

9-1.2.3.9 Composite Explosives

Composite explosives consist of two or more substances; none of which is an explosive. Typically they consist of the mixture of a substance that serves as a fuel with a substance that serves as an oxidizer. The mixture of the oxidizer ammonium nitrate, which is difficult to explode by itself, and common fuel oil is an example of a composite explosive that has become well-known as a cheap blasting agent.

9-1.2.4 Compatibility y of Materials

One of the more important characteristics necessary to achieve good producibility of explosives is compatibility. This is critical in the explosive device itself as well as in any tools, jigs, or fixtures that come in contact with the material, Ref. 4 lists all explosives and their compatibility with various metals.

Additionally, the Plastics Technical Information Center (PLASTEC), US Army Armament Research and Development Command, Dover, NJ 07801, offers a computer program for retrieving data on the compatibility of polymers and other materials with explosives and propellants. This program, known as COMPAT, can be used by all Government agencies and by private industry on a service fee basis. The program offers access to a unique body of data covering the effects of explosives and propellants on polymer behavior. It also contains a supplemental program called “Hazard Failure” containing information on known deficiencies or problems of polymers.

9-2 OPTICAL COMPONENTS

Although the machines, materials, and methods of producing optical components have changed considerably in recent years, the basic processes have changed very little. This is largely due to the limited knowledge that exists concerning the phenomena of polishing and grinding. The production of optical components, specifically the polishing and grinding processes, is an art that has not been reduced to science and, therefore, only limited mechanization exists. There has been some limited application of computer-aided techniques applied to the engraving of retitles and to the grinding of gradient or radial optics, but no widespread automation efforts have been undertaken. The aspects of producibility of importance to the designer and briefly described in this paragraph are material considerations, manufacturing processes, inspection and test procedures, and a basic understanding of current practices in specifying optical requirements.

9-2.1 OPTICAL MATERIALS

Materials for optical components generally include glass, crystals, and plastics. Some general properties of these materials are shown in Table 9-5.

9-2.1.1 Glass

Glass is created by mixing silica sand (SiO_2) with carefully controlled quantities of various inorganic substances and a proportion of scrap glass (cullet), followed by heating the mixture to about 1550° C and

TABLE 9-5. GENERAL PROPERTIES OF OPTICAL MATERIALS

Property	Glasses	Crystals	Plastics
Refractive index	1.45-1.95	1.54-1.76	1.49- 1.7
Infrared transmission	Fair	Good	Very poor
Visible transmission	Very good	Very good	Very good
Ultraviolet transmission	Fair	Good	Very poor
Heat resistance	Very good	Excellent	Fair
Thermal stability	Very good	Excellent	Poor
Mechanical strength	Fair	Very good	Good
Mar resistance	Good	Very good	Poor
Weather resistance	Fair to very good	—	Poor to Very good
Chemical resistance	Fair to very good	Very good	Poor to excellent
Specific gravity	Moderate	High	Low
Formability	Poor to good	Poor	Very good

cooling the melt at a rate designed to prevent crystallization. This is followed by an annealing process. The modern tank furnace melts the raw materials required for a continuous flow of glass, which is needed for automatic forming machinery. Glass forming processes are all based on the fact that the viscosity of glass increases as the temperature falls. Sheet glass is drawn upward continuously from a tank—the ribbon is started on a metal former known as a bait. The rate of drawing determines the thickness, and the width is kept constant by passing the edges of the ribbon through cooled rollers, which chill the edges of the glass. The chilled edges then act as supports for the less viscous glass suspended between them. Molten glass may also flow continuously from a tank between water-cooled rollers that control the thickness and may give a surface pattern to the glass. Alternatively, parallel surfaces may be ground and polished in the same continuous process to give polished plate glass. There are several processes used in the manufacture of glass; these include the float, flat draw, cast and rolled, and pot processes. Applications and general qualities of the glass produced by these three processes are shown in Table 9-6. For precise optical qualities the pot process is used.

9-2.1.1.1 Float Process

A recent development is the float process in which a continuous ribbon of glass, about 3.4 m (11 ft) wide, flows from the tank to float on the surface of an inclosed bath of molten tin at a controlled temperature in a controlled atmosphere (Fig. 9-6). The ribbon is held in a chemically controlled atmosphere at a high enough temperature for a long enough time for the irregularities to melt out and for the surfaces to become flat and parallel, which gives undistorted vision and does not require a subsequent grinding or polishing process. Because the surface of the molten tin is dead flat, the glass also becomes flat. The ribbon is then cooled while still advancing across the molten tin until the surfaces are hard enough for it to be taken out of the bath without the rollers marking the bottom surface. The resulting ribbon is of uniform thickness with bright, fire polished surfaces.

9-2.1.1.2 Flat Draw Process

In the modern flat draw process, as shown in Fig. 9-7, sheet glass is manufactured in a large tank. The raw materials, which consist of the actual ingredients and broken glass, known as “cullet”, are fed into the filling pocket of the tank. At the exit end of the furnace, the molten glass is drawn in a thin sheet up a 9.14-m (30-ft) high annealing tower. At the top of the tower the glass is cut into large plates and removed with suction pads. A glass tank, which may be as large as 36.6 m (120 ft) long by 10.97 m (36ft) wide and 1.524 m (5 ft) in depth, has sides and bottom made of clay blocks and a roof of silica bricks and may contain up to 1089 tonnes (1200 tons) of molten glass, with temperatures varying from 1200° C to 1530° C in different parts of its length. The amount of glass flowing down the middle of the tank, due to convective currents, is about 20 times as much as that being withdrawn at the working end.

To form the glass into a sheet, molten glass first

TABLE 9-6. APPLICATIONS AND GENERAL QUALITIES OF GLASS

Manufacturing Process	Applications	Thickness, mm
Float process	Mirrors, graticules, and theodolite circles. Used where a controlled refractive index is not required, but reflection and transmission are essential properties.	3-15
Flat draw process	House windows, factory windows, and greenhouses. Used anywhere good through-vision is not required. Has some distortions.	2-6
Cast and rolled	Factory roof lights and similar applications where light transmission is desired. Has poor vision properties due to major distortions.	
Pot process	Used for very small quantities of high quality glass where a controlled refractive index is required, such as lenses and prisms.	150-200

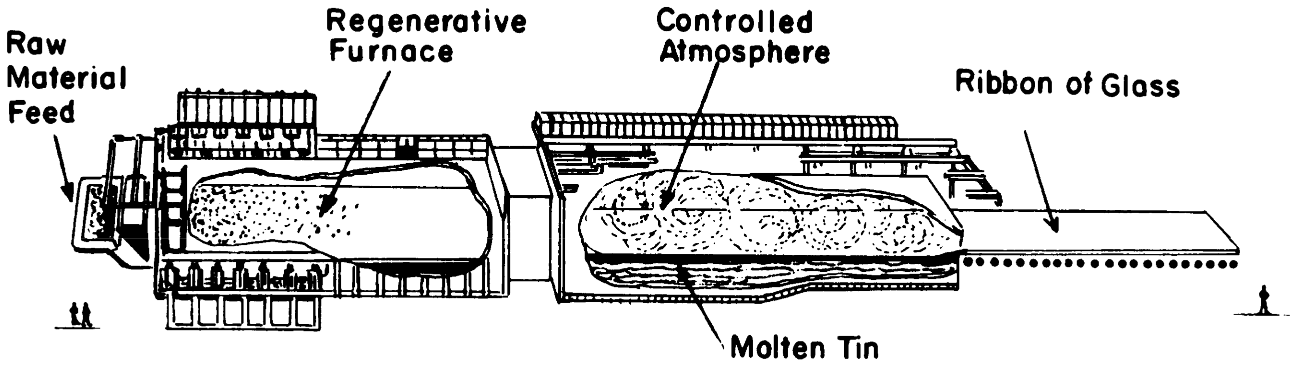

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Figure 9-6. The Float Glass Process (Ref. 7)

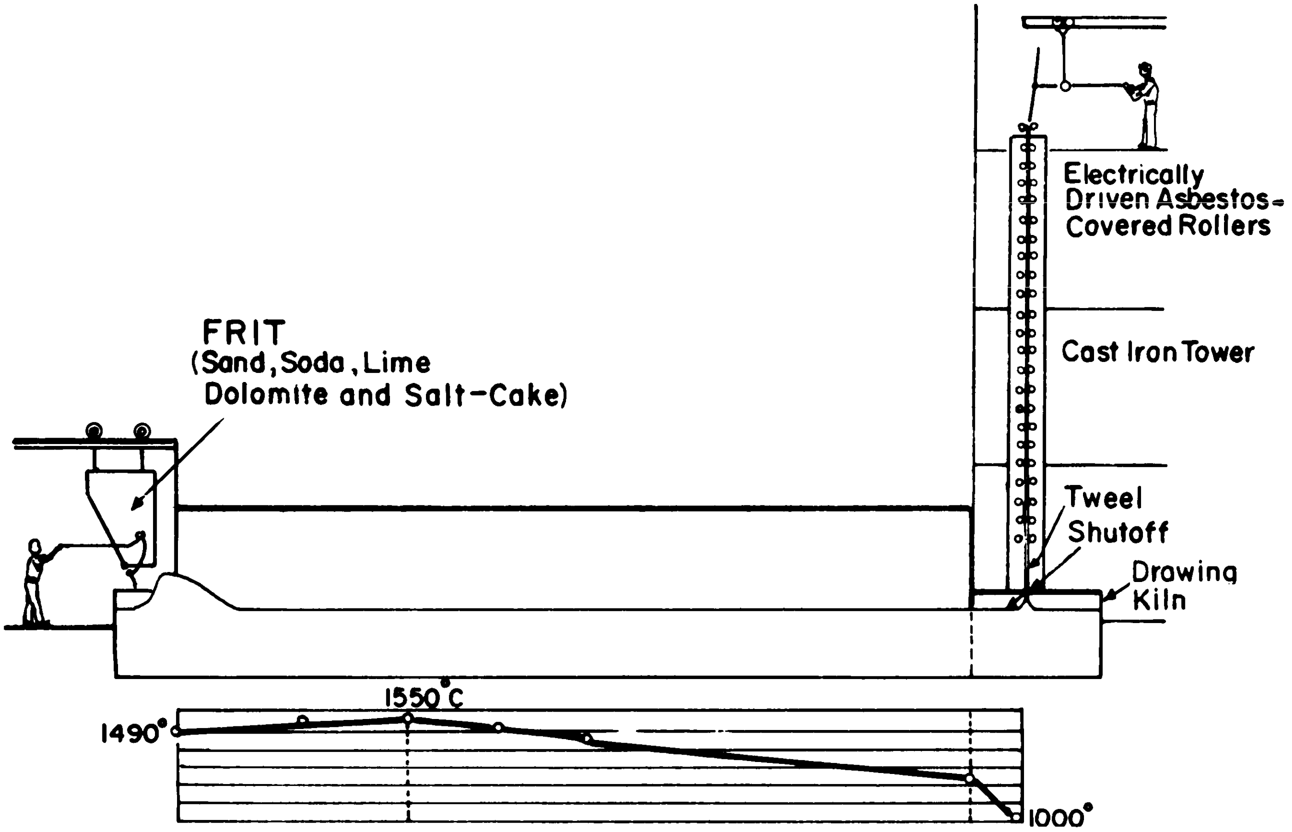

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Figure 9-7. The Flat Draw Process (Ref. 7)

passes from the tank into a drawing kiln, a relatively small extension to the tank. The kiln is separated from the tank above the level of the glass surface by a tweel and shutoff. The tweel is a slab of refractory material suspended from one edge and lowered until it rests on the shutoff and completes the seal between the tank atmosphere and the atmosphere of the kiln. The shutoff is a block of refractory material that floats on the surface of the glass. There are usually four to five drawing kilns to each melting tank. After entering the drawing kiln underneath the shutoff, the glass flows around either side of the submerged clay block and is drawn up in the form of a sheet from the surface through a series of electrically driven asbestos-covered rollers, which are mounted in pairs in a cast-iron tower. To start the process, an iron grille, known as the “bait”, is lowered between the tower rollers into the glass of the kiln. When the bait has remained there for a short period, the molten glass sticks to the iron, and the bait is slowly lifted and draws behind it a sheet of glass. When the leading edge of the sheet has passed between the first few tower rollers, the bait can be cracked off from the glass. The rollers—engaging the sheet of glass, which has followed the bait—draw up a continuous strip or sheet into the annealing tower. Facing the sheet at a postion just above the level of the glass in the kiln are water-cooled steel boxes. These assist in solidifying the sheet as soon as it has been formed. Once the sheet has been formed, it may be drawn continuously as long as raw materials are fed into the filling pocket. As the glass is drawn up the tower, which acts as an annealing oven, it gradually cools, and at a height of 9.14 m (30 ft) above the drawing kiln, it is sufficiently cool to be cut. Trimming consists of the removal of the edges of the glass that bear the marks of the knurled rollers. The glass lost by this edge trimming is returned as cullet to the tank and remelted. (It has been found that anywhere from 40% up to even 100% cullet may be used; the greater percentage of cullet drastically reduces the need for pollution abatement.)

9-2.1.1.3 Cast and Rolled Process

This process is a continuous method of casting in which the raw materials are fed into one end of a gas-heated tank, melted, refined, cooled, and then drawn from the other, or working, end of the tank in the form of a horizontal, continuous ribbon and not vertically, as described for flat draw sheet glass. The ribbon passes on rollers into an annealing oven, at the end of which it is examined and cut into the required sizes. Rolled and roughcast glasses are used where clear vision is not required, for example, in factory roofs or vertical glazing.

9-2.1.1.4 The Pot Process

This process, as currently used, is intended for the production of small quantities of high quality glass. The real production of glass starts in the mixing machine where often more than 10 compounds in the proper proportions are thoroughly mixed and then ladled into a hot fireclay pot. The regenerating chambers on each side of the furnace contain a refractory bar system and are heated by the hot exhaust gases. The incoming air, necessary for burning the oil, is passed over hot bars on the way to the furnace. The intake air and exhaust gas automatically alternate from one side of the furnace to the other every few minutes, Ladling the raw material mixture for glass into the pot takes several hours according to the type of glass. The slower the mixture melts, the slower it is ladled into the pot.

It may take 40 h to fill the pot with some glasses that are difficult to melt. The hot flames of the furnace burner cause the mixture to consolidate and melt at a temperature of about 1200° to 1400°C into a viscous liquid. Bubbles are formed by the chemical reaction of the mixture ingredients and also by the gases leaving the mixture. The procedure for removing bubbles is to increase the temperature from 1300° to 1500°C so that the clearing ingredients, which have been added to the mixture, can remove the gas. This process takes several hours, and when the glass is clear of bubbles, the temperature is reduced until the desired viscosity for stirring is reached. At the end of stirring to achieve the required homogeneity, the temperature is gradually decreased so that the glass becomes even more viscous. Immediately after stirring, the pot is taken out of the furnace. A special pouring crane pours the glass into an iron mold that has been preheated to about 200°C.

The iron mold, filled with molten glass, is taken to a preheated cooling furnace. In this furnace the glass is cooled to room temperature over several weeks or even months in order to avoid strains. The quality of the glass is decisively influenced by this process because only a carefully cooled glass shows a consistent homogeneity without cracks. When cool, the glass block is freed from the iron mold and opposite faces are ground and polished for examination. Since it is not possible to identify film faults in the glass from the inspection windows in the block, it is necessary to make some polished test pieces. In a darkened room the glass test pieces are examined for striae, bubbles, and other defects, such as stones. Defective pieces are cut off the block with a diamond saw, for which paraffin is a lubricant. The remaining good glass can either be worked as a large piece or can be cut up into many small pieces for lenses or prisms. It takes about 20 weeks from preparation of the pot to dispatching of the completed glass.

9-2.1.1.5 Physical Properties

Any process used for producing glass is controlled primarily by the specifications of the product application. The secondary controls are the physical properties of the specific batch of material. In the production of glass the physical properties that most influence the process are viscosity and devitrification.

Glass has no definite melting point. If it is heated, it first softens so that it can be bent. As the temperature rises, it reaches a point where it becomes a thick, syrupy liquid, ie., a state in which it can be “worked”. At still higher temperatures it becomes a thin, watery liquid.

Although weathering properties can be assured by a lime content, there is always the danger of crystallization. Above a certain temperature, known as the devitrification temperature, glass may be kept in a liquid condition without any change occurring, but if the glass is kept slightly below the devitrification temperature for any length of time, crystallization or devitrification occurs. It is, therefore, essential in any process that the time and temperature function of the operation not allow devitrification. The tendency to devitrify can be reduced by decreasing the amount of lime and increasing the amount of soda, but this can only be done at the expense of the weathering properties.

9-2.1.2 Crystals

The transparency of ordinary optical glass extends very little beyond the visible range of the spectrum. Consequently, optic components designed to operate in the ultraviolet or infrared wavelengths must consider other materials. In most cases these are in the form of individual crystals. Crystals are important to the family of optical materials for several reasons. They have good transmission in the ultraviolet and infrared spectral regions, they have a good relationship between refraction and dispersion, and they have high thermal stability with good mechanical strength.

9-2.1.2.1 Natural Crystals

Natural crystals of quartz, calcite, rock salt (sodium chloride), sylvine (potassium chloride), fluorite (calcium fluoride), and sapphire (aluminum oxide) have all been used for optical components. Natural crystals that are clear and of sufficient size are relatively scarce and expensive.

9-2.1.2.2 Artificial Crystals

Artificial crystals are comparable with natural crystals in optical qualities. Although they may be grown from solution, most optical crystals are grown from the molten state. They are grown from very pure materials, and the rate of growth must be closely controlled.

Important characteristics of crystals are discussed:

1. *Crystal Sizes.* The maximum size of crystal ingot growth is a factor of the process used, the desired optical qualities sought, and the nature of the material itself. Consequently, it is difficult to establish a firm limitation on size. Thermal stresses in a crystal tend to increase with the size of the crystal. This has an adverse effect on the application of the crystal for X-ray diffraction. It would be of little importance, however, if the application of the crystal were for infrared transmission. For the design engineer interested in producibility, it can safely be assumed that crystals of halides, silicon, and aluminum oxide are available in diameters up to 203.2 mm (8 in.).

2. *Properties of Optical Crystals.* The refractive index; which is dependent on the wavelength, is probably the most used optical property. Fig. 9-8 shows the relationship between wavelength and refractive index for a number of the more common optical crystals.

3. *Nonoptical Properties.* Some of the more important nonoptical properties of the crystals in both the standard and nonstandard ranges are shown in Table 9-7. A discussion follows:

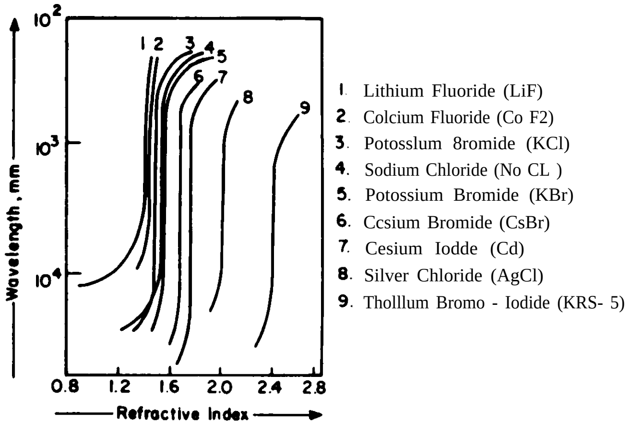

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Figure 9-8. Refractive Indices of Artificial Crystals (Ref. 7)

a. *Cleavage.* Many of the materials listed exhibit the phenomenon known as cleavage when struck with a sharpened tool suitably oriented along a cleavage direction. When a crystal cleaves, the surfaces revealed are approximately smooth and flat and can be identified with a set of planes in the crystal structure. The table lists the relevant planes in the cases of those crystals that do cleave.

b. *Volubility.* The volubility in water of the listed materials is important because it governs the conditions under which they may be handled and used. The values given represent the weight of material that will dissolve in 100 g of water at room temperature.

c. *Hardness.* Several methods exist to define the hardness of surfaces, notably those of Knoop and Mobs. None are completely satisfactory, and the results are occasionally contradictory. The problem is further complicated by considerable variations between different crystals of the same material due to quite small changes in purity and also as a function of crystal orientation. (This results in a further problem because cleavage becomes more difficult to effect with increasing softness.) Therefore, the results quoted are intended only as a rough guide and are comparative rather than absolute. The standard comparison is general optical lithium fluoride, which is assigned the value unity.

d. *Elastic Stiffness.* Crystals have relatively unique physical properties based on their crystalline structure. For a general crystalline structure the theory of elasticity would require 21 constants. This reduces to three independent elastic constants for cubic crystals—C_{11}, C_{lz}, and C_{44}. For cubic crystals these three constants define the physical properties. Table 9-7 provides values of these three stiffness constants in units of 10^{11} Pa.

A summary of the applications and qualities of optical materials is given:

TABLE 9-7. NONOPTICAL PROPERTIES OF CRYSTALS

Material	Structure	Cleavage	Volubility (g/100 g H_2O)	Melting Point °C	Hardness (ref: LiF)	Elastic Moduli, 10^{11} Pa		
						C_{11}	C_{12}	C_{44}
LiF	Cubic NaCl	100	0.27	842	1.00	1.14	0.48	0.64
NaC1	Cubic NaCl	100	35.7	901	0.4	0.49	0.13	0.13
NaI	Cubic NaCl	100	184	651	0.1	0.30	0.09	0.07
KC 1	Cubic NaCl	100	34.7	776	0.9	0.41	0.07	0.06
KBr	Cubic NaCl	100	53.48	730	0.07	0.35	0.05	0.05
KI	Cubic NaCl	100	127.5	725	very soft	0.28	0.05	0.04
CsBr	Cubic CsC1	none	124.3	640	0.2	0.31	0.08	0.08
CsI	Cubic CsC 1	none	44	621	very soft	0.25	0.07	0.06
CaF$_2$	Cubic CaF$_2$	111	0.0016	1360	1.6	1.64	0.47	0.34
MgF$_2$	Tetragonal Rutile	poor	0.0076	1255	4.0	not applicable		
KRS-5	Cubic NaCl	**n n**	0.05	414	0.4	0.33	0.13	0.06
AgC1	Cubic NaCl	none	0.0021	458	very soft	0.60	0.36	0.06
NaBr	Cubic NaCl	100	116	755		0.40	0.11	0.10
NaF	Cubic NaCl	100	4.22	980	0.8	0.97	0.24	0.28
KF	Cubic NaCl	100	92.3	851		0.66	0.15	0.13
RbF	Cubic NaCl	100	130.6	760		0.55	0.14	0.09
RbC1	Cubic NaCl	100	77	715	3.63	0.06	0.05	0.06
RbBr	Cubic NaCl	100	98	683		0.31	0.05	0.04
CsF	Cubic NaCl	100	367	690				
SrF$_2$	Cubic CaF$_2$	111	0.011	1400	1.5	1.24	0.43	0.31
BaF$_2$	Cubic CaF$_2$	111	0.12	1280	0.8	0.89	0.40	0.25
PbF$_2$	Cubic CaF$_2$	poor 111	0.064	822		0.93	0.44	0.21

1. *Standard range lithium fluoride (LiF).* It is a widely used optical material with useful infrared transmission and the farthest ultraviolet transmission of all the optical cyrstals. It has low water volubility and a long working life.

a. General optical. Standard quality for plates, infrared windows, etc.

b. Far ultraviolet, Specifically for transmission down to the limit of the ultraviolet range, a transmittance of 50% through 2 mm thickness is guaranteed. Due to its high purity, this material is soft and difficult to cleave.

c. X ray. This material is intended for use in X-ray applications and is selected for its good structural quality.

d. Low dislocation density (LDD). A small demand exists for crystals of very LDD, mainly for research purposes, and crystals up to 25 mm (1 in.) in diameter are available.

2. *Sodium chloride (NaCl).* This material is widely used for windows and prisms in infrared spectroscopy. It is not expensive and is easy to handle. Although water soluble, it is relatively unaffected by atmospheric moisture in instruments in which the temperature is kept only a few degrees above ambient.

3. *Sodium iodide (NaI).* In its pure form NaI is sometimes used as a light guide in scintillation detectors employing thallium-doped NaI as the basic scintillater. It is also of some interest in applications for pure research but is very hydroscopic and thus difficult to handle.

4. *Potassium chloride (KC1).* The KC1 infrared cutoff is beyond that of NaCl but falls short of that of KBr. Like all the alkali-halides it is used in basic research studies.

5. *Potassium bromide (KBr).* It is widely used in infrared applications for which transmission beyond the NaCl cutoff is required; it suffers from surface fogging by atmospheric moisture unless kept in a suitably dry environment.

6. *Potassium iodide (KI).* In this material infrared transmission extends farther even than KBr, but it is

very hydroscopic and also very soft. For most practical applications KBr is preferred.

7. *Cesium bromide (CsBr).* CsBr is useful as an optical component in the infrared; it is, however, hydroscopic, and finished surfaces will be attacked by atmospheric moisture. This may show up as a separation along grain boundaries.

8. *Cesium iodide (CsI).* It has the farthest infrared transmission of all optical crystals. Wide use is limited by the fact that it is very soft and difficult to polish. CsI components are considerably more expensive than those of similar size of KBr.

9. *Calcium fluoride (CaF_2).* CaF_2 is useful for infrared and ultraviolet work, especially the latter, where its transmission is exceeded only by LiF and MgF_2. It is hard, takes an excellent polish, and because it is insoluble, it can be left for long periods without surface deterioration.

10. *Magnesium fluoride* (MgF_2). MgF_2 is hard and insoluble like CaF_2, but in its molten form it is less stable and therefore more difficult to grow. It exhibits birefringence (*no*= 1.37770, *no* = 1.38950), and current applications include the manufacture of polarizing prisms for the ultraviolet

11. *Thallium bromo-iodide* (KRS-5). This material transmits almost as far as CsI into the infrared and is not water soluble to any significant extent; therefore, it is useful as an infrared window in field applications. At the other end of the scale its ultraviolet cutoff is, in fact, in tile visible range, so that its width of useful transmission is limited. It has a very high refractive index (*n* = 2.22 at 4.0 µm).

12. *Silver chloride (AgCl).* AgCl has useful infrared transmission applications. It is insoluble and can be used as windows in cells containing aqueous solutions. Although soft, dilffcult to polish, and exhibiting no cleavage, it is ductile and can be rolled into sheets of the desired thickness.

9-2.1.3 Plastics

Optical components fabricated from plastics are of significant interest to the design engineer interested in producibility. These plastics have distinct economic advantages because they can be molded; they do not have to be ground and polished. Although relatively lightweight and much less brittle than crystal or glass, they should not be used without considering their disadvantages of poor scratch resistance, low softening temperature, and greater thermal expansion. Table 9-8 shows some of the commercially available optical plastics and their properties.

9-2.2 OPTICAL COMPONENT MANUFACTURING PROCESSES

These processes can be summarized into four basic opetations-cut the blank, rough grind to approximate size, finish grind to final size, anti polish. The manufacturing processes for producing optical components could be most accurately described as the art of grinding and polishing optical components. However, even though grinding and polishing represent the significant operations in optical component production, there are others to be considered. The manufacturing employed in each of the four basic operations is discussed.

TABLE 9-8. OPTICAL PLASTIC PROPERTIES

Plastic Material	Density, g/cm^3	Coefficient Expansion, 10^6/°C	Upper Limit Stability, “c
Allyl diglycol carbonate	1.32	90 to 1000	60 to 70
Polymethyl methacrylate	1.19	63	70 to 100
Polystyrene	1.10	80	70
Copolymer styrene methacrylate	1.14	66	95
Copolymer methylstyrene-methyl methacrylate	1.17	—	110 to 120
Polycarbonate	1.20	70	120 to 135
Polyester-styrene	1.22	80 to 150	50 to 120
Cellulose ester	1.30	80 to 100	50 to 60
Copolymer styrene-acrvlonitrile	1.07	70	90

9-2.2.1 Acquiring the Blank

Several methods of acquiring the blank include

1. *Trepanning. This* method is used for cutting circular discs from a slab of material. A drilling machine can be converted for the purpose. A trepanning tool is placed in the spindle, and provisions are made for a flow of lubricant through the spindle. The trepanning tool consists of a steel cylinder that bears a ring of impregnated diamonds on the cutting edge.

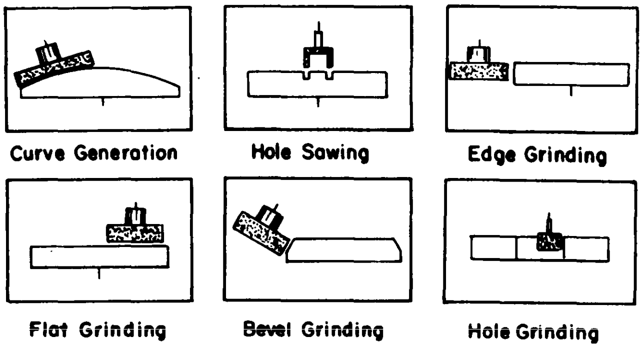
2. *Moldings.* Moldings are available either directly from the glassmaking machine on line for large quantities of spectacle lenses, camera lenses, binocular lenses, and prisms or alternatively as molds in a separate molding furnace. The remold process consists of cutting and chipping the slab to an accurate weight demanded by the particular molding, heating the glass in a furnace to the correct plastic temperature, and pressing in the mold, followed by annealing in a furnace over a number of hours to restore homogeneity, These moldings are consistent for diameter and thickness within close limits, and this high degree of consistency permits the preparation of collets, fixtures, and holding tools for long production runs in a secondary process,

3. *Bandsaw.* A bandsaw with a hard-edge, flexible-back blade about 3 mm (O. 125 in.) wide can be used to saw crystals. Soluble crystals can be edged to correct diameter by rolling them in a film of water.

4. *Friction Saws. These* are like a large circular saw but are equipped with carbide or diamond blades. These are used to make straight-line cuts in a variety of materials.

9-2.2.2 Rough Grinding

Equipment for grinding and curve generation of optical components is designed with varying degrees of automation capabilities for production applications. Generally, the functions shown in Fig. 9-9 are representative of the capabilities of this equipment.



Curve Generation Hole Sawing Edge Grinding

Flat Grinding Bevel Grinding Hole Grinding

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Figure 9-9. Grinding Equipment Functions (Ref. 7)

9-2.2.3 Curve Generators

Modern curve-generating machines will consistently produce accurate spherical surfaces, which are ready for fine grinding before polishing. Curve generators are used in two ways: (1) to generate the spherical surface on a blank or individual molding and (2) to generate a block filled with blanks or moldings. There is a smaller range of machines available with a maximum capability of 100 mm diameter lenses and blocks. A larger range of machines will take lenses up to 550 mm in diameter. These machines employ either a vertical or a horizontal spindle; however, the basic principle of operation is the same regardless of layout. The lens is held in a chuck and rotated at a low speed 0.5 to 2.6 rad/s (5 to 25 rpm). In this mode the lens is presented to a round-nosed, diamond-impregnated tool rotating on a high-speed spindle 210 to 1680 rad/s (2000 to 16,000 rpm). Some typical rough grinding curve generators are described,

1. *Four-Spindle Curve Generator.* The suitability of this machine for mass production of single lenses or small blocks warrants special merit. The work spindles will take a lens size of 4.75 mm to 70 mm in diameter. The high-speed spindle rotates at 100 rad/s (1000 rpm) and the work spindle at 2.1 rad/s (20 rpm). The lens thickness can be controlled to 0.013 mm (0.0005 in.), and curvature accuracy to 0.0020 mm (0.00008 in.). This machine is also available in a single-spindle form. Like the four-spindle, the single-spindle model has an electrohydraulic cycling circuit with process timers for quick and precise setting of the required dwell period. The control gives repetition on both curvature and thickness. Typically, a lens will take 45 s to grind, 15 s to dwell, and 10 s to load and unload.

2. *High-Capacity Generator.* This is a larger machine suitable for either long runs on blocks of lenses or varied jobbing work. The work spindle will take blocks from 25 mm to 150 mm in diameter, and the maximum sag at 150 mm in diameter is 50 mm. Diamond tools from 25 mm to 101 mm in diameter can be accommodated.

3. *Automatic Lens Curve Generator.* This machine is unique in that it has automatic lens feed from a magazine for single surface work up to 65 mm in diameter. It has a maximum working range of 100 mm in diameter for a single lens and recess blocks, The single lenses are held by collet chucks with quick release or by vacuum. Recessed, multiple lens blocks are centered by a centering flange and are secured by means of a draw bar. Generation of curves over the hemisphere is a feature of the machine design. A fine adjustment device enables exact repetition of angular settings, which reduces the setup time and downtime of the machine. The cycle time varies from 30 s to 4 min, and in the case of the automatic lens feed model, the time is not controlled by the movements of the opera-

tor. The grinding spindle speed is approximately 1260 rad/s (12,000 rpm).

9-2.2.4 Finish Grinding or Smoothing

Most finish grinding or smoothing machines have this in common: they provide for one tool to be rotated around a vertical axis as the other is moved to and fro in an approximately straight line in harmonic motion. At this stage of the process, the lens is mounted on a fixture or holding tool called a block so that the finished surface of the lens is coincident with the finished surface of a smoothing tool; this process is described more fully in Ref. 7. A block with the lens or lenses attached is held against the smoothing tool, and different grades of abrasive slurry are used as the smoothing medium. Some machines have a means of continuously feeding the abrasive slurry onto the tools. After lapping deep-curved tools together with an appreciable thickness of abrasive, their surfaces may both be spherical, but the radii of curvature will differ by the thickness of the abrasive and will create two different radii. Therefore, if they are cleaned and put into contact, they will touch in the middle. Although the thickness of the abrasive is only about 0.005 mm (0.0002 in.), it is quite sufficient to produce a noticeable effect.

The diamond smoothing process, coupled with the use of recessed blocks of lenses, will substantially reduce times for smoothing and subsequent polishing. The effects on the smooth finish are very good, i.e., the process produces a semipolished surface. Diamond smoothing tools have a sintered coating in the form of pellets that have been affixed to the tool shell. Diamond smoothing gives a time saving of more than 50% when compared with fine grinding with loose abrasive. Uniform and geometrically accurate surfaces can be obtained, and the, diamond tools enable curves with an accuracy of three rings (see par. 9-2.4.3) to be achieved.

Diamond smoothing machinery is available in many different types and configurations. Typical is a two-spindle diamond smoothing machine with independent controls to each spindle. Work pressure is pneumatically provided and can be regulated. The working range is up to plus or minus 50 mm radius. The time cycle is 10 s to 3 min, and the spindle speed is 230 to 360 rad/s (2200 to 3500 rpm), A similar machine with a larger capacity up to a radius of plus or minus 100 mm has a time cycle of 15 s to 5 min and a spindle speed of .50 to 160 rad/s (500 to 1500 rpm.)

9-2.2.5 Polishing

The mechanics of the polishing process are similar to those of the finish grinding process, but the polishing tool is lined with a specially prepared pitch or plastic, and the polishing compound is a slurry of water and cerium oxide or similar material. The polishing pitch, which is softer and more pliable than the workpiece, will take the shape of the work in a short time. The process of optical polishing of spherical surfaces depends mainly on the fact that a pair of spherical or plane surfaces will fit only each other in all relative positions.

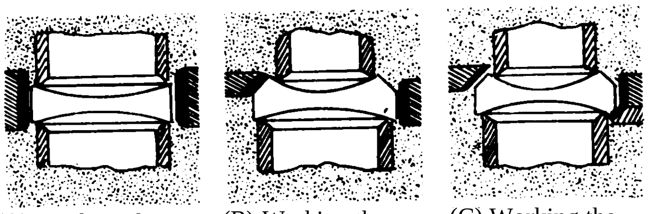
Most machinery in this category is very much like the finish grinding machinery. Three of the more typical machines are described:

1. *Medium Lens Grinding and Polishing Machine.* This machine will produce, by traditional polishing methods, flatwork and blocks of spherical or cylindrical lenses up to 203.2 mm (8 in.) in diameter. The latest design has independent drive to each spindle and infinitely variable speed motors with a spindle speed range from 6 to 42 rad/s (60 to 400 rpm). Automatic abrasive supply to each spindle (with thermostatic temperature control of the slurry) is available.
2. Precision *Scientific Lens Polishing Machine.* The precision polishing machine will polish a shallow curve up to 381 mm (15 in.) in diameter but is equally efficient on steeper curves down to block diameters of 101.6 mm (4 in.). Extremely fast polishing times are possible with no loss of quality. In the fully automatic version the spindle is controlled by an infinitely variable speed motor with timer control, and although the spindle can rotate at 80 rad/s (800 rpm) maximum, the normal speed with 279.4-mm (11-in.) diameter blocks is 30 rad/s (300 rpm). With the same size block polishing with Swedish pitch and with pressure on the runner of approximately 9 kg (20 lb), excluding the weight of the tool, output will be about three high quality (two-ling) blocks per 8-h shift when polishing with cerium oxide compound.
3. *Cylinder Grinding and Polishing Machine.* A need is met by this machine for a reliable cylinder-polishing machine. Maximum working range is a 500-mm radius, and maximum workpiece size is 150 x 100 mm, The constant working pressures guarantee uniform wear of tools, which is particularly important for cylindrical surfaces.

9-2.2.6 Edging and Chamfering

Having polished the lens to the specified radius and accuracy on both sides, the blank is now ready for reduction to the required diameter while, at the same time, insuring that the edge generated is coaxial with the optical axis. There are two methods of centering lenses for normal commercial accuracy: (1) visually—by examination of the reflected images from the lens and (2) automatically—by bell-chuck clamps. The oldest method (and the only satisfactory method for shallow lenses) employs an accurately turned spindle and chuck. The lens is affixed on the chuck with pitch, and reflections of a lamp are observed in the lens —possibly with the aid of a microscope for additional accuracy.

The spindle is then rotated, and while the pitch is soft, the lens is moved to a position at which the image of the lamp remains stationary. Once the lens is centered on the machine edging, the appropriate edge or chamfer is provided. Typical edging and chamfering are shown in Fig. 9-10.



(A) Working the Cylinder (Preliminary and Final Grinding)
(B) Working the Cylinder and One Face
(C) Working the Cylinder and Two Faces

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Figure 9-10. Typical Edging and Chamfering (Ref. 7)

9-2.3 SPECIFYING OPTICAL REQUIREMENTS

MIL-STD-34 provides the standards for dimensioning drawings and the code used in referring to typical defects. Fig. 9-11 shows an example of the tolerance code as used on a working drawing. Table 9-9 explains the tolerance code and the units of measure used in referring to permissible defects, the Table 9-10 is a list of some typical manufacturing tolerances in commercial use.

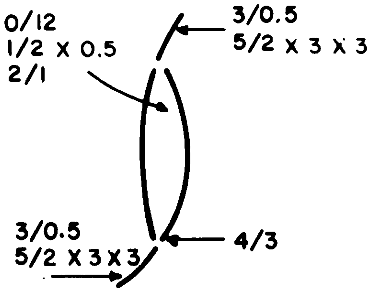

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Figure 9-11. Example of Tolerance Code (Ref. 7)

9-2.4 INSPECTION AND TEST PROCEDURES

Almost all optical component testing is conducted using optical techniques. These, for the most part, produce high precision components. Consequently, most all optical component specifications are in optical terms, i.e., refractive index, strain, and Newton rings. Each of the component specifications is discussed.

9-2.4.1 Refractive Index

A critical element in very high quality lenses is the refractive index. Readings of the refractive index are obtained in less than a minute and to an accuracy of ± 2 in the fifth decimal place. The refractive index is measured in terms of the angle through which a ray of light is deviated when passing through a prism block (the V block) and the specimen. The index is then obtained by reference to tables supplied with the appropriate instrument. The V block consists of two glass prisms—one a complete 45-deg prism, the other a 45-deg prism with one end truncated. Both have been worked to a high degree of accuracy in angle and surface flatness and are joined by heat treatment to form (in effect) a single block with a V-shaped niche in the top; the sides of this niche are at right angles to each other. The specimen is roughly prepared as a right angle prism and then is placed in the V-shaped niche. Small surface irregularities in the specimen are compensated for by using a contact fluid between it and the V block.

9-2.4.2 Strains

A condition in which molecules are separated by a greater distance in one direction than in any direction at right angles to it is defined as strain in glass. This causes the incident electromagnetic waves to separate into two waves traveling through the glass at two different speeds, which results in double refraction. The degree of double refraction varies with the strain from point to point and may be detected by a simple form of polariscope known as a strain viewer. Glass that has not been sufficiently annealed after the chilling (which takes place in molding) shows double refraction. The effect can be quite marked in a strain viewer without, in itself, causing optical parts made from the glass to be defective. The form of strain viewer normally used embodies a half-wave plate that shows up regions of stress in vivid color contrast. Well-annealed specimens have no effect on the color of the magenta background although regions of stress become light blue or red according to the direction of stress.

9-2.4.3 Newton Rings

If a shallow, convex glass surface is laid on a flat one, a system of rings is seen around the point of contact. These are called Newton rings or fringes. When two flat surfaces are put together and one is very slightly inclined to the other, the colors are not arranged in rings but in more or less parallel lines or curves, and they are called Newton bands. The thickness of the film of air at any point of such a system of rings or bands can

TABLE 9-9. TOLERANCE CODE

Code	Defect	Explanation
0/	Birefringence	Variation of refractive properties when light is polarized; graded by maximum difference in optical path length, in nanometers per centimeter of glass path for light polarized in perpendicular directions.
1/	Inclusions	Bubbles, seeds, etc.; graded by maximum number permitted multiplied by maximum dimension in millimeters.
2/	Homogeneity	Lack of uniformity in optical properties, veins, etc.; graded so that no defect is detected when examined against: (1) point source of light (2) light dark boundary (3) light/background.
3/	Form Error	Extent from which surface departs from its geometrical form; graded by number representing, in fringes, the maximum radial separation of concentric spheres between which the surface may be contained.
4/	Centering Error	Condition existing in a lens when the optical surfaces are not true to the axis defined by the ground edge; graded by the maximum deviation, in minutes of arc, of a ray incident along the axis of a ground edge.
5/	Surface Quality	Surface defects, scratches, pits, etc.; graded by number permitted multiplied by illumination reference number multiplied by viewing magnification. (Special equipment is available with controlled illumination conditions.)

TABLE 9-10. TYPICAL MANUFACTURING TOLERANCES

Product	Tolerance
16-mm Zoom lens	Spherical surfaces within five rings centered within 3 min of arc.
Orthoscopic eyepiece	Spherical surfaces within 10 rings centered within 3 min of arc.
Focusing telescope	Spherical surfaces within two rings centered within 2 min of arc.
Collimating lens	Spherical surfaces within one fringe. Centering error less than 15 s of arc.
Aerial camera lens	Spherical surfaces within one fringe. Centering error less than 15 s of arc.
Refractor block	Flat surfaces within one-half fringe. Surfaces parallel to within 2 s of arc. Optical flats to one-half fringe and parallel to within 5 s of arc.
100-mm Theodolite circle	Flat surfaces within five fringes. No blemish to be visible under x 30 microscope with light field illumination.
Pentagonal prism	Flat surfaces within one-fourth fringe. Right-angle deviation within 1 s of arc.
Polygon	Polished flat surfaces within one-fourth fringe. Faces equispaced within 30 s of arc. After manufacture polygons are calibrated to 0.1 s of arc.

NOTE: Rings and fringes are defined in par. 9-2.4.3.

be determined by counting the number of rings from the point of contact, and for practical purposes the thickness change from one band to another is half the wavelength of the incident radiation, e.g., 0.28 µm (0.000011 in.) for helium light. Fig. 9-12 shows how curvature is calculated from Newton bands. Band curvature can be estimated to one-tenth of a band interval or to 0.025 µm (1 µin.).

9-2.5 FIBER OPTICS

Fiber optics makes use of bundles of individual glass fibers to produce flexible, light-transmitting members. Abundant information is available on the physical characteristics of different types of glass, and the technology of glass fiber drawing is already well established for the production of fiberglass yarn. A high refractive index glass rod about 15 mm to 30 mm in diameter is

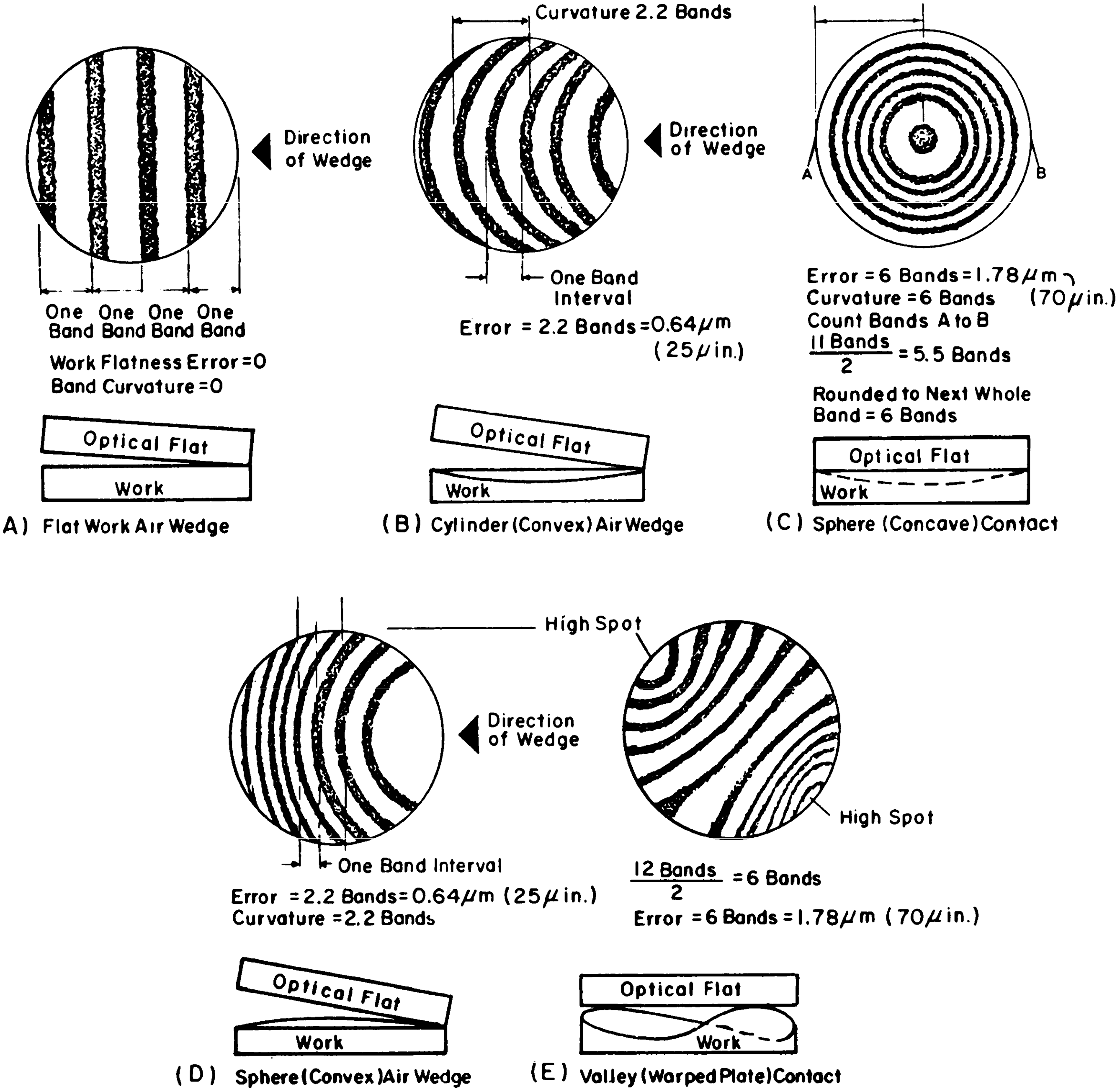

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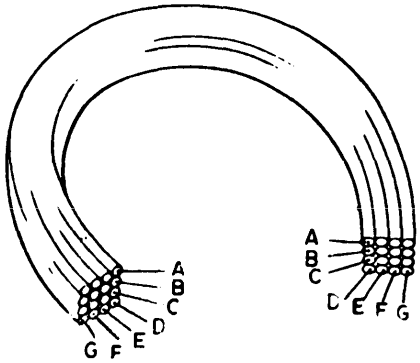
Figure 9-12. Newton Bands (Ref. 7)

inserted in a tube of compatible, low-index glass; the assembly is placed in a hollow cylindrical furnace and is drawn into fibers down to about 10 µm in diameter. There are two different types of fiber optic bundles—coherent and noncoherent (Fig. 9-13).

(A) Noncoherent Bundles



(B) Coherent Bundles

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Figure 9-13. Coherent and Noncoherent Bundles (Ref. 7)

The noncoherent bundle transmits light for illumination, but the coherent bundle has the fibers in logical order at both ends and therefore can transmit an image from one end to the other end of the fiber optic. A faceplate is a coherent bundle in which the end viewing area is considerably greater than the bundle area, and the individual fibers are fused into a solid plate (Fig. 9-14). Faceplates are short, image-transmitting optical systems for large surfaces. The individual fibers are fused together exactly parallel to allow images to be transmitted point by point. Depending on the surface of the faceplate, plane images can be bent, or curved images flattened.

The main applications of faceplates are as front plates of cathode-ray tubes for transmitting the fluorescent image onto the surface of a screen and as flatteners of image fields in classical optical systems. If a coherent bundle is fitted with an objective lens and an eyepiece, it becomes a flexible form of periscope or fiberscope. Applications include the inspection of hard-to-reach areas, including medical endoscopes for examination of internal body cavities.

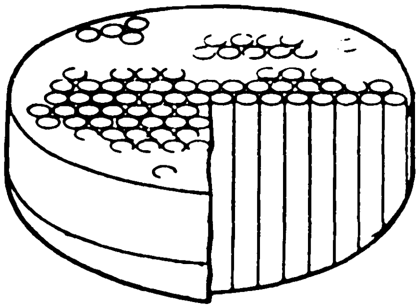

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Figure 9-14. Fiber Optic Faceplates (Ref. 7)

Methods of fiber production are by extrusion, hot drawing from molten bulk material through an orifice, or drawing of uncoated, coated, and multiple fibers from rods or tubes through a hollow, cylindrical furnace. Uncoated quartz fibers down to 1 nm in diameter or less can be produced, and they compare favorably in strength with the strongest of materials. Quartz fiber, for optical purposes, has the advantage of transmission in the ultraviolet and infrared regions of the spectrum. Unfortunately, its very high softening point, small thermal working range, and lack of thermal compatibility with most low-index coating materials make quartz fiber unsuitable for fiber optics.

Fiber optics and optical products in general are produced by specialty manufacturers, and the engineer should be careful to avoid overspecifying these products. The manufacturers have highly developed techniques for manufacturing lenses, providing accurately scribed retitles, and in general providing a wide variety of optical products.

9-3 CERAMICS

Generally, ceramics are described as products made for earthenware, porcelain, brick, glass, and enamels and result from firing inorganic, nonmetallic minerals at high temperatures.

Ceramics are being used in many applications for which metals are normally used, such as load bearing engineering applications. This substitution is occurring because of the uniformity, reproducibility, and efficiency under continuously increasing extremes of pressure, temperature, voltage, vibration, and mechanical stress. They are also more abundant and lower in cost than conventional materials. The family of materials shown in Fig. 9-15 includes carbons and salts,

In this paragraph ceramic materials, properties, applications, and manufacturing processes are discussed. For a more complete description and discussion of ceramics, the reader is referred to Ref. 8. Ceramic

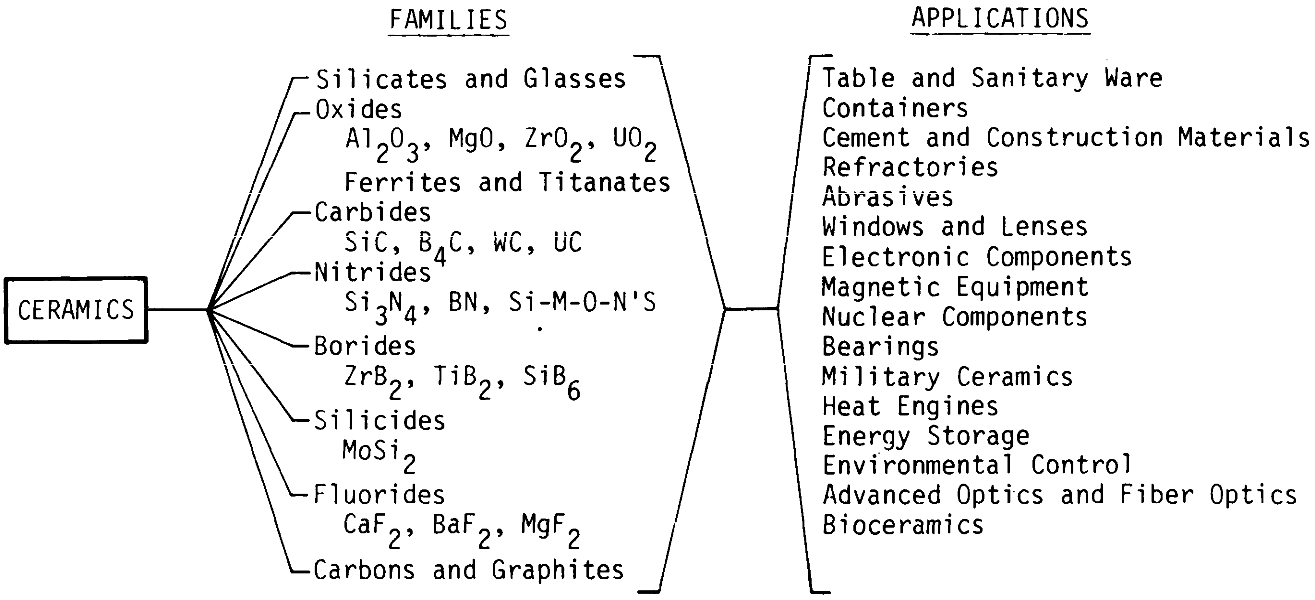

Figure 9-15. Various Ceramic Material Families and Typical Applications

materials are subdivided into the general classifications shown in Table 9-11.

TABLE 9-11. DIVISIONS OF CERAMIC MATERIALS

Division	Product Type
1. Refractories	Technical ceramics for hybrid engineering applications
2. Structural clay	Brick, clay pipe, abrasives, and quarry tile
3. Concrete and cement	Self-explanatory
4. Abrasives	Carbide and similar products
5. Glass	Self-explanatory
6. Enamel	Baked, glazed surface finishes
7. Whitewares	Kitchen and bathroom fixtures
8. Electronics	Substrates for integrated circuits (IC) chips
9. Special	Special materials for unique applications

9-3.1 CERAMIC MATERIAL SELECTION FACTORS

Early methods of making the crudest ceramics, such as clay bowls or bricks, were relatively simple. The potter or brickmaker simply worked a clay with water to obtain the proper consistency for processing into the final product. Conventional ceramics are blended and combined in a number of different methods and processes. Modern industrial ceramics, which must meet much more stringent standards, are truly engineering materials and are more often than not engineered for specific applications. Ceramics maybe produced in a laboratory or a large manufacturing plant, but in either case two characteristics are sought—uniformity and reproducibility. These characteristics are prime elemerits of producibility. The raw materials for ceramics are usually in the form of fine powders. The ingredients are precisely blended and mixed, either wet or dry. If necessary, to cause essential preliminary reactions, the ingredients are heated (calcined) to a temperature of 6000 to 1500°C. Despite this heat the materials do not necessarily melt. The heat will cause a reaction between two or more solid components in the form of a change in the crystalline structure. Some selected ceramic base materials are shown in Table 9-12 with their more common applications. Some specific applications for high alumina ceramics are shown in Table 9-13.

9-3.1.1 Ceramic Material Properties

Unlike most other materials, ceramics do not achieve their full properties until after being shaped, sized, and fired. As a consequence, the significance of these properties to producibility is limited to component performance rather than to manufacturing constraints. How-

TABLE 9-12 SOME CERAMIC BASE MATERIALS AND APPLICATIONS

ALUMINUM OXIDE: A variety of grades and forms providing high strength with good electrical and mechanical properties.	IRON OXIDE: A colorant for face brick and tile as well as a source of iron for ferrites.
ALUMINUM SILICATE: Unique combination of clay, mica, and silica. Air-floated. Versatile filler/extender in plastics, adhesives, coatings, rubber carpet backing, felt, gasketing, joint compounds, plaster, insecticides, pellet binders, carriers. Also used extensively in foundries and refractories for hot strength workability and release.	IRON PYRITES: Ferric disulfide. Decomposes when heated to yield sulfur dioxide. Serves as a colorant in glass for producing a brown or amber color and as a source of sulfur in other applications. KAOLIN, Calcined: A high-fired, 47% minimum alumina content aluminum silicate grog with low alkali and iron content.
BAUXITE, Calcined: A high-fired 70% minimum alumina content aluminum silicate grog with low impurities. Kiln run through ball mill sizings.	KAOLIN, Calcined Bauxitic: A high-fired 60’% minimum alumina content aluminum silicate grog with low impurities.
BAUXITE, RASC Demerara: An 86% minimum, calcined alumina for the refractory trade. Necessary in many castables. cements. and bodies.	SILICON CARBIDE: Relatively low thermal coefficient of expansion used for fuel elements and structural parts.
BORON CARBIDE: Good electrical properties, mechanical and structural characteristics. Used for control and shielding devices.	KYANITE, Raw and Calcined: An aluminum silicate mineral with unusual refractory properties. Used in ramming mixes, tiles, kiln furniture, insulating refractories, and other ceramic bodies.
CELESTITE: Strontium sulfate. A source of strontium in the production of certain ferrites.	
CHROMITE: Air-floated for use as a colorant by the brick industry.	
INVESTMENT CASTING GRAINS: Mulgrain grains and flours are superior ceramic refractory mold media, precision sized to meet today’s investment casting needs. Mulgrain is produced from calcined mullite that is precisely sized through a series of screens which are continuously air swept to minimize dust.	ZIRCON: Zirconium silicate. Excellent high temperature properties make this material an essential ingredient in many refractory bodies. It also serves as a molding sand in the foundry and an opacifier in glazes and frits.
CRISTOBALITE: A silica product with special thermal expansion characteristics for investment casting.	FUSED SILICA: Thermally stable silica with excellent shock resistance for kiln furniture, pouring nozzles, and foam blocks.
MAGNESIUM OXIDE: A raw material for most basic refractories and for electrical grade, fused magnesia.	FUSED MAGNESIA: High purity for ferrites, refractories, and ceramics, Also electrical grade, specially compounded for individual applications.
ILMENITE: Iron titanate. Incorporated in some welding rod coatings and as a surface coating for face brick.	
MANGANESE DIOXIDE: A variety of grades to produce special effects for the face brick industry. Quality materials also available in battery grades.	

ever, the design engineer who is considering postfiring manufacturing processes will find these properties very confining and a decided barrier to producibility. General properties of selected ceramic materials are shown in Table 9-14. For more complete descriptions and a bibliography of related data, the reader is referred to Ref. 9.

9-3.1.1.1 Density

The density of a ceramic is a clue to whether it has been properly fired. Deviations in the firing process may cause less than optimum density. For this reason, density is specified as a minimum value below which the material is considered unacceptable. Most manufacturers try to achieve maximum density because this

TABLE 9-13. APPLICATIONS FOR ALUMINA CERAMICS

Mechanical

- Armor
- Balls, Grinding
- Bearings
- Blades, Disintegrator
- Brazing Fixtures
- Bushings
- Capstans, Wire-Drawing
- Cams
- Chokes
- Cleaners, Tape
- Cutting Tools
- Cyclones
- Dies, Extrusion
- Dies, Forming
- Forming Tools
- Gages
- Guides, Thread and Wire
- Guides, Tape
- Heat Exchangers
- Jars, Pebble Mill
- Jets, Orifice
- Jigs, Welding
- Liners, Cylinder
- Liners, Ball Mill
- Linings, Chute
- Mortars and Pestles
- Nozzles, Sand Blast
- Nozzles, Mud Gun
- Nozzles, Spray
- Nozzles, Welding
- Plates, Wear
- Plates, Surface
- Plungers, Pump
- Pulverizer Parts
- Rings, Shaft Seal
- Rotors
- Seals, Rotary Pump
- Seals, High-Pressure
- Shafts
- Sleeves
- Supports, Work
- Springs
- Spheres, Hollow
- Studs, Tire
- Tumbling Media
- Valve Parts
- Valve Seats

Refractory

- Containers
- Crucibles
- Heat Exchange Media
- Nose Cones
- Reflectors, Heat
- Special Refractories
- Trays, Rectangular
- Tubes, Combustion
- Tubes, Protection

Chemical

- Catalyst Carriers
- Crucibles
- Filters
- Pump Parts
- Tower Packing
- Tubing
- Valve Seats

Electronic and Electrical

- Bushings
- Coil Forms
- Capacitor Leads
- Electronic Packages
- Envelopes, Tube
- Insulators, Antenna
- Insulators, Cyclotron
- Insulators, Spark Plug
- Insulators, Thermocouple
- Insulators, Tube Element
- Housing, Lamp
- Magnetron Parts
- Printed Circuit Boards
- Radomes
- Resistor Bases
- Supports, Tube Element
- Shafts, Condenser
- Substrates
- Terminals
- Tube Windows
- Transformer Bushings
- Tuner Coupling Arms

condition is considered to be consistent with the best of other properties. Consequently, the common means of describing density is as a percentage of theoretical. This permits the user to determine immediately how close his material is to the maximum theoretically attainable.

9-3.1.1.2 Thermal Expansion

Thermal expansion is a property exhibited by all materials. The fact that some ceramics have very low thermal expansion is what makes them applicable to thermal environments requiring good thermal shock resistance. The high melting point and good strength at elevated temperatures make all ceramics desirable for adverse thermal environments.

9-3.1.1.3 Absorption

The amount of water or other liquid that is absorbed when a material is immersed in it or the depth of penetration of a dye solution in a given length of time are further indications of porosity. The ability to make ceramics very dense and impervious to liquids enhances their applications for uses in moisture laden environments.

9-3.1.1.4 Modulus of Elasticity

The resistance of a material to deformation under a given load is a quality of ceramics. In the green state they have excellent plasticity to enhance their shaping and forming characteristics. Conversely, in the fired state they are quite brittle with very little plasticity and essentially no plastic flow.

9-3.1.1.5 Compressive, Tensile, and Transverse Strengths

Ceramic units must be strong enough for handling while being assembled into electronic components and other devices. They also must be strong enough to withstand the stresses they will meet in their operating environments. Achieving these strengths will significantly affect material selection and the manufacturing processes and could adversely affect producibility. Minimum specifications should be set on crushing strength, tensile strength, and cross-breaking strength in accordance with the demands of the expected use. Ceramics generally have very high compressive strength compared to their tensile and transverse properties. The brittleness associated with ceramics makes them extremely sensitive to notches and surface defects. Consequently, the designer should avoid tensile and bending loads because any surface flaws will act as stress risers. This characteristic can be used by the designer to create etch lines in ceramic surfaces that will serve as part separation lines, such as those used in integrated circuit blanks.

TABLE 9-14. GENERAL PROPERTIES OF SELECTED CERAMICS (Ref. 10)

Material	Melt Point, °C	Density, g/cm^3	Linear Coefficient Thermal Expansion, x 10^{-6} (°C)	Young Modulus of Elasticity at 20°C kPa (psi) x 10^6	General Remarks and Applications
Alumina Al_2O_3	2050	3.98	6(20°C) 7(500°C)	358.5(52)	High strength, excellent electrical and mechanical properties. Superior wear and chemical resistance. The most versatile of the ceramics.
Beryllia BeO	2530	2.86	8(100°C) 8(500°C)	310.3(45)	Excellent electric and thermal transfer properties. Very dense. For electronic and heat sink applications.
Magnesia MgO	2800	3.58	11(100°C) 13(500°C)	82.7(12)	Good electrical properties. Accurate dimensions. High strength insulator for radio frequency and applications.
Titania TiO_2	1830	4.17	7.5(100°-500°C)	96.5(14)	Very strong and hard superior wear and chemical resistance. Conducts static electricity. Also used as a paint filler.
Aluminum Silicate	1410	3.4	3.3(25°-300°C) 3.6(25°-900°C)	—	Good electrical and heat resistance. Excellent for close tolerances. Primary use is in substrates.
Zirconia (stabilized) ZrO_2	2600	5.35	7.2(70°-1000°C)	248.2(36)	Good electrical properties. High strength and good thermal shock resistance. Electrical properties good at low temperature. Conducts at high temperature.
Beryllium Carbide Be_2C	2100	2.44	10.8(38°-982°C)	310.3(45)	Good thermal and mechanical characteristics. Used for fuel elements, structural parts, and thermal reflectors.
Boron Carbide B_4C	2450	2.51	4.5(25°-800°C)	448.2(65)	Good electrical properties, mechanical and structural characteristics. Used for control and shielding devices.
Silicon Carbide SiC	2200	3.2	4.7(20°-1500°C)	—	High performance structural ceramic. Being used in engineering applications such as gas turbines. Biggest use is in abrasives.
Tantalum Carbide TaC	3800	14.48	8.2(20°-2380°C)	—	Good structural and thermal characteristics. Good application for structural parts.
Titanium Carbide TiC	3140	4.93	7.4(24°-500°C)	351.6(51)	Ceramics designed especially for capacitors.

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TABLE 9-14. (cont'd)

Material	Melt Point, °C	Density, g/cm^3	Linear Coefficient Thermal Expansion, x 10^{-6} (°C)	Young Modulus of Elasticity at 20°C kPa (psi) x 10^6	General Remarks and Applications
Forsterite $2MgO\text{-}SiO_2$	1470	3.3	10.0(25°-300°C) 11.7(25°-900°C)	144.8(21)	Low heat loss, close tolerances, high coefficient of expansion at the expense of heat shock resistance.
Tungsten Carbide W_2C	2777	15.7	5.2(20°C) 7.3(1930°C)	703.3(102)	Good thermal and wear resistance with excellent structural properties. Well-known edge treatment for cutting tools.
Zirconium Carbide ZrC	3530	6.7	6.7(24°-500°C)	337.8(49)	Good structural and thermal characteristics. Primary application for structural parts.
Graphite C	3700	1.55	3.3(25°-1800°C)	6.9(1)	Good structural and thermal properties. Primary uses are elements in fusion furnaces and in crucibles.

Material	Water Absorption, %	Strength, MPa (psi x10^3)			Max. Service Temp, °C	Dielectric Constant, at 10^6 Hz, dimensionless	Hardness Mohs Scale
		Compressive	Tensile	Transverse			
Alumina Al_2O_3	0.00	2585.5(375)	172.4(25)	317.2(46)	1550	9.3	9
Beryllia BeO	0.00	1275.5(185)	151.7(22)	172.4(25)	1500	6.5	9
Magnesia MgO	0.03	13.8(2)	—	3.4(0.5)	1500	4.7	6
Titania TiO_2	0.00	689.5(100)	51.7(7.5)	137.9(20)	1000	8.5	8
Aluminum Silicate	3.0	275.8(40)	17.2(2.5)	62.1(9)	1100	5.3	6
Zirconia ZrO_2	0.00	689.5(100)	82.7(12)	151.7(22)	1100	8.8	8
Beryllium Carbide Be_2C	0.03	723.9(105)	—	—	1450	—	9

(cont'd on next page)

TABLE 9-14. (cont'd)

Boron Carbide B_4C	0.00	2854.4(414)	—	275.8(40)	1800	—	10.5
Silicon Carbide SiC	0.00	565.4(82)	—	365.4(53)	1540	—	9.5
Tantalum Carbide TaC	0.00	—	103.4(15)	551.6(80)	2850	—	6
Titanium Carbide TiC	0.00	751.5(109)	—	137.9(20)	2380	—	9.5
Forsterite $2MgO\text{-}SiO_2$	0.00	586.1(85)	68.9(10)	137.9(20)	1000	6.2	7.5
Tungsten Carbide W_2C	0.00	—	344.7(50)	579.2(84)	2150	—	7.5
Zirconium Carbide ZrC	0.00	1034.2(150)	124.1(18)	179.3(26)	1600	6.5	8
Graphite C	0.00	—	—	—	1750	—	—

9-3.1.1.6 Maximum Service Temperature

As with most materials, the material properties of a ceramic part will begin to degrade sufficiently to impair its intended purpose when the maximum service temperature has been surpassed. However, since this temperature is so high compared to most other materials, the maximum service temperature of most ceramics, as shown in Table 9-14, is one of their more outstanding attributes.

9-3.1.1.7 Dielectric Constant

The ratio of the capacitance of a material placed between two conducting plates to the capacitance with a vacuum between the plates defines the dielectric constant. Many factors must be considered in selecting a ceramic for a material. Pure silica glass has the lowest dielectric constant, i.e., about 3.8. This can be raised by the addition of various other oxides but only at the risk of some undesirable effects, such as high electrical losses or undesirable conductivity. Ceramics, as shown in Table 9-14, have very desirable dielectric constants; this is one of numerous reasons for their use as an electronic component substrate.

9-3.1.1.8 Hardness

Hardness is a basic common property of ceramics. It is this hardness that makes the material ideal as an edging for cutting tools and also makes the material extremely difficult to machine or otherwise process after firing.

9-3.1.2 Material Availability

The worldwide shortage of critical metals for high-temperature applications (chromium, columbium, nickel, and cobalt) makes the natural availability of most ceramic materials very attractive. Some ceramic materials are based on substances that exist in nature although not precisely in the form now used by industry. Many applications for ceramics are for an environment (high strength, temperature extremes, and electronics) that is currently served by a conventional material that is on the worldwide critical materials list. Most ceramic materials are based on elements that do not suffer from material criticality and in most cases are better suited for the hostile environments.

9-3.1.3 Material Cost

The substitution of high-performance ceramic materials—such as silicon nitride, silicon carbide, various glass ceramics, and oxide ceramics—for most conventional engineering materials will come about because they are abundant, low-cost, high-strength with low thermal expansion, high-temperature materials. The fact that ceramics are abundant is significant in designing for producibility. Table 9-15 provides the relative cost of selected ceramic materials. However, it should be noted that the data are only relative and have a wide range of variations, as shown in the table, and are highly dependent on purity, size, shape, processing procedures, and quantity of material ordered. Other than the supply of electronic substrates for developmental purposes, only magnesium silicate, which is a machinable ceramic, is sold in standard shapes and forms. It is sold as rods, tubes, plates, and blocks. Electronic substrates can be acquired from most suppliers in a 25-mm (1-in.) square, 0.635 mm (0.025 in.) thick for prototype development. These can also be acquired in a form known as a “snapstrate”, i.e., a standard square with scribe lines pressed into the surface that permit the part to be subsequently broken into smaller pieces.

TABLE 9-15. RELATIVE COST OF SELECTED CERAMICS

Material	Relative Cost $/kg	Relative Cost $/lb
Aluminum Oxide (Alumina)	352	160
Beryllium Oxide (Beryllia)	396	180
Magnesium Oxide (Magnesia)	55	25
Titanium Oxide (Titania)	770	350
Zirconium Oxide (Zirconia)	132	60
Beryllium Carbide	44-880	20-400
Boron Carbide	44-880	20-400
Silicon Carbide	704-1320	320-600
Tantalum Carbide	286-374	130-170
Titanium Carbide	44-440	20-200
Tungsten Carbide	77-132	35-60
Zirconium Carbide	66-297	30-135

9-3.2 CERAMIC MANUFACTURING PROCESSES

Manufacturing of ceramics requires consideration of all aspects of the material processing since ceramics go from the basic material to the final product. They are true net shape processes performed while the material is still green and before it has attained all of its properties, which occurs after firing. Ceramic components may be produced by any one of several processes. Casting is the basic process used for glass and glass/ceramic materials as well as for single crystal ceramics as discussed in more detail in par. 9-2. Ceramics other than glass/ceramics are generally formed into products by consolidation of powders. A general flowchart of ceramic processing by the powder consolidation process is shown in Fig. 9-16. As shown, the process starts

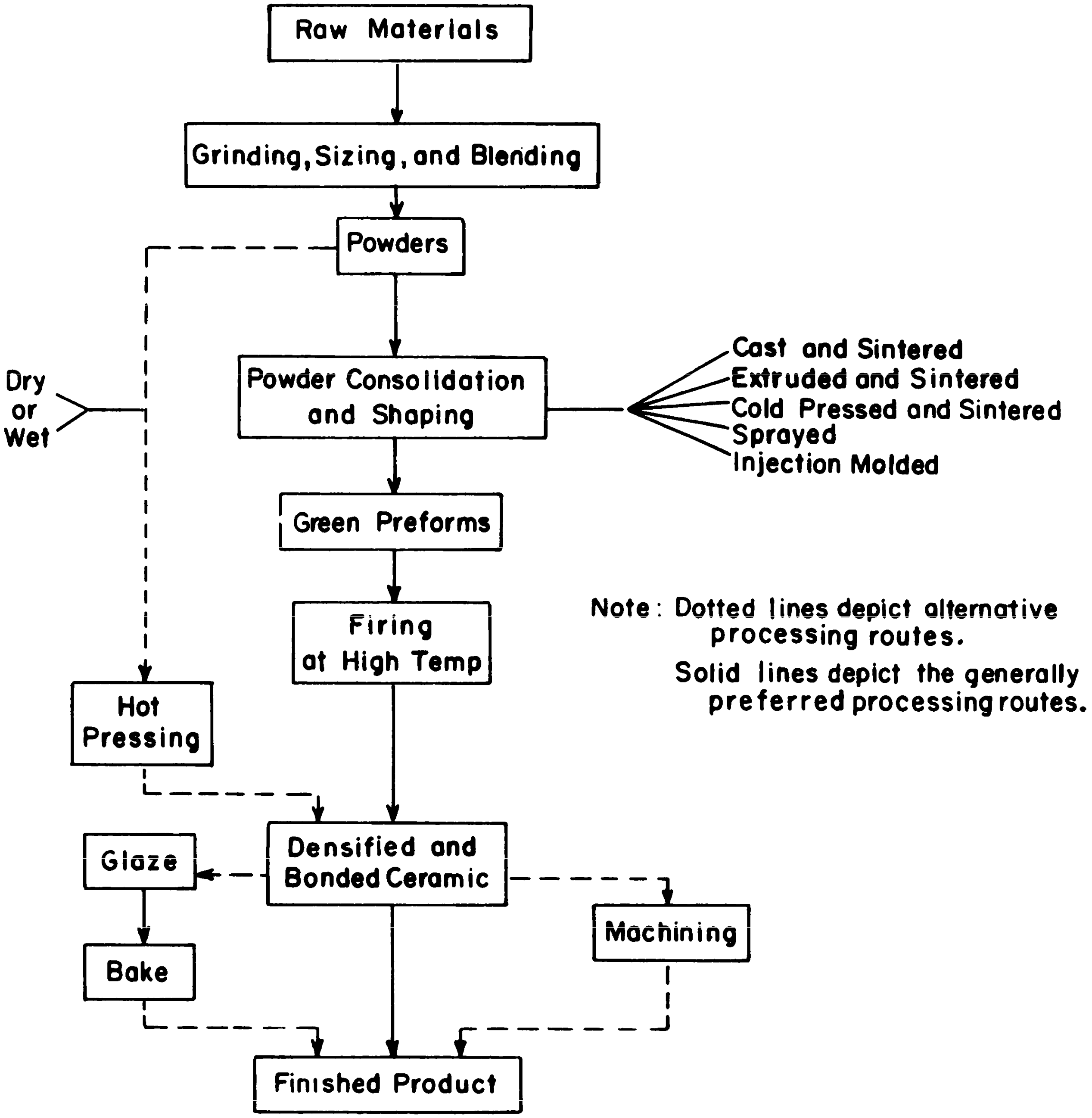

Figure 9-16. Ceramic Processing (Information for this figure from Ref. 11)

with the grinding, sizing, and blending of raw powder, which is then consolidated and shaped via any of numerous processes including casting, extruding, cold pressing, spraying, or injection molding. These processes create green preforms, which are then fired at high temperatures to create densified and bonded ceramics. An alternative route for creating densified and bonded ceramics is via the hot pressing method, which is shown with the dotted line. The densified and bonded ceramic may, in some cases, become the finished product as it may be glazed and baked to create the finished product. It may also be necessary to perform some machining operation on the densified and bonded ceramic before it becomes a finished product. However, the hardness associated with fired structural ceramics makes them very difficult to machine. As a consequence, fabrication methods that can minimize or eliminate machining or subsequent operations are essential to the element of producibility.

9-3.2.1 Implied Manufacturing Processes

As with other materials discussed in previous chapters, the selection of a material places certain constraints on the selection of manufacturing processes. Not all materials can be processed by all manufacturing processes, a fact that can be significantly important to producibility. For example, refractory liners offer the possible advantage of deferring the firing operation. The finished product is fired after installation where the thermal characteristics of the firing process will be duplicated. Thus the implied manufacturing process should become an integral part of the material selection procedure. Table 9-16 gives the applicable manufacturing processes for a select group of ceramic materials. Ceramic processing is performed by several methods: (1) melt formation and single crystal growth is the basis of glass/ceramics, (2) chemical vapor deposition is used for polycrystalline and single crystal processing, (3) and the bulk of engineering ceramics processing is done by consolidation of powders.

9-3.2.2 Manufacturing Process Descriptions

Ceramic powders are intimately mixed with small percentages of selected additives and formed into shapes by extruding, pressing, casting, and other fabricating processes. Many high alumina ceramic parts can be pressed or molded directly to shape with allowances provided for firing shrinkages. Other parts, because of their particular shape or special dimensional specifications, may require secondary machining or grinding before firing. The machining may consist of turning diameters, boring, drilling, threading, tapping, or other operations. Because of the highly abrasive nature of ceramics, carbide tooling is generally required. Some of the machining can be performed with grinding wheels prior to firing. It is considerably easier to machine before firing, and this should be done whenever possible. Since the ceramic undergoes considerable shrinkage during the firing operation, the machined sizes are expanded dimensions that will shrink to the desired size during the firing operation. Following fabrication, parts are fired at high temperatures to mature the ceramic and to develop the desired characteristics. During firing, the pieces may sag or distort if not properly supported. For this reason, it is sometimes necessary to make elaborate supports that may be more costly than the product itself, To reduce firing costs, large unsupported or overhanging sections should be avoided if possible.

A glaze may be applied if desired, The glaze is a vitreous coating generally 0.05 to 0.25 mm (0.002 to 0.010 in.) thick, which provides a smooth, glossy, easily cleaned surface and which has better water-repellent qualities than unglazed surfaces. The glaze softens during firing and so must not contact any other part, or support, or sticking will occur, Adequate surface area must therefore be left unglazed for contact with firing supports.

Grinding and lapping of high alumina ceramics are common practices after firing. These operations are performed to obtain closer than standard tolerances. Grinding is usually accomplished by the use of diamond wheels, although silicon carbide or alumina wheels are sometimes used. Lapping for flatness and parallelism is accomplished by use of diamond, boron carbide, silicon carbide, or alumina powder.

The color of alumina ceramics may vary from one composition to another. Differences in color are generally attributable to small percentages of metallic oxides, which are added to develop specific properties. At one extreme of the color spectrum, opaque (dark brown or black) compositions are provided to be used for encapsulation of light-sensitive electronic devices. The quality of an alumina ceramic application should be judged by its properties rather than by its color.

9-3.2.2.1 Machining

The machining processes for ceramic materials are generally described in the optics paragraph, specifically, subpars. 9-2.2.4 and 9-2.2.5, and in Chapter 4. Parts designed for machining should avoid sharp edges or corners and allow generous fillets. All tapped holes should be slightly countersunk and specified in accordance with the tolerances listed in par. 9-3.3. Standard threads in ceramic machining are V-threads 1.57 radian ± 0.05 rad (90° ± 3°). All others are specials. The bottom of each thread must be radiused. More detailed information on this subject can be found in Ref. 10.

9-3.2.2.2 Extruding

This process is applied in the green, or plastic, state before firing and is very similar to metal extruding as described in Chapter 4. A binder is usually needed to extrude ceramic powders. Parts to be extruded should be designed with uniform wall thickness. The wall thickness should not be less than 10’% of the outside diameter with a minimum of 0.38 mm (0.015 in.). If the length-to-width ratio is greater than 6:1, the wall thickness should be increased to 20% or more of the outside diameter.

9-3.2.2.3 Pressing

In this process the raw material in the green state is placed in a die containing the configuration of the finished part with appropriate allowance for shrinkage. The die is then closed under pressure (this is done either hot or cold), and the part is finished and ready for firing. Uniform thickness of the part is essential in this process. Cavities and blind holes should not be deeper

TABLE 9-16. APPLICABLE MANUFACTURING PROCESSES

Materials	Manufacturing Processes						
	Machining	Casting	Hot Pressing	Cold Pressing	Injection Molding	Extruding	Spraying (Flame or Plasma)
Alumina		x	x	x	x	x	x
Beryllia		x	x	x		x	x
Magnesia		x	x	x		x	x
Titania		x		x		x	x
Urania		x	x	x		x	x
Zirconia		x	x	x		x	x
Beryllium carbide			x				
Boron carbide			x				
Silicon carbide		x	x	x	x	x	
Tantalum carbide			x	x			
Titanium carbide			x	x			
Uranium carbide			x	x			
Tungsten carbide			x	x			
Zirconium carbide			x	x			
Graphite	x					x	
Boron			x				

NOTE: Machining refers only to processes other than grinding performed after firing.

than one-half of the part and preferably only one-third. Thin walls should be avoided and should never be less than the thickness of the piece and even then never less than 0.77 mm (0.030 in.).

9-3.2.2.4 Injection Molding

As noted in Ref. 11, much progress has been made in the injection molding of ceramic preforms to very close tolerances. The injection molding process is described more fully in Chapter 5 (par. 5-3.1). The most promising advance in ceramic processing technology has been the marriage of polymer and ceramic processing to produce green preforms. The injection molding of ceramic-filled polymer preforms has become highly developed. For example, the injection molding process applies to reaction-bonded silicon nitride, reaction-sintered silicon carbide, and conventionally sintered alumina. In the case of injection-molded, reaction-bonded silicon nitride, a polymer is filled with silicon metal powder (about 70%), which is injected at modest temperatures (100 to 200°C) into a die that produces a preform with precise dimensions. This preform is then heated slowly to 300°C to remove the polymer. The heating normally causes a 25% volumetric expansion. The silicon preform is carefully placed in a furnace and nitrided in an atmosphere of pure N_2 at 1300° to 1450°C for 24 to 48 h. The net result of this process is that a product of an engineering ceramic in complex shapes can be mass produced to tight dimensional tolerances with little or no machining and at a low cost. The reader is referred to Ref. 11 for a more in-depth discussion of high-performance ceramics.

9-3.2.2.5 Sintering

As described in Ref. 8, this process involves the application of heat or in the case of hot pressing the simultaneous application of heat and pressure. In general this process causes an aggregation of ceramic powders to become a well-bonded polycrystalline body. The driving force for the sintering process is the reduction of surface energy allowing the powders to aggregate. Sintering will usually occur when the surface free energy of a grain boundary is less than twice the surface free energy of a powder surface in contact with its vapor environment, i.e., air, nitrogen, argon, etc. Thus when the individual powders consolidate into a densified and bonded ceramic, there is a net reduction in the free energy of the system. If heat and pressure are maintained, the system will continue to strive to lower its free energy by the process known as grain growth. Often sintering, densification, and grain growth are accelerated by the use of additives, which may or may not produce a separate grain boundary phase. Grain boundaries tend to be favored sites for segregation of impurities and trapped gases. Thus it can be anticipated that grain boundary composition, structure, and processes occurring at grain boundaries can dictate the properties of the ceramic component.

9-3.2.2.6 Metallizing

High alumina ceramics are particularly adaptable to the manufacture of ceramic-metal assemblies because of the ability of ceramics to react with metals to form high-strength bonds. There are several methods for making vacuum or hermetically tight components. In essence, such seals consist of metal hardware bonded to the ceramic by means of suitable alloys and reactions. For an example of a ceramic-metal metallizing process, refer to ASTM F 19-64, Appendix A, *Typical Metallizing Procedure*. The acceptability of metallized alumina ceramics depends upon mutual understandings between the manufacturer and the purchaser. The most common measure of acceptance is the ability of the ceramic-metal component to resist a specified rate of helium leakage, as determined by a helium mass spectrometer. From the general quality standpoint, it is expected that all assemblies will be neat in appearance. The metal should not overlap glazed areas nor extend appreciably beyond joint areas. Braze or solder fillets should be at a practical minimum. Customer inquiries should supply the following applicable information:

1. Configuration, with critical dimensions and maximum tolerances
2. Mechanical requirements
3. Thermal requirements, to include in-plant processing and end-use requirements
4. Electrical requirements
5. Hermetic requirements
6. Metal and ceramic finish (plating, glazing, etc.)
7. Other requirements, e.g., radiation, corrosive gases, specifications, etc.

The type of seal between ceramic and metal is a basic consideration in designing ceramic and metal assemblies. There are four seals commonly used, and all are applicable for the ceramic metal interface: (1) external, (2) tapered, (3) internal, and (4) butt. For good design it is always best to use the thinnest possible metal cross section. The thinner the metal, the smaller the stresses that are set up on the seal and the ceramic. The metal for external seals should be held to a maximum thickness of 0.50 mm to 0.76 mm (0,020 in. to 0.030 in.). For internal seals 0.25 mm to 0.38 mm (0.010 in. to 0.015 in.) is as thick as the metal should ordinarily be. For a butt seal maximum thickness of the metal should be 0.38 mm (0.015 in.). However, thicker metal can be used for butt seals in stacked assemblies because the resulting additional stresses are divided between the ceramic on each side of the metal.

9-3.2.2.7 Slip Casting

In the slip casting process a plaster of paris cavity prepared to the configuration of the part to be cast is filled with a ceramic slurry, The plaster of paris mold absorbs the moisture from the ceramic slurry, and the ceramic is allowed to harden. Appropriate shrinkage allowance is provided in the plaster of paris cavity. Guidance for wall thickness and hole depths is the same as that given in subpar. 9-3.2.2.3.

9-3.2.2.8 Flame Spraying

Flame-sprayed coatings are applied by spraying molten material onto a previously prepared surface. Its principal value is in increasing the wear resistance as well as in providing corrosion protection and heat and oxidation resistance. Generally, flame-sprayed coatings are applied to metals. Flame-sprayed ceramic eating can be applied to cast iron, steel, aluminum, copper, brass, bronze, molybdenum, titanium, magnesium, nickel, and beryllium. There are two principal methods of applying flame-sprayed coatings:

1. *Oxyacetylene Spraying*. An oxyacetylene flame is used to melt the material to be sprayed. The material is fed into a chamber as wire 3.175 mm to 4.750 mm (0.125 in. to 0.187 in.) in diameter, as a powder, or as a rod. The material, after being melted, is atomized by an air blast and blown onto a previously prepared surface of the material to be coated.
2. *Plasma .Spraylng*. This method uses the same plasma arc gun used for plasma are cutting (described in Chapter 4, subpar. 4-4.2.2). The high temperatures (up to 1093.3°C) of the plasma are enable it to spray any known solid, inorganic material that will melt without decomposition. The coating material is fed into the gun in the powder form. This process yields a denser and better bonded metal or ceramic coating than is possible with either oxyacetylene or oxyhydrogen spraying due to its ability to control inert gases in the spraying atmosphere.

The coating materials that can be used with flame spraying include metals, ceramics, carbides, borides, and silicides. Ceramic materials are useful as coatings because they provide refractory properties, insulation, erosion resistance, oxidation and corrosion resistance, or electrical resistance. The oxides of aluminum and zirconium are the most commonly used materials. The carbides with metallic binders are used generally for wear-resistant coatings; tungsten is the most common. Flame-sprayed borides are used as neutron absorbers in nuclear applications, and the silicides are useful in high-temperature applications.

9-3.3 TOLERANCES

Ceramics can be fabricated in many complex shapes. From an economic standpoint, however, it is desirable to design for simplicity in confriguration and to avoid close dimensional tolerances unless necessary. Close tolerances required on dimensions should be fully specified; standard tolerances will be assumed for all other dimensions. Edges and corners should have chamfers or radii to minimize chipping areas of stress (concentration. It is desirable that parts be dimensioned from one reference point. The following are suggested design guides that should be followed whenever possible: the general dimensional tolerances listed here are to be considered standard for most unground high alumina ceramics, particularly those of simple geometry and good symmetry. Unique designs are always considered as individual cases because it may be necessary to apply broader tolerances to them. Grinding and other finishing operations permit closer dimensional tolerances and fine finishes comparable to those obtainable on metal, Since grinding generally is done with diamond tools and is an expensived operation, careful consideration should be given to the actual need for close tolerances.

1. Unglazed *Surfaces* . *A* tolerance of ± l% hut not less than ± 0.127 mm (0.005 in.) is standard.

2. *Glazed .Surfaces.* A tolerance of ± 2% but not less than ± 0.305 mm (0.012 in.) is standard.

3. Angular *Dimensions. A* tolerance of ± 0.0349 rad (2 deg) is standard.

4. *Parallelism.* This will be considered satisfactory if the thickness measured at any point is within the dimensional tolerance.

.5. *Flatness.* Flatness is specified as the allowable deviation of a surface from a reference plane. Flatness is measured directly or by optical means, but in both cases the total deviation from the reference plant is expressed in linear units.

6. *Ellipticity.* Ellipticity or "out of roundness" is determined by dividing the maximum diameter by the minimum diameter, measured in the same planes, perpendicular to the axis. A maximum value of 1.02 should be allowed when the wall thickness is 12% or more of outside diameter. For a wall thickness of 10% of outside diameter, a maximum value of 1.03 is standard.

7. *Concentricity.* This shall be expressed as a displacement of centers. Normally, a total indicator reading of 1% of the outside diameter or 0.254 mm (0.010 in.), whichever is larger, will be permitted where al] diameters are either all ground or all unground. For tubes concentricity can be measured by using double the tube thickness.

8. *Camber.* The ratio between are height and the maximum length of the part is camber. A maximum camber of 0.006 mm/mm (0.006 in./in.) of length is standard unless otherwise specified. It is important to note that camber is measured from the mean thickness. and consequently, a tolerance accumulation can occur.

9. Screw *Threads.* Screw threads shall be in accordancc with the *Screw Threads Standard.s for Federal Service*, National Bureau of Standards Handbook, H28. Threads smaller than 6-32 are not recommended.

10. *External Threads.* In high alumina ceramics external threads shall accept a Class 1 nut.

11. *internal Threads.* These should not be required to meet machine screw standards for any class of fit. All regular internal threads shall be acceptable if they will accept a Class 1 A corresponding metal screw. Holes should not be tapped to a depth of greater than six threads. Internal thread requirements of diameters larger than 9.525 mm (0,375 in.) shall be considered special cases.

12. *Surface Finish.* This is the deviation of the heights and depths of surface irregularities from a central reference line. The value obtained is the arithmetic average deviation of the magnitude of surface irregularities taken at equally spaced intervals. The value is expressed in micrometers or microinches. The finishes on alumina cearmics are either "natural" or "applied"; natural surface finishes refer to the finish of the "as fired" material. Ceramic materials have distinctive granular surfaces in the as fired condition that will var depending upon the ceramic composition, crystal size, and the method of forming parts prior to the firing operation. An applied finish results from a modification of the as fired condition by grinding, lapping, polishing, tumbling, or glazing. Glazed surfaces provide the smoothest surfaces with finishes of 25.4 nm (l µin.) or better being fairly common. Until recently, ground, lapped, or tumbled finishes were invariably smoother than as fired surfaces. Currently, there is considerable overlapping in surface finish of as fired and ground pieces due to the various compositions available. Compositions specifically designed to have smooth as fired finishes can be made with surface finishes of 254 nm (10 µin.) or smoother, whereas compositions designed for other applications may run up to 1524 nm (60 µin.). Ground parts will normally be somewhat smoother than the same material in the as fired condition, and the finish can be further improved by lapping or polishing. The finishes are specified to ANSI Standard B46.1-1962, which is based on a measuring instrument stylus having a 0.0127-mm (0.0005-in.) radius. A typical commercial industrial specification is shown in Fig. 9-17.

SPECIFICATIONS:

Parameter	AQL	Standard
Outside dimensions	1.5 cum	± 1% less than ± 0.076 mm (0.003 in.)
Critical dimensions (when required)	1.5 cum	± 0.5% none less than ±0.076 mm (0.003 in.)
Hole centers	1.5 cum	± 1% none less than ± 0.076 mm (0.003 in.)
Hole diameters	1.0 cum	± 10% none less than ± 0.025 mm (0.001 in.) and none more than ± 0.127 mm (0.005 in.)
Thickness	1.0	± 10% in range of 0.254 mm (0.010 in.) through 0.0864 mm (0.034 in.)
SNAP-STRATES		With correct procedure, substrates should break to ± 1% none less than ± 0.152 mm (0.006 in.)
Camber	2.5	0.004 mm/mm (0.004 in./in.) none less than 0.002 mm/mm (0.002 in./in.)
Visual:		
over 5806 mm^2 (9 in^2.)	—	To be negotiated based on your need.
up to 5806 mm^2 (9 in^2.)	4.0 cum	Maximum for any one defect is 63.5 mm (2.5 in.)

1. Camber is determined by checking thickness away from edge with 2.032-mm (0.080-in.) diameter anvil micrometers and plotting until normal curve appears. Add camber allowance to mode value and set parallel plates at value obtained. Parts must pass through these plates under their own weight.

2. Visual defects are

   all pits larger than 0.178 mm (0.007 in.)
   all cracks
   all excess material more than 0.025 mm (0.001 in.) high
   all spots
   all scratches deeper than 0.0178 mm (0.0007 in.)
   all indentations larger than 0.178 mm (0.007 in.)
   all humps more than 0,051 mm (0.002 in.) high
   chips: reasonable with substrate size. If this is critical with your application, specific values can be mutually met.
   on SNAP-STRATES, visual defects are judged on the small substrates they yield and not on the part as a whole.

Figure 9-17. Typical Commercial Specification for Ceramic Component Tolerances

9-4 TEXTILE COMPONENTS

In the design of textile components particular emphasis must be given to those steps that most influence producibility}. This includes the formation of individual filaments, fibers, or strands and compounding these strands into woven, or otherwise formed, textile material. For more in-depth information on the design of fabric. see Ref. 12.

9-4.1 MATERIAL CONSIDERATIONS

The two primary classes of textile materials are those produced from natural fibers and those produced from man-made, or synthetic, fibers. Synthetic fibers are the most prevalent as evidenced by the rise in mill consumption of various fibers as shown in Fig. 9-18. This has resulted in significant activity in the commercial development of synthetic fiber technology.

9-4.1.1 Natural Fibers

Natural fibers constitute a small percentage of the total fibers being consumed by United States textile mills today; however, their importance as a blending element with synthetic fibers should not be overlooked. The physical properties of two selected natural fiber cloths are given in Table 9-17.

TABLE 9-17. PHYSICAL PROPERTIES OF SELECTED NATURAL FIBER CLOTH

	Width mm (in.)		Weight per m^2 kg	(ounces)	Breaking Strength, N	(lb)	Tearing Strength, N	(lb)
Cotton sateen cloth	889	(35)	0.3062	(10.8)	756.2	(170)	17.8	(4.0)
Cotton duck cloth	889	(35)	0.5245	(18.5)	822.9	(185)	26.7	(6.0)

9-4.1.2 Synthetic Fibers

The basic substance for the three cellulosic fibers (acetate, rayon, and triacetate) is cellulose, which comes from purified wood pulp. It can be dissolved for extrusion into fibers. The substances used in the production of the noncellulosic fibers generally are melted or chemically converted into a liquid state. Most man-made fibers are formed by extruding the syrupy liquid under pressure through the tiny holes of a device called a spinneret. In their original state the fiber-forming substances exist as solids and, therefore, must first be converted into a liquid state for extrusion. This is achieved by dissolving them in a solvent or melting them with heat. If they cannot be dissolved or melted directly, they must be chemically converted into soluble derivatives. Unlike natural fibers, the man-made ones can be extruded with different fineness, i.e., denier. A denier is a unit of fineness equal to 1g 9000 m or 111.1 mg 1000 m. A 15-denier monofilament is often used to achieve ultimate sheerness. Because they give greater strength, yarns of 840 denier are used in tires for trucks, automobiles, planes, and other vehicles.

9-4.1.2.1 Synthetic Fiber Production

The three basic extrusion methods for producing synthetic fibers are wet spinning, dry spinning, and melt spinning. Each is discussed.

1. *Wet Spinning.* As the filaments emerge from the spinneret, they pass directly into a chemical bath where they are solidified or generated. Because of the bath, this process for making fibers is called wet spinning. Acrylic and rayon are produced by this process. See Fig. 9-19.
2. Dry *Spinning. As* filaments emerge from the spinneret they are solidified by being dried in warm air. This is called dry spinning. and it is used in the production of acetate, acrylic, modacrylic, spandex, triacetate, and vinyon. See Fig. 9-20.
3. *Melt Spinning.* When the fiber-forming substance is melted for extrusion and hardened by cooling, the process is called melt spinning. Nylon, olefin, polyester, aramid, and glass are produced by the melt spinning process. See Fig. 9-21.

Man-made fibers also can be extruded from the spinneret in different shapes (round, trilobal, pentagonal, octagonal, and other), whereas natural fibers are avai1-able only in the form in which nature provided them. Trilobal-shaped fibers reflect more light and give an attractive sparkle to textiles.

9-4.1.2.2 Synthetic Fiber Forms and Physical Properties

Staple fibers are produced by first extruding many continuous filaments of specific denier from the spin-

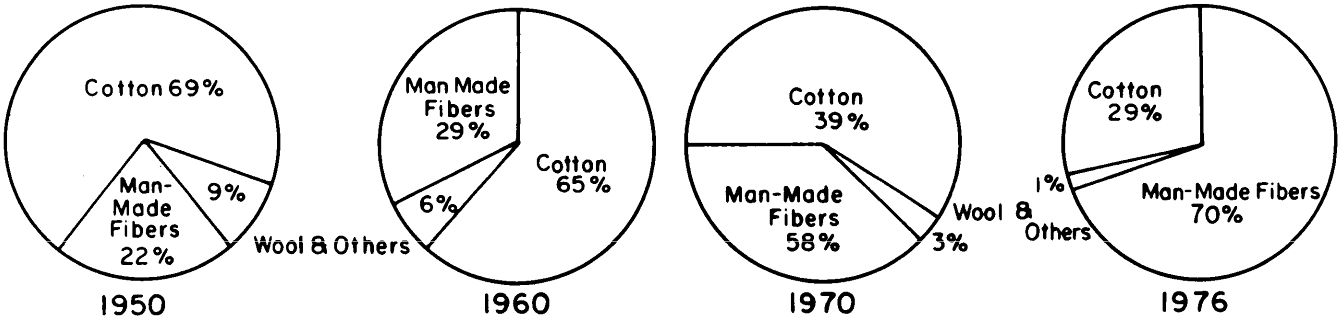

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Figure 9-18. United States Mill Consumption of Fibers (Ref. 13) neret in a large, rope-like bundle called a tow. A tow may contain as many as 200,000 continuous filaments.

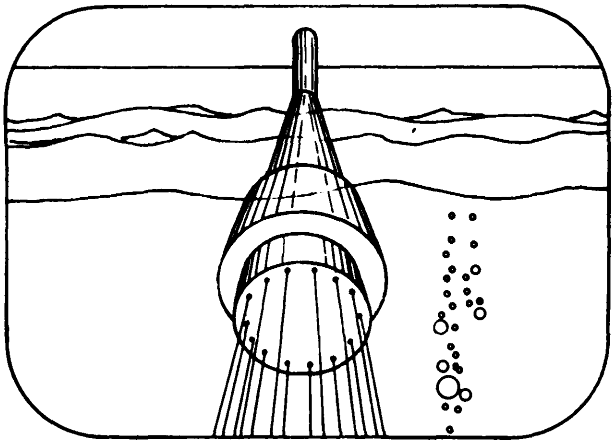

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Figure 9-19. Wet Spinning (Ref. 13)

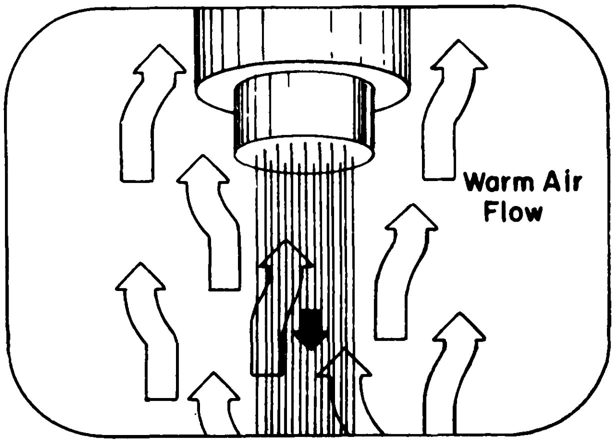

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Figure 9-20. Dry Spinning (Ref. 13)

These big bundles of fibers are crimped and then mechanically cut into the desired short staple lengths, usually 25.4 to 101.6 mm (1 to 4 in.). Combination yarns can be formed by combining spun staple and filament yarns in numerous ways to give added strength.

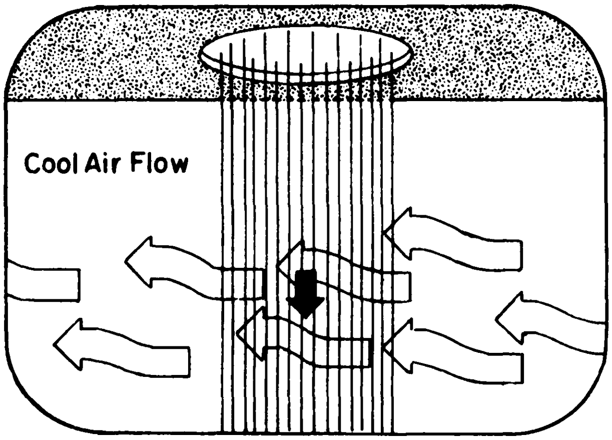

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Figure 9-21. Melt Spinning (Ref. 13)

The short fibers, or staple may be twisted or spun just as short lengths or natural fibers are spun. Staples of various lengths and denier are designed for use in various systems of spinning. Man-made fibers can be blended with other fibers—either natural or man-made. When two or more types of staple fibers are blended, they often bring together the best properties of each into a single yarn. With man-made fibers the concept of blending, or combining, different materials can actually be taken all the way back to the extrusion process. Two different polymers can be extruded side by side in a single fiber emerging from the spinneret to create a bicomponent. One of the polymers will usually have greater heat and/or moisture sensitivity than the other, will spiral during the finishing process, and will create a fiber with greater bulk and comfort. There are basically four different forms of synthetic fibers—continuous monofilament, multifilament yarn, staple, and tow yarn as shown in Fig. 9-22. Definitions of the various forms follow:

1. *Continuous Monofilament.* A single filament (fine thread) of continuous length
2. *Multifilament Yarn.* Two or more continuous monofilaments assembled or held together by twist or otherwise
3. *Staple.* Discontinuous lengths of fibers that have been cut or broken into desired lengths from large bundles of continuous monofilament (tow)
4. *Tow.* Large bundles of continuous monofilament assembled without twist.

Some of the physical properties of synthetic fibers are given in Table *9-18,* and some typical applications of synthetic materials are shown in Table 9-19.

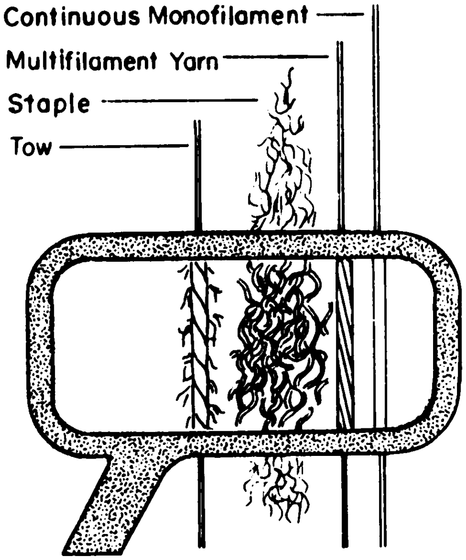

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Figure 9-22. Synthetic Fiber Forms (Ref. 13)

9-4.2 MANUFACTURING PROCESS CONSIDERATIONS

The general manufacturing process flow sheet for textile components is shown in Fig. 9-23. This process flow sheet is valid regardless of the type of fiber being used, natural or synthetic. The only significant difference is the use of adhesives for synthetics in the assembly process. For a discussion and description of the joining processes for synthetics, refer to Chapter 5, par. 5-5. The other processes in the flow sheet are discussed in the paragraphs that follow.

9-4.2.1 Patternmaking and Grading

When the design of a product is complete, the first step in its production is patternmaking and grading. No attempt will be made in this handbook to discuss all of the technical aspects; for this the reader is referred to Ref. 14.

The actual layout of the component patterns into a combination designed to yield maximum use of yardage is the next important step in achieving an optimum cutting plan. Generally, this is accomplished through miniaturization. In this process miniature scale patterns are arranged on scaled blanks of the raw material as shown in Fig. 9-24. The purpose of this process is to maximize the raw material usage. The designer of textile products should keep this thought in mind during the design process. The design process can do much to enhance later producibility gains. Usually just laying out the major components of a proposed design will be sufficient to determine preferred material widths and to produce significant producibility gains.

Grading, or working from a common design to establish different sizes of the same design, is a process that is currently undergoing significant change. Computer programs for accomplishing this laborious task are currently available in the apparel industry; however, they are not in widespread use. One such system uses a minicomputer, an input/output device, and a plotting table. This system takes as input the digital description of the components of a garment of a single size and creates the design of the components for all other sizes. The output is used to draw the paper patterns on the plotting table or as direct input to control a fabric cutting machine. The machine performs this task in one-sixth the time it takes a trained patternmaker and optimizes the use of available raw material.

9-4.2.2 The Cutting Room

The key word in cutting is accuracy. One miscut component is expensive to replace and may present a shape problem. Furthermore, the quality of assembly in the sewing room is largely dependent upon the quality of the cutting operation. The principal items of cutting equipment, all of which are being used to some degree by various manufacturers, include band knife, straight knife, round knife, single dies, and multiple dies. These tools, used to accomplish what is normally considered the cutting operation, are supplemented by strip cutters, pocket slitters, drills, hand notchers, etc. More recent developments beginning to emerge from technology development laboratories include laser beam cutters and water jet cutters.

9-4.2.2.1 Cutting Equipment

1. *Band Knife.* The band knife looks and operates like a large bandsaw and is perhaps the most accurate of all equipment in cutting exceptionally high lays, or, at least, it has the greatest potential for accuracy. It requires that maneuverable sections of the spread be transported to the knife from the spreading area. While the knife remains in a fixed position, the operator guides the pattern outline into the cutting edge.

2. *Die Cutting.* This also requires that the block of material be brought to the clicking machine. The clicker is a heavy, hydraulic-powered machine used to drive cutting dies through the pile of material. As a rule, only those parts requiring extreme accuracy in cutting are die cut; the remaining components are cut on the cutting table with a straight knife.

3. *Multiple Dies.* Multiple dies are used to cut more than one part at a time and can be used to cut complete sections with one downward stroke. The most advanced machine for multiple die cutting develops 363 metric tons (400 tons) of downward force, or about 14.0 MPa

TABLE 9-18. SOME PHYSICAL PROPERTIES OF SYNTHETIC FIBERS (Ref. 13)

Fiber	Breaking Tenacity[1] (grams per denier)		Specific Gravity[2]	Standard Moisture Regain[3] %	Effects of Heat
	Standard	Wet			
Acetate (filament and staple)	1.2 to l.5	0.8 to 1.2	1.32	6.0	Sticks at 177°C to 191°C. Softens at 205°C to 230°C. Melts at 260°C. Burns relatively slowly.
Acrylic (filament and staple)	2.0 to 3.5	1.8 to 3.3	1.14 to 1.19	1.3 to 2.5	Sticks at 232°C to 258°C depending on type.
Aramid (Kevlar)					
regular tenacity filament	4.8	4.8	1.38	5	Decomposes above 427°C.
high tenacity filament	22	22	1.44	2.7 to 7	Decomposes above 482°C.
staple	3 to 4.5	3 to 4.5	1.38	5	Decomposes above 427°C.
Modacrylic (filament and staple)	2.0 to 3.5	2.0 to 3.5	1.30 to 1.37	0.4 to 4.0	Will not support combustion. Shrinks at 121°C. Stiffens at temperatures over 149°C.
Nylon					
nylon 66 (regular tenacity filament)	3.0 to 6.0	2.6 to 5.4	1.14	4.0 to 4.5	Sticks at 229°C. Melts at about 260°C.
nylon 66 (high tenacity filament)	6.0 to 9.5	5.0 to 8.0	1.14	4.0 to 4.5	Same as above.
nylon 66 (staple)	3.5 to 7,2	3.2 to 6.5	1.14	4.0 to 4.5	Same as above.
nylon 6 (filament)	6.0 to 9.5	5.0 to 8.0	1.14	4.5	Melts at 212°C to 220°C.
nylon 6 (staple)	2.5	2.0	1.14	4.5	Melts at 212°C to 220°C.
Olefin (polypropylene) (filament and staple)	4.8 to 7.0	4.8 to 7.0	0.91	—	Melts at 163°C to 168°C.
Polyester					
regular tenacity filament	4.0 to 5.0	4.0 to 5.0	1.22 or 1.38*	0.4 or 0.8*	Melts at 249°C to 288°C.
high tenacity filament	6.3 t0 9.5	6.2. to 9.4	1.22 or 1.38*	0.4 or 0.8*	Melts at 249°C to 288°C.
regular tenacity staple	2.5 to 5.0	2.5 to 5.0	1.22 or 1.38*	0.4 or 0.8*	Melts at 249°C to 288°C.
high tenacity staple	5.0 to 6.5	5.0 to 6.4	1.22 or 1.38*	0.4 or 0.8*	Melts at 249°C to 288°C.
Rayon (filament and staples)					
regular tenacity	0.73 to 2.6	0.7 to 1.8	1.50 to 1.53	13	Does not melt. Decomposes at 177°C to 240°C. Burns readily.
medium tenacity	2.4 to 3.2	1.2 to 1.9	1.50 to 1.53	13	
high tenacity	3.0 to 6.0	1.9 to 4.6	1.50 to 1.53	13	
high wet modulus	2.5 to 5.5	1.8 to 4.0	1.50 to 1.53	13	
Segmented polyurethane (spandex) (filament)	0.6 to 0.9	0.6 to 0.9	1.20 to 1,21	0.75 to 1.3	Degrades slowly at temperatures over 149°C. Melts at 230°C to 270°C.

(cont'd on next page)

TABLE 9-18. (cont'd)

Fiber	Breaking Tenacity[1] (grams per denier) Standard	Wet	Specific Gravity[2]	Standard Moisture Regain[3] %	Effects of Heat
Vinylidene chloride (saran) (filament)	up to 1.5	Up to 1.5	1.70		Softens at 116°C to 138°C. Self-extinguishing.
Triacetate (filament and staple)	1.2 to 1.4	0.8 to 1.0	1.3	3.2	Before heat treatment, sticks at 177°C to 191°C. After treatment, above 240°C. Melts at 302°C.
Vinyl chloride (vinyon) (staple)	0.7 to 1.0	0.7 to 1.0	1.33 to 1.35	up to 0.5	Becomes tacky and shrinks at 66°C. Softens at 77°C. Melts at 127°C. Will not support combustion.

*Depending on type.

[1] Breaking tenacity: The stress at which fiber breaks, expressed in terms of grams per denier.

[2] Specific gravity: The ratio of the weight of a given volume of fiber to an equal volume of water.

[3] Standard moisture regain: The moisture regain of a fiber (expressed as a percentage of the moisture-free weight) at 21° C and 65% relative humidity.

Note: Data given in ranges may fluctuate according to introduction of fiber modifications or additions and deletions of fiber types.

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TABLE 9-19. TYPICAL APPLICATIONS OF SYNTHETIC MATERIALS

	Acetate	Acrylic	Anidex	Aramid	Azion	Modacrylic	Nylon	Nytril	Olefin	Polyester	Rayon	Saran	Spandex	Triacetate	Vinyon
Clothing	**X**	**X**	**X**			**X**	**X**	**X**	**X**	**X**	**X**		**X**	**X**	
Rainwear			**X**				**X**				**X**				
Filters	**X**			**X**		**X**			**X**						
Protective clothing				**X**											
Bulletproof vest				**X**											
Marine				x	x					x					
Tires				x			x			x	x				
Rope, cable, and nets				x			x		x	x					
Insulation					x					x					
Air hoses							x								
Parachutes							x								
Conveyors							x								
Sleeping bags							x								
Tents							x								
Sandbags									x						
Fire hose										x					
Chemical industry															x
Upholstery	x	x	x				x		x		x	x			

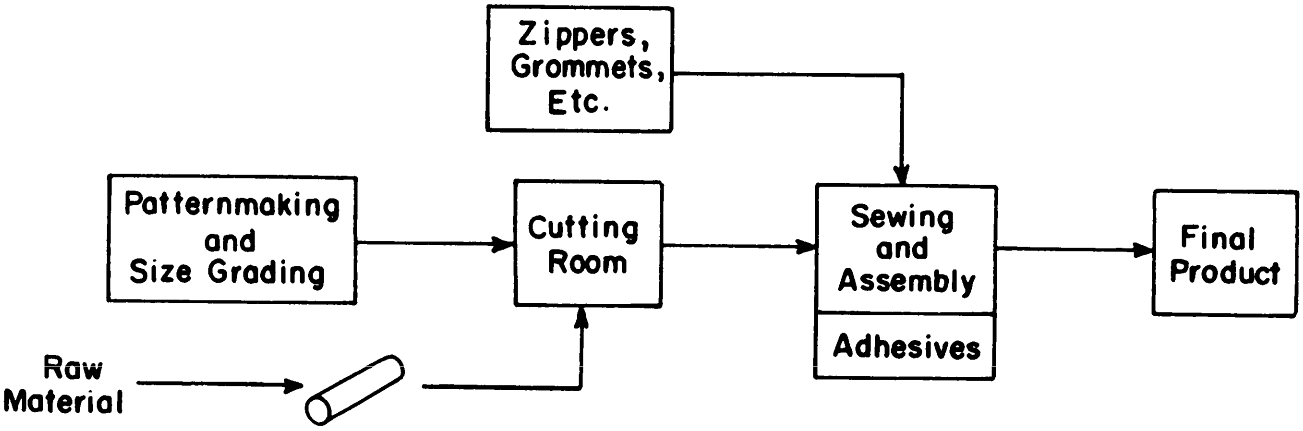

Figure 9-23. Manufacturing Process Flow Sheet for Textile Components

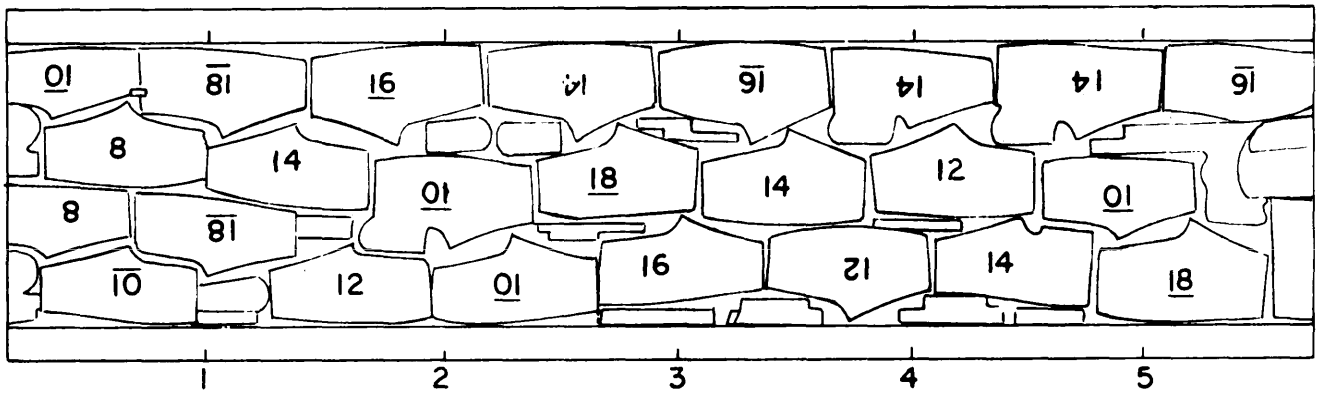

Figure 9-24. Miniature Pattern Layout

(2000 psi). It is used to cut 2.44- to 2.74-m (8- to 9-ft) sections 144-ply high. Output is approximately 300 to 400 strokes per hour.

4. *Straight Knife.* This conventional electric-powered cutting machine remains in widest use throughout the industry. Equipped with a flat base, which moves on rollers between the table and the bottom ply of material, and a straight knife that is perpendicular to the material, these machines are pushed along pattern lines by the operator. This permits high cutting heights and wide flexibility in achieving economy in pattern layout. Sections can be of any desired length, and there is *no* necessity for moving uncut material blocks from the spreading table to a stationary cutting machine. Straight knives are equipped with automatic sharpeners. Depending on the fabric, various types of blades are used with either a 380-01 190-rad/s (3600-or 1800-rpm) motor. The 190-rad/s (1800-rpm) motor is recommended for synthetic fabrics, which tend to fuse together from the heat generated by high-speed cutting. Possibly the major drawback with the straight knife is inaccuracy in cutting small parts. This inaccuracy is caused by (1) distortion of the pile of material as the knife base is inserted between it and the table and (2) leaning of the pile caused by operator handling and by turning of the blade in light spots.

9-4.2.2.2 The Cutting Process

After spreading multiple layers of cloth, the marker, or template pattern, is rolled out on top of the lay. If the marker is subject to slippage against the top ply, as is generally true with paper, it is stapled to the top ply of material. Many manufacturers then staple serially numbered work tickets to the various parts in each section before cutting begins. However the identification of components subsequent to cutting is also frequently done. If the particular component being cut requires drill holes, they are usually drilled by the cutters before the cutting operation begins. Every precaution should be taken to see that the base of the drill is placed flat upon the surface of the lay and that the drill bit is sharp. If these precautions are not taken, the drill bit will have a tendency to drift, which will cause improperly located holes on the lower plys of cloth. Drill holes made by conventional drilling equipment tend to close up on certain types of fabrics, which makes it difficult to locate the drill holes in sewing. Two solutions are frequently used to overcome this difficulty. The first is the use of a hot drill, which actually burns a small hole in the fabric as the drill bit is lowered. Another is the use of a fluorescent solution on the end of the drill bit. The drill hole is then illuminated during the striving operation through use of a special light mounted on the sewing machine tabletop. Laser beam and water jet cutting both offer considerable potential fol cutting and are described in the following paragraphs.

1. *Laser Beam Cutting:*

This cutting process uses a focused laser beam. The coherent and essentially monochromatic charaacteristics of laser radiation account for its ability to be focused into a very small spot and to produce a very high energy density. The energy is transferred to the material upon which the focused spot falls resulting in a rapid increase in temperature. The cutting process can be accomplished either by vaporization of the material or by a combustion process. The vaporization process is generally used with nonmetallic materials. The laser energy focused to a spot size of the order of 0.254 mm (0.010 in.) vaporizes the material under the spot. A jet of air or nitrogen removes the vaporized debris and smoke from the cut and acts to quench combustion and prevent flaming. In a laser cutting system this vaporization, burning, and charring is confined to a very small zone.

Being an optical system, the laser cutter suffers from the limitation common to all optical focusing systems, that is, having a limited depth of focus. This means that the spot produced by focusing is minimum at the focal plane but increases in size in either direction from this plane. In a typical laser cutting system the spot diameter will increase 10% with a distance of 5.1 mm (0.2 in.). Doubling the spot diameter increases the depth of focus by four, and it reduces the cutting speed by one-half since twice as much material is removed. If the material depth were to be increased by four, corresponding to the increased depth of field, the cutting speed would have to be reduced to one-eighth. This interrelationship of spot diameter, depth of cut, and cutting speed leads to the necessity of optimizing productivity by trading off the depth of cut (ply height).

2. *Water Jet Cutting:*

The second cutting system is the water jet. A very high velocity, small diameter stream of water is created by applying high pressure water to a nozzle. The resulting jet is capable of cutting by a mechanical process in which the tool is the jet of water that tears the fibers by impact and entrainment. It forms a cut by actually tearing out a bit of the fabric, which goes along with the jet and appears somewhere in the effluent liquid.

The jet takes a cut of width at least equal to the jet diameter. Being a mechanical cutting process, there is a tool (the hydraulic stream) that at high velocity has sufficient momentum to act as a solid tool encountering the fabric and tearing it along the outer circumference of the jet stream.

As with the laser beam, attention must be given to the depth to which the water jet can successfully cut. The jet can stop short of penetrating the full depth of material, thus flooding the cut. Short of this, attempting to cut too great a depth can result in poor cutting quality at the bottom of the cut compared to that at the top because the jet increases in diameter as it penetrates deeper, which increases the cut width. The jet is slowed as it penetrates the cut and so loses its energy and cutting ability. The result is that thick layers (high ply layups) must be cut more slowly than thin layers of material.

9-4.2.3 Sewing and Assembly

Sewing is a highly labor-intensive element. Some progress has been made toward automating this function, but thus far penetration has been minimal. Generally speaking, sewing consists of large quantities of sewing machine operators at individual machines. The elements of primary importance to the designer are stitches, seams, and stitching. These are covered in finite detail in Ref. 13 and are briefly reviewed here as important elements of producibility. A complete index of all stitches, scams, and stitchings is shown in Table 9-20.

9-4.2.3.1 Stitches

Stitches are divided into seven classes, which are identified by the first digit of three-digit numerals. Each class is divided into several types, which are identified by the second and third digits. All stitch types must conform to the drawing unless otherwise specified. Each stitch class defined here ‘is only one of many different types within each class.

1. *Stitch Class 100.* This stitch is formed with one or more needle threads, and its general characteristic is interlooping. A loop, or loops, of thread is passed through the material and secured by interlooping with a succeeding loop, or loops, after passing through the material to form a stitch. (See Fig. 9-25.)

2. *Stitch Class 200.* This stitch is formed by hand with one or more needle threads. A general characteristic is that each thread passes through the material as a single line of thread, and the stitch is secured by the single line of thread passing in and out of the material or interloping of the threads. When more than one thread is used, the threads pass through the same perforation in the material. (See Fig. 9-26.)

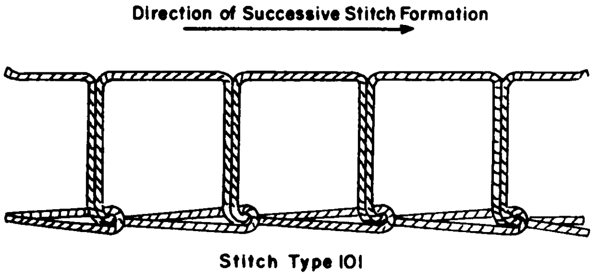

Figure 9-25. Stitch Class 100 (Ref. 14)

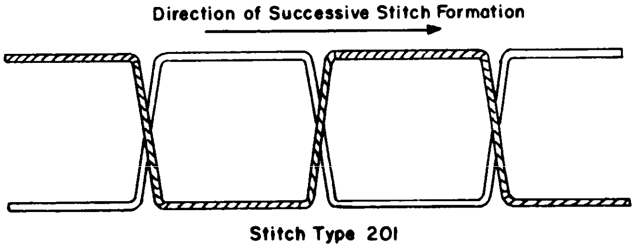

Figure 9-26. Stitch Class 200 (Ref. 14)

3. *Stitch Class* 300. This stitch is formed with two or more groups of threads. A general characteristic is the interlacing of the two groups. Loops of the first group are passed through the material where they are secured by the thread, or threads, of the second group to form a stitch. (See Fig. 9-27.)

TABLE 9-20. INDEX OF STITCHES, SEAMS, AND STITCHING (Ref. 14)

STITCHES	STITCHES	SEAMS	SEAMS	SEAMS	STITCHINGS
Stitch Class 100	Seam Class SS	Seam Class SS	Seam Class LS	Seam Class LS	Stitching Class EF
Stitch type	Seam type	Seam type	Seam type	Seam type	Stitching type
101	518	SSap	LSan	LScu	EFf
102	519	SSaq	LSap	LScv	EFg
103	520	SSar	LSaq	LScw	EFh
104	521	SSas	LSar	LScx	EFj
105'	Stitch Class 600	SSat	LSas	LScy	EFk
106	Stitch type	SSau	LSat	LScz	EF1
Stitch Class 200	601	SSav	LSau	LSda	EFm
Stitch type	602	SSaw	LSav	LSdb	EFn
201	603	SSax	LSaw	LSdc	EFp
202	604	SSay	LSax	LSdd	EFq
203	605	SSaz	LSay	Seam Class BS	EFr
204	606	SSba	LSaz	Seam type	EFs
Stitch Class 300	607	SSbb	LSba	BSa	EFt
Stitch type	Stitch Class 700	SSbc	LSbb	BSb	EFu
301	Stitch type	SSbd	LSbc	BSC	EFv
302	701	SSbe	LSbd	BSd	EFw
303	Seams	SSbf	LSbe	BSe	EFx
304	Seam Class SS	SSbg	LSbf	BSf	EFy
305	Seam type	SSbh	LSbg	BSg	EFz
306	SSa	Seam Class LS	LSbh	BSh	EFaa
307	SSb	Seam type	LSbj	BSj	EFab
308	SSc	LSa	LSbk	BSk	EFac
309	SSd	LSb	LSbl	BS1	EFad
310	SSe	LSc	LSbm	BSm	EFae
311	SSf	LSd	LSbn	BSn	EFaf
312	SSh	LSe	LSbo	BSo	EFag
313	SSj	LSf	LSbp	BSp	EFah
314	SSk	LSg	LSbq	BSq	
Stitch Class 400	SSl	LSj	LSbr	BSr	
Stitch type	SSm	LSk	LSbs	BSs	
401	SSn	LS1	LSbt	Seam Class FS	
402	SSp	LSm	LSbu	Seam Type	
403	SSq	LSn	LSbv	FSa	
404	SSr	LSp	LSbw	FSb	
405	SSs	LSq	LSbx	FSc	
406	SSt	LSr	LSby	FSd	
407	SSu	LSs	LSbz	FSe	
Stitch Class 500	SSv	LSt	LSca	FSf	
Stitch type	SSw	LSu	LScb	STITCHINGS	
501	SSx	LSv	LScc	Stitching Class OS	
502	SSy	LSw	LScd	Stitching type	
503	SSz	LSx	LSce	OSa	
504	SSaa	LSy	LScf	OSb	
505	SSab	LSz	LScg	OSc	
506	SSac	LSaa	LSch	OSd	
507	SSad	LSab	LScj	OSe	
508	SSae	LSac	LSck	OSf	
509	SSaf	LSad	LSc1	OSg	
510	SSag	LSae	LScm	OSh	
511	SSah	LSaf	LScn	Stitching Class EF	
512	SSaj	LSag	LSco	Stitching type	
513	SSak	LSah	LScp	EFa	
514	SSal	LSaj	LScq	EFb	
515	SSam	LSak	LScr	EFc	
516	SSan	LSal	LScs	Efd	
517	SSao	LSam	LSct	EFe	

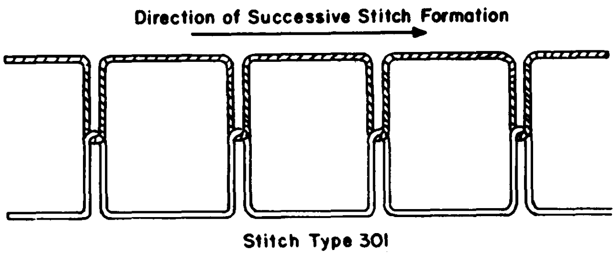

Figure 9-27. Stitch Class 300 (Ref.14)

4. Stitch Class 400. This stitch is formed with two or more groups of threads. A general characteristic is the interlacing and interlooping of the loops of the two groups. Loops of the first group are passed through the material and are secured by interlacing and interlooping with loops of the second group to form a stitch. (See Fig. 9-28.)

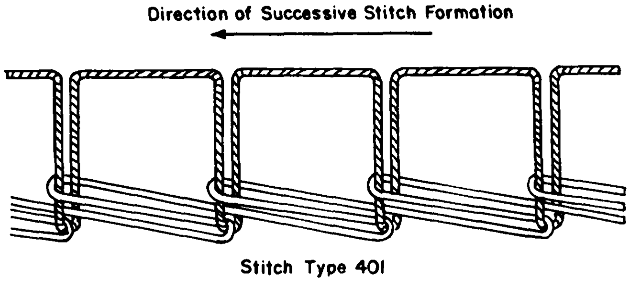

Figure 9-28. Stitch Class 400 (Ref. 14)

5. Stitch Class 500. This stitch is formed with one or more groups of thread. A general characteristic is that loops from at least one group of thread shall pass around the edge of the material. Loops of one group of thread are passed through the material and are secured by interlooping with themselves before succeeding loops are passed through the material. They can also be secured by interlooping with loops of one or more interlooped groups of threads before succeeding loops of the first group are again passed through the material. (See Fig. 9-29.)

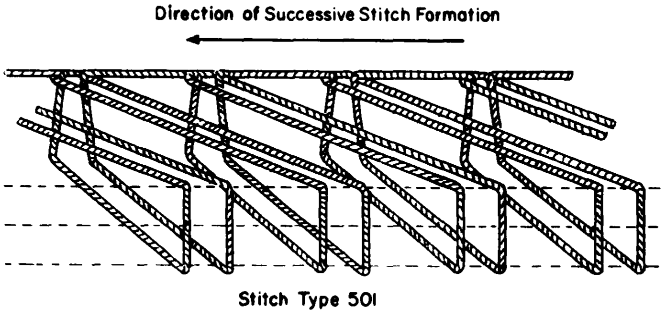

Figure 9-29. Stitch Class 500 (Ref. 14)

6. Stitch Class 600. This stitch is formed with two or more groups of threads. A general characteristic is that two of the groups cover the raw edges of both surfaces of the material. Loops of the first group of thread are passed through loops of the third group already cast on the surface of the material and then through the material where they are interloped with loops of the second group of thread on the underside of the material. The one exception of this procedure is Stitch Type 601 where only two groups of thread are used, and the function of the third group is performed by one of the threads in the first group. (See Fig. 9-30.)

7. Stitch Class 700. This stitch is formed with a single, continuous needle thread. A general characteristic is that at the penetration of the first stitch, a portion of the needle thread @ wound onto a reel in the lower mechanism of the machine. The stitches are formed by interlacing the needle thread with the thread wound on the reel. The interlacing of this stitch class, except for the initial stitch, is identical to that of Stitch Class 300. (See Fig. 9-3 1.)

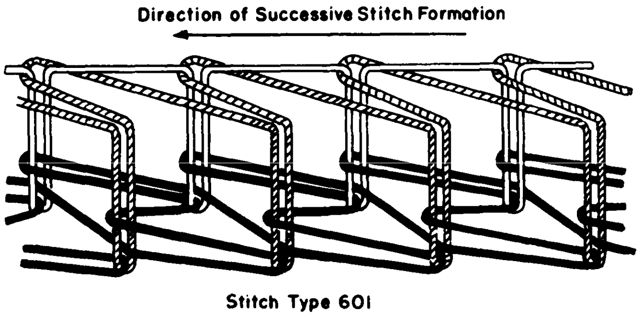

Figure 9-30. Stitch Class 600 (Ref. 14)

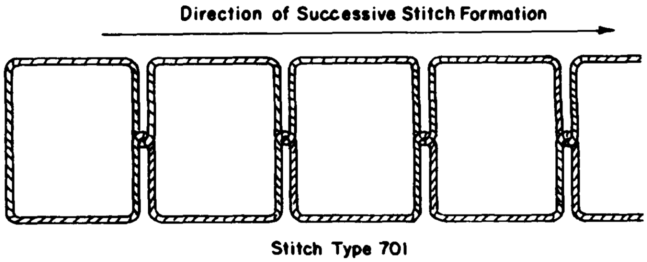

Figure 9-31. Stitch Class 700 (Ref. 14)

9-4.2.3.2 Seams

The seam is the joint through which the stitch is made. There are four classes of seams, and there are numerous types of seams within each class; only a few of each are included for illustrative purposes. The seams in each class are designated by two or more uppercase letters. The types within each class are designated by one or more lowercase letters. The number of rows of stitching are designated by one or more Arabic numerals. Example: The symbol for a simple, superimposed seam with one row of stitches is SSa-1. The seam classes are defined:

1. *Superimposed Seams, Class SS.* A general characteristic of this seam is that the plies of material are superimposed and seamed with one or more rows of stitches. (See Fig. 9-32.)
2. *Lapped Seam; Class LS.* A general characteristic of this seam is that the plies of material are lapped and seamed with one or more rows of stitches. (See Fig. 9-33.)
3. *Bound Seam, Class BS.* This seam is formed by folding a binding strip over the edge of one or more plies of material and seaming the binding strip to the material with one or more rows of stitches. (See Fig. 9-34.)

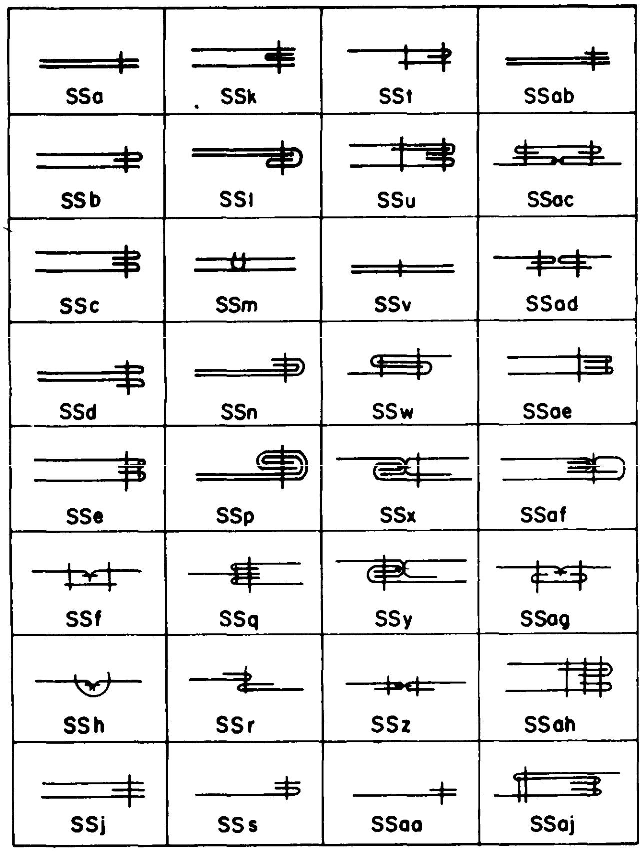

Figure 9-32. Seam Class SS (Ref. 14)

4. *Flat Seam, Class FS.* This seam is formed by seaming the abutted edges of material together in such a manner that the stitches extend across and cover, or tend to cover, the edges of the plies joined. (See Fig. 9-35.)

9-4.2.3.3 Stitchings

Stitchings are divided into two classes, and within each class there are several types. All stitching types shall conform to the applicable drawings unless otherwise specified. ‘I-he classes are defined:

1. *Ornamental Stitching, Class OS.* A general characteristic of this class of stitching is that a series of stitches are embodied in a material either in a straight line, a curve, or following a design for ornamental purposes. (See Fig. 9-36.)
2. *Edge Finishing, Class EF.* In this class of stitching a general characteristic is that edge finishing is accomplished by either (a) stitching a series of stitches at or over the edge of a material (the edge may or may not be folded as specified) or (b) the edge of the material is folded and stitched to the body of the material with a series of stitches. (See Fig. 9-37.)

Table 9-21 illustrates some general applications of the various types of stitches, seams, and stitchings.

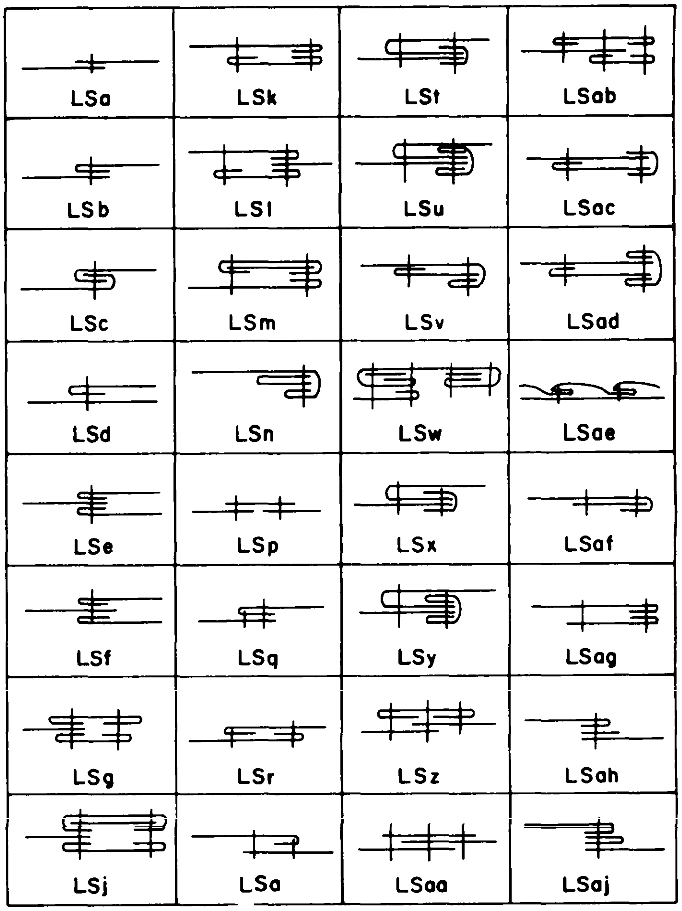

Figure 9-33. Seam Class LS (Ref. 14)

9-4.2.4 Characteristics of Seams and Stitchings

The characteristics of a properly constructed seam or stitching are strength, elasticity, durability, security, and appearance. These characteristics must be balanced with the properties of the material to be joined to form the optimum seam. The end use of the item will govern the relative importance of these characteristics, and the selection of the seam or stitching type and stitch type should be based upon these considerations for optimum producibility.

9-4.2.4.1 Strength

The strength of the seam or stitching should equal that of the material it joins to have balanced construction that will withstand the forces encountered in the use of the item of which the seam is a part. The elements affecting the strength of a seam or stitching are stitch type, thread strength, stitches per inch, thread tension, seam or stitching type, and seam efficiency of the material.

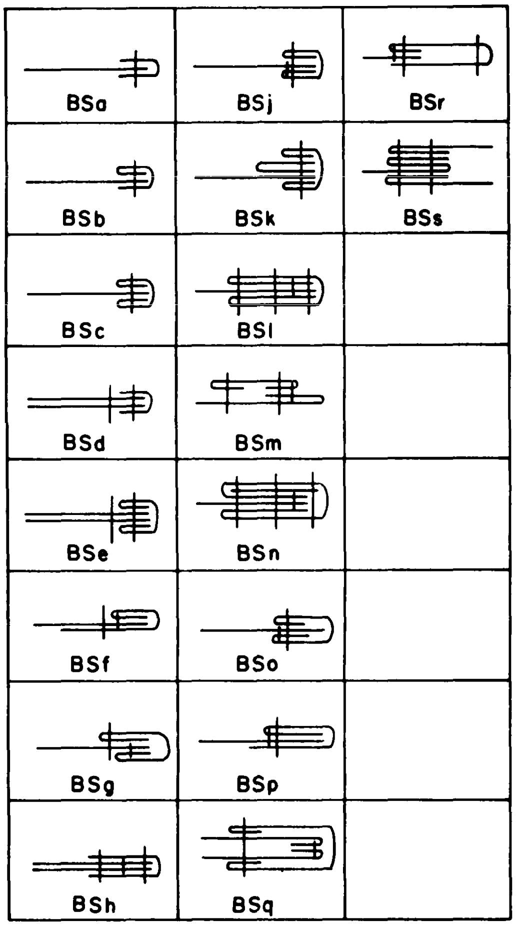

Figure 9-34. Seam Class BS (Ref. 14)

9-4.2.4.2 Elasticity

The elasticity of a seam or stitching should be slightly greater than that of the material which it joins so that the material will support its share of the forces encountered in the end use of the sewn item. The elasticity of a seam or stitching depends upon stitch type and thread elasticity.

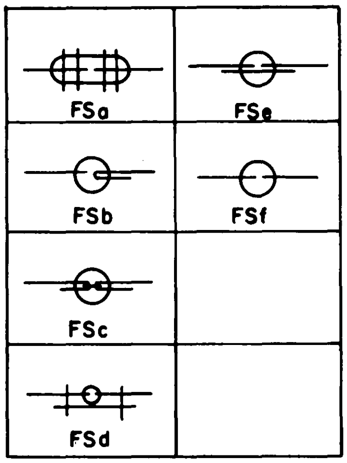

Figure 9-35. Seam Class FS (Ref. 14)

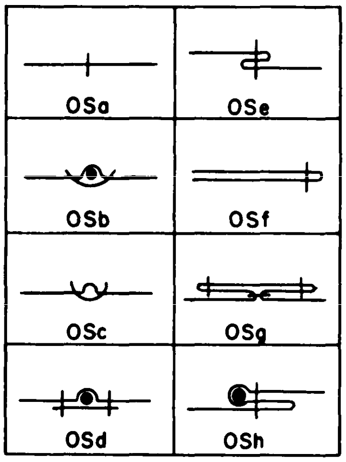

Figure 9-36. Stitching Class OS (Ref. 14)

9-4.2.4.3 Durability

The durability of a seam or stitching depends largely upon its strength and the relation between the elasticity of the seam and the elasticity of the material. However, in the less elastic, tightly woven, dense materials, there is a tendency for plies to "work" or slide on each other. To form a durable seam or stitching in such materials, the thread size must be judiciously chosen and the stitches well set to the material (without undue tension which will unbalance the elasticity and cause puckering) to minimize abrasion and wear by contact with outside agencies.

TABLE 9-21. APPLICATIONS OF STITCHES, SEAMS, AND STITCHINGS (Ref. 14)

Seam Type	Application	Types of Standard Stitches Suitable
Superimposed seams		
SSa-1	Seaming (bags, jute, cotton)	101,104,301,401.
	Basting	101.
	Seaming (straight)	301,401.
	Seaming (zigzag)	304,404.
	Seaming (overedge)	501 to 513.
	Seaming (using waxed thread)	101,201,301.
SSa-2	Seaming and serging	301,401,501 to 507,515 to 519,602.
SSb-1 and SSb-2	Seaming (straight)	301,201,401,402.
	Seaming (where similar stitch is essential on both surfaces).	301.
SSc-1 and SSc-2	Seaming	301,302,401,402.
SSd-1	Seaming	301,401.
SSe-2 and SSe-3	Seaming and edge finishing	301,302,401,402.
	Making cuffs, collars, etc., and edge stitching on coats and shoes.	
SSf-3	Taping or staying	301,401.
SSh-2	Cover seaming	302,402,406.
SSj-1	Seaming	201,301,401.
SSk-1	Seaming and cording	201,301,401.
SSl-1	Seaming	201,301,401.
SSm-1	Seaming or felling, where a blind stitch is required	103.
	Padding lapels, felling tapes, etc.	103.
SSn-1	Seaming	101,301,401,
SSp-1	Seaming	301,401.
SSq-2 and SSq-3	Seaming	301,302,461,402.
SSr-1	Seaming	301,401.
SSs-1 and SSs-2	Seaming and staying	301,401.
SSt-2 to SSt-4	Seaming and taping	301,401.
SSu-2 to SSu-4	Attaching elastic	301,401.
SSu-2	Making pocket jettings	301.
SSv-1 to SSv-3	Quilting	301,401.
SSw-2	Seaming	301,401.
SSx-2	Seaming (crotch pieces and linings to trousers)	301,401.
SSy-2	Seaming	301,401.
SSz-3	Seaming	301,401.
SSaa-1	Taping (coat fronts and armholes)	301.
SSab-1	Taping (coat fronts and armholes)	301.
SSac-3	Taping (crotch seams on trousers)	301.
SSad-3	Seaming and staying	301,401.
SSae-2 and SSae-3	Seaming	301,401.
SSaf-2	Seaming and staying	301,401.
SSag-3	Seaming and staying	301,401.
SSah-3 and SSah-4	Seaming	301,401.
SSaj-3	Seaming	301,401.
SSak-1	Attaching slide fasteners	301,401.
SSal-2	Attaching slide fasteners	301,401.
SSam-2	Seaming	301,401.
SSan-2	Seaming	301,401.
SSao-2	Seaming	301,401.

(cont'd on next page)

TABLE 9-21. (cont’d)

Seam Type	Application	Types of Standard Stitches Suitable
Superimposed seams—(cont’d)		
SSap-3	Seaming	301,401.
SSaq-2	Seaming	301,401.
SSar-3	Attaching end of left fly lining to crotch seam	301,401.
SSas-4	Attaching buttonhole strips	301,401.
SSat-2	Attaching buttonhole strips	301,401.
SSau-2	Staying	301,401.
SSav-2	Seaming and welting	301,401.
SSaw-2	Seaming and welting	301,401,504.
SSax-2	Seaming and welting	301,401,504.
SSay-2	Making waistbands	301,401.
SSaz-1	Seaming neckties	104.
SSba-3	Book seaming	103 and 301 or 401.
SSbb-3	Seaming and staying	301,401.
SSbc-1	Attaching interlining to cuff	103,306.
SSbd-}	Seaming	301,401.
SSbe-2	Seaming and edge finishing	301,306,401.
SSbf-3	Seaming and welting	301,401.
SSbg-3	Seaming and welting	301,401.
SSbh-3	Seaming	301,401.
Lapped seams		
LSa-1	Seaming knitted materials or underwear and similar garments.	602,603,604,605.
LSa-1 and LSa-2	Seaming	301,401,402,406,407.
	Seaming (using waxed thread)	101,201,301.
LSb-1 and LSb-2	Seaming	301,401,402,406.
LSc-1 to LSc-4	Seaming	301,401.
LSd-1 to LSd-3	Attaching pieces to body of material	301,304,401.
LSe-1 to LSe-3	Seaming	301,401.
LSf-1 and LSf-2	Seaming	301,401.
LSg-2 to LSg-4	Facing (center plaits, stays, etc.)	301,401.
LSj-2 and LSj-4	Facing (center plaits, stays, etc.)	301,401.
LSk-2 and LSk-4	Facing (center plaits, stays, etc.)	301,401.
LS1-2 and LS1-4	Facing and seaming (center plaits, stays, etc.)	301,401.
LSm-2 and LSm-4	Facing (center plaits, stays, etc.)	101,301,401.
LSn-1	Facing (center plaits, stays, etc.)	301,401.
LSp-2 and LSp-4	Joining with overlapping strip	301,401.
LSq-2 and LSq-3	Seaming	201,301,401.
LSr-2	Seaming	301,401.
LSs-2	Seaming	301,401.
LSt-2	Seaming	301,401.
LSu-2	Seaming	301,401.
LSv-2	Facing and Staying	301,401.
LSw-4	Joining band (plain, elastic, etc.)	301,401.
LSx-2 and LSx-3	Seaming	301,401.
LSy-2 and LSy-3	Seaming	301,401.
LSz-3 and LSz-4	Seaming	301,401.
LSaa-3	Seaming	301,401.
LSab-3 and LSab-4	Banding	301,401.
LSac-2	Facing and binding	301,401.
LSad-2	Facing and binding	301,401.

(cont‘d on next page)

TABLE 9-21.—(cont'd)

Seam Type	Application	Types of Standard Stitches Suitable
Lapped seams—(cont'd)		
LSae-1	Undersewing cushion	301,401.
LSaf-2	Staying automobile quarters	301,401.
LSag-2	Staying automobile quarters	301,401.
LSah-1	Seaming	301,401.
LSaj-1	Seaming	301,401.
LSak-2	Seaming	301,401.
LSal-2 and LSal-4	Facing (center plaits, stays, etc.)	301,401.
LSam-2 and LSam-4	Facing (center plaits, stays, etc.)	301,401.
LSan-2 and LSan-4	Facing (center plaits, stays, etc.)	301,401.
LSap-1	Finishing	301,401.
LSaq-1	Finishing	301,401.
LSar-2 to LSar-4	Facing and seaming	301,401.
LSas-2	Seaming and gathering	301,401.
LSat-2	Seaming and staying	301,401.
LSau-2 to LSau-4	Seaming	301,401.
LSav-4	Seaming and reinforcing	301,401.
LSaw-3	Seaming	301,401.
LSax-4	Seaming	301,401.
LSay-4	Sewing on band with elastic	301,401.
LSaz-4	Seaming and staying	301,401.
LSba-2	Seaming	301,401.
LSbb-4	Seaming and staying	101,301,401.
LSbc-2 to LSbc-4	Facing	301,401.
LSbd-2	Seaming	301,401.
LSbe-2	Seaming	301,401.
LSbf-2 to LSbf-4	Binding (center plait)	301,401.
LSbg-1	Seaming	301,401.
LSbh-1 and LSbh-2	Binding, inserting tape between binding and body material.	301,401.
LSbj-1	Attaching pieces to body material	301,401.
LSbk-2	Attaching pieces to body material	301,401.
LSbl-2	Attaching pocket flaps and belt loops	301,401.
LSbm-3 and LSbm-4	Seaming	301,401.
LSbn-2	Seaming	301,401.
LSbo-3	Seaming	301,401.
LSbp-2	Joining yoke to shirt	301,401.
LSbq-2	Joining yoke to shirt in loosely woven material	301,401.
LSbr-3	Seaming	301,401.
LSbs-1	Attaching slide fasteners	301,401.
LSbt-2	Attaching slide fasteners	301,401.
LSbu-2	Attaching slide fasteners	301,401.
LSbv-3	Attaching slide fasteners	301,401.
LSbw-3	Seaming and binding	301,401.
LSbx-2	Forming welt on set-in pockets	301,401.
LSby-2	Forming welt on set-in pockets	301,401.
LSbz-2	Forming pocket welts	301,401.
LSca-2	Forming pocket welts	301,401.
LScb-2	Top edge of hip pocket with a stay and facing	301,401.
LScc-2	Top edge of hip pocket	301,401.

(cont'd on next page)

TABLE 9-21. (cont'd)

Seam Type	Application	Types of Standard Stitches Suitable
Lapped seams—(cont'd)		
LScd-3	Top edge of hip pocket	301,401.
LSce-2	Forming welt on bottom edge of set-in hip pockets	301,401.
LScf-2	Attaching cuffs, waistbands, or collars	301,401.
LScg-2	Attaching cuffs, waistbands, or collars	301,401.
LSch-2	Attaching cuffs, waistbands, or collars	301,401.
LScj-3	Attaching cuffs, waistbands, or collars	301,401.
LSck-3	Attaching cuffs, waistbands, or collars	301,401.
LSc1-3	Attaching cuffs, waistbands, or collars	301,401.
LScm-3	Attaching cuffs, waistbands, or collars	301,401.
LScn-3	Attaching cuffs, waistbands, or collars	301,401.
LSco-4	Attaching cuffs, waistbands, or collars	301,401.
LScp-4	Attaching cuffs, waistbands, or collars	301,401.
LScq-4	Attaching cuffs, waistbands, or collars	301,401.
LScr-4	Attaching cuffs, waistbands, or collars	301,401.
LScs-3	Attaching left fly to trouser fronts	301,401.
LSct-2	Attaching waistband linings	301,401.
LScu-2	Finishing bottoms of caps	301,401.
LScv-3	Seaming curtains on waistbands	301,401.
LScw-3	Making sewn-on belts or bands	301,401.
LScx-3	Making sewn-on belts or bands	301,401.
LScy-3	Seaming and staying	301,401.
LScz-2	Seaming	301,401.
LSda-2	Making flag headings	301,401.
LSdb-2	Facing	301,401.
LSdc-3	Trouser crotch seam	301,401.
LSdd-2	Cut-on shirt front	301,401.
Bound seams		
BSa-1 and BSa-2	Binding, bound seaming	301,304,401,404,406.
BSb-1 and BSb-2	Binding, bound seaming	301,304,401,404.
BSc-1 and BSc-2	Binding, bound seaming	301,304,401,404.
BSd-2	Seaming and binding	301,401.
BSe-2	Seaming and binding	301,401.
BSf-2	Seaming and binding	301,401.
BSg-2	Seaming and binding	301,401.
BSh-3	Seaming and binding	301,401.
BSj-2	Binding, bound seaming	301,304,401,404,406.
BSk-1	Binding and welting	301,401.
BS1-4	Binding flag headings	301,40).
BSm-3	Facing pockets	301,401.
BSn-4	Binding flag headings	301,401.
BSo-2	Binding, bound seaming	301,304,401,404,406.
BSp-2	Making pocket welts	301,401.
BSq-2	Seaming and binding	301,401.
BSr-2 and BSr-4	Seaming and binding	301,401.
BSs-2	Binding flag headings	301,401.

(cont'd on next page)

TABLE 9-21. (cont'd)

Seam Type	Application	Types of Standard Stitches Suitable
Flat seams		
FSa-1	Seaming	304,404,606,607
	Attaching collars, cuffs, borders, etc., to knitted articles.	602,603,606.
	Attaching edging, lace, etc.	601,602,603.
FSb-1	Seaming	304,602,603,606.
FSc-1	Seaming	304,404.
FSd-3	Seaming and staying	304,404.
FSe-1	Seaming and staying	304,404.
FSf-1	Hosiery toe closing	521.
	Seaming fur pelts, or seaming with overedge stitching where a flat butted seam is desired.	501 thru 505.
Ornamental stitching		
OSa-1 to OSa-3	Ornamental	101,102,104,201,203,204,301,302, 303,304,305,306,307,309,310,311, 312,402,403,404,405,406.
OSb-1	Cording	102,302,402,406,
Osc-1	Cording	102,302,402,406.
OSd-2 and OSd-3	Cording	101,301,401.
OSe-1	Tucking or plaiting	101,301,401.
Osf-1	Tucking and mock seaming	101,301,401.
OSg-3	Making box or inverted plait	301,401.
OSh-3	Welting	301,401.
Edge finishing		
EFa-1 and EFa-2	Hemming (one fold)	101,102,301,302,401,402,406.
EFb-1 and EFb-2	Hemming (two folds)	101,301,401,402,406.
EFc-1	Blind hemming (woven)	301.
	Blind hemming (knit)	301,401,502,503,505.
EFd-1	Edge finishing (serging)	502,503,504,505.
	Ornamental edge finishing	304,502,503,504,505,601,603,604, 605,607.
EFe-1	Ornamental edge finishing (zigzag)	304,404.
EFf-1	Hemming with elastic tape	101,301,401.
EFg-2	Hemming with elastic tape	101,301,401.
EFh-1	Making loops or straps	406.
EFj-1 and EFj-3	Making straps	301,401.
	Making straps (using waxed thread)	101,301.
EFk-2 and EFK-4	Cut-on center plait (shirt fronts)	301,401.
EF1-1	Blind hemming	103,301,306,401,502,503.
EFm-1	Blind hemming	103,301,306,401,502,503.
EFn-2 and EFn-4	Making straps or loops	301,401.
EFp-1 and EFp-2	Making straps or loops	301,401.
EFq-2	Inserting elastic in hems	301,401.
EFr-2	Inserting elastic in hems	301,401.
EFs-2	Making straps or loops	301,401.
EFt-2 andf EFt-4	Hemming shirt fronts	301,401.
EFu-1	Making drawstrings or loops	301,401.
EFv-2 and EFv-4	Cut-on center plait (shirt fronts)	301,401.
EFw-1	Hemming (three folds)	101,301,401,402,406.

(cont'd on next page)

TABLE 9-21. - (cont'd)

Seam Type	Application	Types of Standard Stitches Suitable
Edge finishing—(cont'd)		
EFx-1	Hemming	101,301,401,402,406.
EFy-1 and EFy-3	Making straps or loops	301,401,406.
EFz-1 and EFz-2	Making straps or loops	301,401,406.
EFaa-1 and EFaa-2	Making straps or loops	301,401,406.
EFab-1	Hemming	502,503,504,505.
EFac-2	Making straps or loops	301,401.
EFad-2	Making straps or loops’	301,401.
EFae-2	Making straps or loops	103.
EFaf-2	Edge finishing	501,502,503,504,505.
EFag-2	Edge finishing	501,502,503,504,505.
EFah-1	Hemming	301,401.

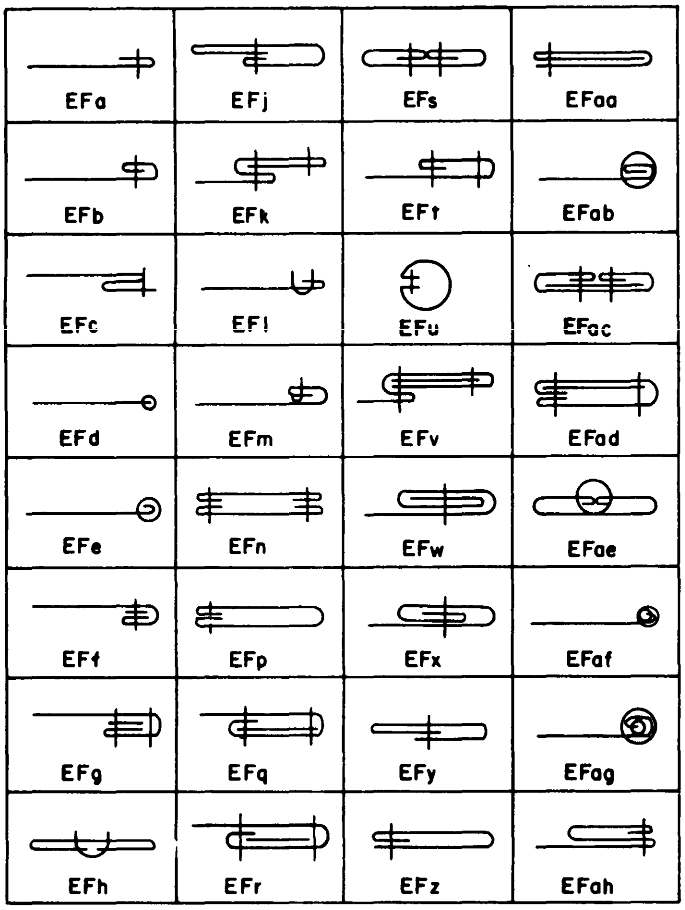

Figure 9-37. Stitching Class EF (Ref. 14)

9-4.2.4.4 Security

The security of a seam or stitching depends chiefly upon the stitch type and its susceptibility to become unraveled. The stitch must be well set to the material to prevent snagging, which can cause rupture of the thread and unraveling of certain of the stitch types.

9-4.2.4.5 Appearance

The appearance of a seam or stitching generally is governed by the proper relationship between the size and type of thread, the length of stitch or number of stitches per inch, and the texture and weight of the fabric. In addition to this relationship, the technique and skill of the sewing machine operators also govern the appearance of the seams and stitchings. Some of the factors that will adversely affect the appearance are as follows:

1. Stitch defects—loose, poorly formed, crowded, tight, and crooked, skipped stitches
2. Seam and stitching defects—puckers, twists, plaits, undulations, runoffs (raised seams), and raw edges exposed (felled seams).

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2. J. Corner, *Theory of the Interior Ballistics* of Guns, John Wiley & Sons, NY, 1950,
3. AMCP 706-175, Engineering Design Handbook, *Solid Propellants, Part One, 1961.*
4. *Encyclopedia of Explosives and Related Items,* Volumes 1-9, National Technical Information Service, Washington. DC.
5. Ph. Naoum, Z. Ges. *Schiess-u-Sprengstoffw,* pp. 181, 229, 267 (27 June 1932).
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7. D. F. Horne, *Optical Production Technology,* Crane Russak & Co., Inc., 347 Madison Avenue, New York, NY 10017, 1972.
8. W. D. Kingery, et al, *Introduction to Ceramics,* John Wiley and Sons, Inc., New York, NY, 1973.
9. *Standards of the Alumina Ceramic Manufacturers Association,* Alumina Ceramic Manufacturers Association, 331 Madison Avenue, New York, NY 10017, Bibliography, pp. 15, 16.

10. S. J. Scheider, Jr., and R. W. Rice, Eds., *The Science of Ceramic Machining and Surface Finishing*, Proceedings of a symposium sponsored by the American Ceramic Society, the Office of Naval Research, and the National Bureau of Standards held 2-4 November 1970 (May 1972).

11. J. Burke, R. Nathan, E. Katz, and Alvin E. Gorum, Eds., *Ceramics for High Performance Applications*, Brookhill Press, Chestnut Hill, MA, 1974.

12. *MIL-HDBK-741, Fabric Design*, 22 July 1974.

13. *Man-blade Fibers Fact Book*, Man-Made Fiber Producers Association, Inc., 1150 Seventeenth Street, NW, Washington, DC 20036, 1978.

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APPENDIX A

INFORMATION SOURCES

A-1 INTRODUCTION

This appendix identifies sources of information useful to individuals concerned with producibility. The information is structured by component type, as are the chapters, to permit easy reference. Within each component type the information is further structured as follows:

1. Technical books
2. Journals and periodicals
3. Documentation and information analysis ten” ters
4. Professional and trade associations.

A-1.1 TECHNICAL BOOKS

This category of sources consists of formally, published books, such as textbooks, that normally present information on the state of the art. They generally will be available in any technical library or directly from the publisher.

A-1.2 JOURNALS OR PERIODICALS

Journals and periodicals are invaluable aids to any designer. A real or potential advancement, which will be of direct benefit to design activities, will be published initially either through a professional association or a technical periodical or journal. These publications provide current information concerning results of research and technical information, and they represent a chronological record of the advances being made in specific subject areas.

Information found in technical journals is often more recent and more specific than that found in books. Unfortunately, such information is more scattered and difficult to obtain.

A-1.3 DOCUMENTATION AND INFORMATION ANALYSIS CENTERS

Documents, including technical reports, are a significant source of available information. To insure the availability of this type of data, centers have been established to collect, abstract, index, and disseminate technical reports and findings. It is becoming increasingly essential that contributors to technology be familiar with and use the services of the documentation centers. Four major documentation centers for general needs follow:

1. Defense Technical Information Center, DTIC
2. National Technical Information Service, NTIS
3. US National Aeronautics and Space Administration Scientific and Technical Information Facility, STIF
4. US Department of Energy Technical Information Center, DOE-TIC.

In addition to documentation centers, information analysis centers have been established to review or analyze scientific or engineering data. The primary function of these centers is to provide answers to questions rather than referrals to documents to be read. These centers are mission-oriented and subject-oriented centers; their purposes are to review, analyze, appraise, and summarize information and to provide evaluation services to users.

A-1.4 PROFESSIONAL AND TRADE ASSOCIATIONS

Most professional disciplines and manufacturing trades are represented by a national association. These associations often maintain data bases of information that are available to assist the producibility engineer. Additionally, they will provide information on individual sources of expertise within their particular field that can provide additional information to assist the engineer interested in producibility. One such organization is the Society of Manufacturing Engineers.

A-2 INFORMATION SOURCES

Some information sources are so general that they will provide data relative to the general subject of producibility or relative to any number of different types of components. Rather than list these repeatedly under the different types of components, they are listed in this paragraph. Generally, these are large information data bases that collect, abstract, index, and disseminate all types of engineering or scientific data.

A-2.1 DEFENSE TECHNICAL INFORMATION CENTER (DTIC)

A-2.1.1 General

The DTIC, a field activity of the Defense Logistics Agency (DLA) of the Department of Defense (DoD), has available from one central depository thousands of the research and development reports produced each year by United States military organizations and their contractors. The center also has computer-based data banks of management and technical information.

DTIC collects, processes, announces, retrieves, and supplies formally recorded technical information in all of the scientific disciplines and engineering fields of interest to the DoD. This information relates to either records of completed work or to ongoing and planned research and development work being conducted by or for the DoD.

A-2.1.2 Data Acquisition

To assist organizations in registering for service, DTIC provides a pamphlet entitled Registration *for Department of Defense Scientific and Technical Information Services*, DSAM 4185.3. The pamphlet outlines registration procedures and is complete with copies of the required DoD forms. To acquire copies of the pamphlet or to obtain additional information, write to Defense Technical Information Center, Cameron Station, Alexandria, VA 22314.

A-2.2 NATIONAL TECHNICAL INFORMATION SERVICE (NTIS)

A-2.2.1 General

The NTIS of the US Department of Commerce is a central source for the public sale of Government-sponsored research, development, and engineering reports, and other analyses prepared by federal agencies, their contractors, or grantees. Also it is a prime source for federally generated machine processable data files.

The public can quickly locate summaries from among 360,000 federally sponsored research reports completed since 1964 by using the agency's on-line computer search service (NTISearch). An additional 180,000 citations of ongoing and recently terminated research projects, compiled by the Smithsonian Science Information Exchange, also are computer retrievable. Copies of whole research reports, either on paper or microfiche, are sold by NTIS.

The NTIS Bibliographic Data File, a magnetic tape of published and unpublished abstracts, is available for lease.

Current summaries of new research reports and other specialized technical information in various categories of interest are published in indexed weekly newsletters, *Weekly Government Abstracts*. An all-inclusive biweekly journal, *Government Report Abstracts, is* published for librarians, technical information specialists, and those requiring all the summaries categorized in a single volume with an index.

A standing order microfiche service (SRIM) automatically provides subscribers with the full texts of research reports selected to satisfy individual requirements.

Other services, such as the coordination, packaging, and marketing of unusual technical information for organizations, may be specially designed at any time.

A-2.2.2 Data Acquisition

To acquire the information services of NTIS or to learn more about the available services, contact Director, NTIS, 5285 Port Royal Road, Springfield, VA 22161.

A-2.3 SCIENTIFIC AND TECHNICAL INFORMATION FACILITY (STIF)

A-2.3.1 General

STIF, an activity of the US National Aeronautics and Space Administration (NASA), collects all data relating to aerospace research and development. For example, STIF gathers information on a broad range of subjects through an active acquisition and exchange operation and disseminates a comprehensive listing of the aerospace report literature.

A-2.3.2 Data Acquisition

Regularly published abstract listings are available. Special studies are also available. For information on accessing STIF, write to the US National Aeronautics and Space Administration, Scientific and Technical Facility, P.O. Box 33, College Park, MD 20740.

A-2.4 US DEPARTMENT OF ENERGY TECHNICAL INFORMATION CENTER (DOE-TIC)

A-2.4.1 General

The DOE-TIC is an activity of the US Department of Energy (DOE), which operates several data bases and abstracting services focusing on energy related subjects including nuclear sciences, engineering materials, and renewable energy resources. DOE-TIC collects, processes, announces, retrieves, and supplies formally recorded technical information in all scientific and engineering fields of interest to the DOE. Completed external and internal work is documented along with reports from ongoing projects.

A-2.4.2 Data Acquisition

DOE-TIC provides regular abstracting services as well as computer access. Special reports are available. To obtain information on ordering, write to DOE-TIC, P.O. Box 62, Oak Ridge, TN 37830.

A-2.5 ARMY MATERIALS AND MECHANICS RESEARCH CENTER (AMMRC)

The Army Materials and Mechanics Research Center (AMMRC), focal point for materials development within the US Army Materiel Development and Readiness Command (DARCOM), is a prime source of information. AMMRC is responsible for Army research and development of new and improved metals, ceramics, organics, and composites, and for the mechanics research necessary to use these materials in the critical design areas of Army equipment.

A-3 GENERAL PRODUCIBILITY CONSIDERATION INFORMATION SOURCES

A-3.1 DARCOM ENGINEERING DESIGN HANDBOOKS

Many of the DARCOM Engineering Design Handbooks discuss facets of producibility. A complete listing of these handbooks comprises the final page and inside back cover of this handbook. The handbooks are available to Department of the Army (DA) activities by submission of an official requisition form (DA Form 17, 17 Jan 1970) directly to Commander, Letterkenny Army Depot, ATTN: SDSLE-SAAD, Chambersburg, PA 17201. "Need to know" justification must accompany requests for classified handbooks. Requestors—DoD, Navy, Air Force, Marine Corps, nonmilitary Government agencies, contractors, private industry, individuals, universities, and others—who are registered with the DTIC and have an NTIS deposit account may obtain these handbooks from DTIC. To obtain classified documents from the DTIC, "need to know" must be established by the submission of DD Form 1540, 1 Jul 71. Requesters, not part of the DA nor registered with the DTIC, may purchase some unclassified handbooks from the National Technical Information Service, Department of Commerce, Springfield, VA 22161.

A-3.2 MILITARY STANDARDS AND SPECIFICATIONS

The Department of Defense Index of Specifications and Standards (DODISS), published annually, contains a listing of military standards, specifications, and handbooks. Also industry documents used by the military are listed in the Index. All DoD activities and contractors with a DoD contractor who are bidding on a DoD contract may obtain items listed in the DODISS from Commanding Officer, Naval Publications and Forms Center, ATTN: NPFC 3015, 5801 Tabor Avenue, Philadelphia, PA 19120.

A-3.3 MANTECH JOURNAL

The US Army ManTech Journal is published quarterly for the US Army by AMMRC, Watertown, MA 02172, through the Metals and Ceramics Information Center, Battelle Columbus Laboratories, 505 King Avenue, Columbus, OH 43201. Individual subscriptions are available from the Metals and Ceramics Information Center of Battelle.

A-4 METAL COMPONENT PRODUCIBILITY INFORMATION

A-4.1 TECHNICAL BOOKS

M. L. Begeman and B. H. Amstead, *Manufacturing Processes*, John Wiley and Sons, Inc., NY, 1969

G. "Bellows, *Nontraditional Machining Guide*, Publication MDC 76-101, Metcut Research Associates, Inc., Cincinnati, OH, 1976

G. Bellows, *Machining, A Process Checklist*, Publication MDC 76-100, Metcut Research Associates, Inc., Cincinnati, OH, 1976

L. E. Doyle, *Manufacturing Processes and Materials for Engineers*, Prentice-Hall, Inc., Englewood Cliffs, NJ, 1969

D. C. Greenwood, Ed., *Engineering Data for Product and Design*, McGraw-Hill Book Company, NY, 1961

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R. A. Lindberg, *Materials and Manufacturing Technology*, Allyn and Bacon, Inc., Boston, MA, 1968

T. Lyman, Ed., *Metals Handbook, Vol. 3, Machining*, American Society for Metals, Metals Park, OH, 1967

E. Oberg and F. D. Jones, *Machinery Handbook*, 17th Edition, The Industrial Press, NY, 1964

S. E. Rusinoff, *Manufacturing Processes, Materials and Production*, American Technical Society, Chicago, IL, 1962

R. K. Springborn, Ed., *Nontraditional Machining Processes*, American Society of Tool and Manufacturing Engineers, Dearborn, MI, 1967

H. E. Trucks, *Designing* for *Economical Production*, Society of Manufacturing Engineers, Dearborn, MI, 1974

F. W. Wilson, Ed., *Machining the Space-Age Metals*, American Society of Tool and Manufacturing Engineers, Dearborn, MI, 1965

Tool Engineers Handbook, McGraw-Hill Book Company, NY, 1959

Materials Engineering 68(5), "Materials Selector Issue", Reinhold Publishing Company, Stamford, CT, October 1978

Unified Numbering System for Metals and Alloys, Society of Automotive Engineers, Inc., Warrendale, PA, 1977

1977 *SAE Handbook Part 1: Materials, Parts and Components,* Society of Automotive Engineers, Inc., Warrendale, PA, 1977

T. Lyman, Ed., *Metals Handbook, Vol. 1, Properties and Selection of Materials,* American Society for Metals, Metals Park, OH, 1976

T. Lyman, Ed., *Metals Handbook, Vol. 2, Heat Treating, Cleaning, and Finishing,* American Society for Metals, Metals Park, OH, 1961

AMCP 706-170, Engineering Design Handbook, *Armor and Its Applications* (U), (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-250, Engineering Design Handbook, *Guns—General*

DARCOM-P706-253, Engineering Design Handbook, *Breech Mechanism Design*

AMCP 706-286, Engineering Design Handbook, *Structures*

AMCP 706-340, Engineering Design Handbook, *Carriages and Mounts—General*

AMCP 706-341, Engineering Design Handbook, *Cradles*

AMCP 706-342, Engineering Design Handbook, *Recoil Systems*

AMCP 706-343, Engineering Design Handbook, *Top Carriages*

AMCP 706-344, Engineering Design Handbook, *Bottom Carriages*

AMCP 706-345, Engineering Design Handbook, *Equilibrators*

AMCP 706-346, Engineering Design Handbook, *Elevating Mechanisms*

AMCP 706-347, Engineering Design Handbook, *Traversing Mechanisms*

AMCP 706-355, Engineering Design Handbook, *The Automotive Assembly*

DARCOM-P706-410, Engineering Design Handbook, *Electromagnetic Compatibility (EM C).*

A-4.2 JOURNALS AND PERIODICALS

Machine and Tool Directory, Annual Edition, Hitchcock Publications, Hitchcock Building, Wheaton, IL 60187

American Machinist Magazine, Monthly, American Machinist, 1221 Avenue of the Americas, New York, NY 10020

Machine and Tool Blue Book, Monthly, Hitchcock Publications, Hitchcock Building, Wheaton, IL 60187

Proceedings of Annual Meeting and Technical Conference, Numerical Control Society, Inc., 1201 Waukegan Road, Glenview, IL 60025

Modern Machine Shop, Monthly, Gardner Publications, Inc., 600 Main Street, Cincinnati, OH 45202.

A-4.3 DOCUMENTATION AND INFORMATION ANALYSIS CENTERS

A-4.3.1 Machinability Data Center (MDC)

The MDC—one of the DoD Information Analysis Centers-is administratively managed and funded by the DLA, Cameron Station, Alexandria, VA 22314. MDC is sponsored by the Army Materials and Mechanics Research Center, Arsenal Street, Watertown, MA 02172. Metcut Research Associates, Inc., operates MDC under Government contract.

MDC collects, evaluates, stores, and disseminates specific and detailed machining and grinding information for the benefit of the Government and industry. Emphasis is given to engineering evaluation to select material removal parameters, such as speeds, feeds, depths of cut, tool materials and geometry, cutting fluids, and other significant variables. Data are continually being processed for all types of materials and a broad range of operations including turning, milling, drilling, tapping, grinding, electrical discharge machining, chemical milling, and laser drilling.

A-4.3.2 Metals and Ceramics Information Center (MCIC)

MCIC is a DoD Information Analysis Center administratively managed and funded by the DLA, Cameron Station, Alexandria, VA 22314. MCIC is sponsored by AMMRC, Arsenal Street, Watertown, MA 02172. Battelle Memorial Institute, Battelle Columbus Laboratories, 505 King Street, Columbus, OH 43201, operates the MCIC under a Government contract.

MCIC collects and disseminates information on design characteristics, processing, forming, joining, fabrication environmental effects, test methods, applications, quality control, sources, suppliers, and specifications for all metals, metal alloys, ceramic materials, composites, and coatings for such materials.

The Mechanical Properties Data Center (MPDC) has been combined with MCIC; hence information relative to mechanical properties is also available from MCIC.

A-4.3.3 Nondestructive Testing Information Analysis Center (NTIAC)

This center is another DoD Information Analysis Center that is administratively managed and funded by DLA, Cameron Station, Alexandria, VA 22314. NTIAC is sponsored by AMMRC, Arsenal Street, Watertown, MA 02172. Southwest Research Institute, 8500 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78284, operates the NTIAC under contract with the Government.

NTIAC collects and disseminates information relative to all nondestructive testing (NT) and/or evaluation techniques and processes involving material—

energy interaction phenomena, such as radiographic, holographic, acoustic, magnetic, etc. Other information of concern to NTIAC includes economic aspects of the NT industry, economic considerations with respect to the selection of techniques and processes and industry trends in applying current NT technologies in research and development, production, maintenance, safety monitoring, and failure prevention of in-service material.

A-4.3.4 Thermophysical and Electronic Properties Information Analysis Center (TEPIAC)

TEPIAC-A DoD Information Analysis Center-administratively managed and funded by DLA, Cameron Station, Alexandria, VA 223 14—is sponsored by AMMRC, Arsenal Street, Watertown, MA 02172. Southwest Research Institute, 8500 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78284, operates the TEPIAC under contract with the Government.

TEPIAC collects and disseminates information relative to thermal conductivity, thermal contact resistance, accommodation coefficient, viscosity, emissivity, absorptivity, reflectivity, transmissivity, absorptance/emittance, specific heat, thermal diffusivity, Prandtl number, linear coefficient of thermal expansion, and volumetric coefficient of thermal expansion. The materials covered include inorganic compounds, alloys, intermetallics, glasses, ceramics, cermets, applied coatings, and polymers.

The electronic properties covered include absorption coefficient, dielectric constant, dielectric strength, effective mass, electric hysteresis, electrical resistivity, Hall coefficient, mobility, energy bands, energy gap, energy levels, magnetic hysteresis, magnetic susceptibility, refractive index, and work function. Additionally, the following property groups are covered: electron emission properties, luminescence properties, magnetoelectric properties; photoelectronic properties, piezoelectric properties, thermoelectric properties, and magnetomechanical properties.

A-4.3.5 Data Acquisition

Each information analysis center has a staff of experienced data analysts who are capable of answering technical inquiries in the respective technical fields. Short telephone inquiries are answered free of charge; others are subject to individual quotation. For additional information contact the operator of the pertinent information analysis center.

A-4.4 PROFESSIONAL AND TRADE ASSOCIATIONS

The following professional and trade associations have all been formed to promote their various representative groups. Contact with any of these can provide excellent references, both personal and written, in their area of specialization.

Society of Manufacturing Engineers
20501 Ford Road, Box 930
Dearborn, MI 48128

Numerical Control Society
1800 Pickwick Avenue
Glenview, IL 60025

American Welding Society
2501 NW 7th Street
Miami, FL 33125

American Society of Mechanical Engineers
345 East 47th Street
New York, NY 10017

American Society for Quality Control, Inc.
161 West Wisconsin Avenue
Milwaukee, WI 53203

American Society for Testing and Materials
1916 Race Street
Philadelphia, PA 19103

American Die Casting Institute
2340 Des Plaines Avenue
Des Plaines, IL 60018

American Metal Stamping Association
2707 Chardon Road
Richmond Heights, OH 44143

American Powder Metallurgy Institute
Box 2054
Princeton, NJ 08540

National Tool, Die, and Precision Machining Association
9300 Livingston Road
Oxon Hill, MD 20022

The Aluminum Association
818 Connecticut Avenue, NW
Washington, DC 20006

Copper Development Association
Chrysler Building, 57th Floor
405 Lexington Avenue
New York, NY 10017

Zinc Institute
292 Madison Avenue
New York, NY 10017

Society of Automotive Engineers
400 Commonwealth Drive
Warrendale, PA 15096

Standards Engineers Society
6700 Penn Avenue South
Minneapolis, MN 55423

American Society for Metals
Metals Park, OH 44073.

A-5 PLASTIC COMPONENT INFORMATION SOURCES

A-5.1 TECHNICAL BOOKS

R. D. Beck, *Plastic Product Design,* Van Nostrand Reinhold Co., New York, NY, 1970

J. Frados, *Plastics Engineering Handbook,* SPI Series, Van Nostrand Reinhold Co., New York, NY, 1976

H. E. Trucks, *Designing for Economical Production,* Society of Manufacturing Engineers, Dearborn, MI, 1974

Leslie Breden, *World Index of Plastics Standards,* National Bureau of Standards Special Publication 352, US Government Printing Office, Washington, DC 20402

Modern Plastics Encyclopedia, publisher McGraw-Hill Publications Co., New York, NY, annually

The International Plastics Selector, Cordura Publications, Inc., La Jolla, CA, 1977

Glanvill, *Plastics Engineers Data Handbook,* Society of Plastics Engineers, 656 W. Putnam Avenue, Greenwich, CT 06830, 1977

The following technical books have been prepared at the Plastics Technical Evaluation Center (PLASTEC), US Army Armament Research and Development Center, (ARDC), Dover, NJ 07801. PLASTEC publications may be obtained from the NTIS, 5285 Port Royal Road, Springfield, VA 22161 by using the cited AD identification number. Those noted with an asterisk in the following list have limited distribution, are not for public sale, and must be requested from the DTIC, Cameron Station, Alexandria, VA 22314.

R. J. Vanes and John Nardone, *Directory in Plastics—Knowledgeable Government Personnel* (Revised), February 1975, NTIS Document AD-AO08 340

Joan B. Titus, *Effect of Low Temperature (O to –65°F) on the Properties of Plastics,* July 1967, NTIS Document AD-661 633

Joan B. Titus, *The Weatherability of Polyolefins,* March 1968, NTIS Document AD-672 513

N. E. Beach and V. K. Canfield, *Compatibility of Explosives With Polymers (II) (An Addendum to Picatinny Arsenal Technical Report 2595),* April 1968, NTIS Document AD-672 061

A. H. Landrock, *Polyurethane Foams: Technology, Properties and Applications,* January 1969,, NTIS Document AD-688 132

A. H. Landrock, *Ecological Disposal of Plastics With Emphasis on Foam-in-Place Polyurethane Foam,* August 1973, NTIS Document AD-771 342

Joan B. Titus, *Weatherability of Polystyrene and Related Copolymers and Terpolymers,* July 1969, NTIS Document AD-700 091

N. E. Beach and V. K. Canfield, *Compatibility of Explosives With Polymers (Ill).* (An Addendum to Picatinny Arsenal TR 2595 and PLASTEC Report 33), January 1971, NTIS Document AD-721 004

A. F. Readdy, *Applications of Ionizing Radiations in Plastics and Polymer Technology,* March 1971, NTIS Document AD-725 940

Joan B. Titus, *Solid-Phase Forming (Cold Forming) of Plastics,* January 1972, NTIS Document AD-752 136

A. F. Readdy, *Plastics Fabrication by Ultraviolet, Infrared, Induction, Dielectric, and Microwave Radiation Methods,* April 1972, NTIS Document AD-756 214

l A M. Shibley, *Plastic Materials for Cartridge Cases,* January 1973, NTIS Document AD-912 075L

l Joan B. Titus, *Nonmetallic Rotating and Obturating Bands: An Annotated Bibliography,* March 1977, NTIS Document AD-B018 466L

J. A. Maciejczyk and A. E. Slobodzinski, *Guidelines for the Generation and Use of Data in Military Handbook, 17A, Part 1, 1969,* NTIS Document AD-A043 914

N. E. Beach, *Government Specifications and Standards for Plastics, Covering Defense Engineering Materials and Applications,* May 1973, NTIS Document AD-771 008

Joan B. Titus, *Trade Designations of Plastics and Related Materials (Revised),* May 1978, NTIS Document AD-A058 345

Joan B. Titus, *Environmentally Degradable Plastics: A Review,* February 1973, NTIS Document AD-760 718

R. Winans, A. M. Shibley, and J. R. Hall, *Weldbonding in the United States: An Annotated Bibliography and History,* December 1974, NTIS Document AD-AO08 048

A. H. Landrock, *Specifications and Other Standardization Documents Involving Cellular Plastics (Plastic Foams), Cushioning and Related Materials,* July 1976, NTIS Document AD-A030 674

J. Nardone, *Computerized Material Property Data Information,* June 1976, NTIS Document AD-A030 675

A. H. Landrock, *Comparison of United States and British Methods for Testing Plastic Materials,* September 1976, NTIS Document AD-A034 734

AMCP 706-312, Engineering Design Handbook, *Rotational Molding of Plastic Powders,* April 1975, NTIS Document AD-A013 178

J. Titus, *New Plastics—Properties, Processing, and Potential Uses,* September 1977, NTIS Document AD-A056 990

*j. Titus, *Plastics in Training Munitions: An Annotated Bibliography,* January 1979, NTIS Document AD-B043069L

A-5.2 JOURNALS AND PERIODICALS

Modern Plastics Magazine, Monthly, McGraw-Hill, Inc., 1221 Avenue of the Americas, New York, NY 10020

Plastics Manufacturing Handbook and Buyers Guide, Annually, National Association of Plastics Fabricators, Inc., 1300 17th Street, NW, Washington, DC 20014

Plastics Engineering, Monthly, Society of the Plastics Engineers, Putnam Avenue, Greenwich, CT 06830

Plastics Design Forum, Bimonthly, Industry Media, Inc., 1129 East 17th Avenue, Denver, CO 80218.

A-5.3 DOCUMENTATION AND INFORMATION ANALYSIS CENTERS

A-5.3.1 The Plastics Technical Evaluation Center (PLASTEC)

A-5.8.1.1 General

Under authority of the Office of the Director of Defense Research and Engineering, PLASTEC evaluates and disseminates technical information on current development, engineering, and application work in the fields of plastics, reinforced plastics, and adhesives. It engages in materials surveys and other special assignments and provides the DoD with technical data and advice on research and development programs on plastics.

A-5.3.1.2 Data Acquisition

Both Government and industry may request information directly from this center. Inquiries that can be handled routinely are accomplished without charge. Charges for those that require time-consuming study by a specialist are decided upon by prior agreement between the requester and PLASTEC. For additional information contact PLASTEC, ARDC, Dover, NJ 07801.

A-5.4 PROFESSIONAL AND TRADE ASSOCIATIONS

Society of Plastics Engineers, Inc.
656 West Putnam Avenue
Greenwich, CT 06830

Society of the Plastics Industry, Inc.
355 Lexington Avenue
New York, NY 10017

National Association of Plastic Fabricators
4720 Montgomery Lane
Washington, DC 20014

National Association of Plastics Distributors
472 Nob Hill Lane
Devon, PA 19333

Society for the Advancement of Material and Process Engineering
P.O. BOX 613
Azusa, CA 91702

A-6 COMPOSITE COMPONENT INFORMATION SOURCES

A-6.1 TECHNICAL BOOKS

Structural Composites Fabrication Guide, Volume 1, Second Edition, Air Force Materials Laboratory, Wright Patterson AFB, OH, May 1979

MIL-HDBK-700, Military Standardization Handbook, *Plastics*

P. F. Turner, *Boron-Epoxy Rudder Program, Final Report*, MCAIR Report H410, McDonnell Douglas/McDonnell Aircraft Division, August 1969

W. P. Benjamin, *Plastic Tooling*, McGraw-Hill Book Company, Inc., New York, NY, 1972

R. D. Hayes, *Flightworthy Graphite Fiber-Reinforced Composite Aircraft Primary Structural Assemblies, AFML-TR-71-276*, Contract F33615-69-C-1490, Northrop Corporation, Aircraft Division, April 1972

R. Bradley, *Manufacturing Processes for Advanced Composite Substructural Shapes*, Boeing Company Report IR-435-2(III), AFML Contract F33615-72-C-1235, December 1972

D. L. Stansbarger, *Manufacturing Methods for Cocuring Advanced Composite Materials*, Northrop Corporation, IR-422-l-V, AFML Contract F33615-71-C-1824, August/October 1972

L. J. Hartsmith, *Design and Analysis of Adhesive Bonded Joints*, Paper presented to AFML Conference on Fibrous Composites in Flight Vehicle Design, AFML TR-72-130, September 1972

AMCP 706-313, Engineering Design Handbook, *Short Fiber Plastic Base Composites*

R. A. Elkin, *Manufacturing Methods for Establishing Polymeric Adhesive Bonding Processes*, Rohr Industries, Inc., IR-419-l(V), AFML Contract F33615-71-C-1942, November 1972

W. H. Shaefer, J. L. Christian, et al, *Evaluation of the Structural Behavior of Filament Reinforced Metal Matrix Composites, AFML-TR-69-36*, Volume II, General Dynamics, Convair Division, January 1969

A. Toy, et al, *Development and Evaluation of the Diffusion Bonding Process as a Method to Produce Fibrous-Reinforced Metal Matrix Composite Materials, AFML-TR-66-350*, October 1966

MIL-HDBK-17A, *Plastics for Aerospace Vehicles, Part 1, Reinforced Plastics*

Advanced Composites Design Guide, Volume II, Analysis, Third Edition, Third Revision, Air Force Flight Dynamics Laboratory, Wright Patterson Air Force Base, OH, January 1977

B. S. Benjamin, *Structural Design With Plastics*, Van Nostrand Reinhold Company, New York, NY 1969

L. E. Nielsen, *Mechanical Properties of Polymers and Composites*, Volume 2, Marcel Dekker, Inc., New York, NY, 1974

S. Tsai and H. T. Hahn, *introduction to Composite Materials*, Technical Report AFML-TR-78-201, Air Force Materials Laboratory, Wright Patterson Air Force Base, OH, 1979

G. Lubin, Ed., *Handbook of Fiberglass and Advanced Plastics Composites*, Krieger Press, Melbourne, FL, 1969

A-6.2 JOURNALS AND PERIODICALS

Composites, Monthly, IPC Science and Technology Press Ltd, IPC House, Guildford, Surrey, England, GU1 3EW

Journal of Composite Materials, Monthly, Technomic Publishing Co., Post Road, Westport, CT 06880

Composites Technology Review, Quarterly, ASTM, 1916 Race Street, Philadelphia, PA 19103

A-6.3 DOCUMENTATION AND INFORMATION ANALYSIS CENTERS

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A-6.3.1.1 General

Under authority of the Office of the Director of Defense Research and Engineering, PLASTEC evaluates and disseminates technical information on current development, engineering, and application work in the fields of plastics, plastic based composites, and adhesives. It engages in materials surveys and other special assignments and provides the DoD with technical data and advice on research and development programs on plastics.

A-6.3.1.2 Data Acquisition

Both Government and industry may request information directly from this center. Inquiries that can be handled routinely are accomplished without charge. Charges for those that require time-consuming study by a specialist are decided upon by prior agreement between the requester and PLASTEC. For additional information contact PLASTEC, ARDC, Dover, NJ 07801.

A-6.3.2 Metals and Ceramics Information Center (MCIC)

A-6.3.2.1 General

MCIC is a DoD Information Analysis Center administratively managed and funded by the DLA, Cameron Station, Alexandria, VA 22314. MCIC is sponsored by the AMMRC, Arsenal Street, Watertown, MA 02172. Battelle Memorial Institute, Battelle Columbus Laboratories, 505 King Street, Columbus, OH 43201 operates the MCIC under a Government contract.

MCIC collects and disseminates information on design characteristics, processing, forming, joining, fabrication environmental effects, test methods, applications, quality control, sources, suppliers, and specifications for all metals, metal alloys, ceramic materials, composites, and coatings for such materials.

A-6.3.2.2 Data Acquisition

Both Government and industry may request information directly from this center. Inquiries that can be handled routinely are conducted without charge. Those inquiries requiring special studies are done for a fee. For additional information contact MCIC, Battelle Memorial Institute, Battelle Columbus Laboratories, 505 King Street, Columbus, OH 43201.

A-6.4 PROFESSIONAL AND TRADE ASSOCIATIONS

Society of Plastics Engineers, Inc.
656 West Putnam Avenue
Greenwich, CT 06830

Society of the Plastics Industry, Inc.
355 Lexington Avenue
New York, NY 10017

National Association of Plastic Fabricators
4720 Montgomery Lane
Washington, DC 20014

National Association of Plastics Distributors
472 Nob Hill Lane
Devon, PA 19333

Society for the Advancement of Material and Process Engineering
P.O. Box 613
Azusa, CA 91702

A-7 MECHANICAL ASSEMBLY INFORMATION SOURCES

A-7.1 TECHNICAL BOOKS

W. V. Tipping, *An Introduction to Mechanical Assembly*, Business Books Limited, London, England, 1969

Albert Damon, Howard Stoudt, Ross A. McFarland, *The Human Body in Equipment Design*, Harvard University Press, Cambridge, MA, 1966

G. Boothroyd, A. H. Redford, *Mechanical Assembly*, McGraw-Hill, Inc., 1221 Avenue of the Americas, New York, NY 10020, 1968

Harold P. Van Cott, Robert G. Kinkad, *Human Engineering Guide to Equipment Design*, American

Institutes for Research, Washington, DC, Superintendent of Documents, US Government Printing Office, Washington, DC, 1972

Raymond G. Archienberg, Product *Design for Automatic Assembly,* society of Manufacturing Engineers, Dearborn, MI, 1974.

A-7.2 JOURNALS AND PERIODICALS

Assembly Engineering, Monthly, Hitchcock Publishing Co., Hitchcock Building, Wheaton, IL 60187

Assemblex Technical Papers, Annually, Society of Manufacturing Engineers, Dearborn, MI.

A-7.3 PROFESSIONAL AND TRADE ASSOCIATIONS

Society of Manufacturing Engineers
20501 Ford Road
P.O. Box 930
Dearborn, MI 48128

American Institute of Industrial Engineers
25 Technology Park/Atlanta
Norcross, GA 30092

Industrial Fasteners Institute
1505 East Ohio Building
1717 East Ninth Street
Cleveland, OH 44114

Robot Institute of America
20501 Ford Road
P.O. Box 930
Dearborn, MI 48128

American Welding Society
2501 NW Seventh Street
Miami, FL 33125

The Material Handling Institute, Inc.
104 Wilmot Road
Deerfield, IL 60015.

A-8 ELECTRONIC COMPONENT INFORMATION SOURCES

A-8.1 TECHNICAL BOOKS

MIL-STD-1562C, Lists *of Standard Microcircuits*

MIL-STD-701L, Lists of Standard Semiconductor Devices

MIL-STD-199C, *Resistors, Selection and Use of*

MIL-STD-198D, *Capacitors, Selection and Use of*

MIL-STD-202F, Test Methods for Electronic and Electrical Component Parts

MIL-STD-750B, Test Methods for Semiconductor Devices

MIL-M-38510E, Microcircuits, General Specifications for

MIL-HDBK-175, *Microelectronic Device Data Handbook*

MIL-S-19500F, *Semiconductor Devices, General Specifications for*

MIL-STD-1286C, *Transformers, Inductors and Coils, Selection and Use of*

MIL-STD-1346A, *Relays, Selection and Application of*

MIL-STD-1132A, *Switches and Associated Hardware, Selection and Use* of

MIL-STD-883B, *Test Methods and Procedures* of *Microelectronics*

MIL-STD-1327A, *Flanges, Coaxial and Waveguide; and Coupling Assemblies, Selection* of

MIL-STD-1328B, *Couplers, Directional (Coaxial Line, Waveguide and Printed Circuit), Selection* of

MIL-STD-1329B, *Switches, RF Coaxial, Selection of*

MIL-STD-454G, Standard General Requirements for Electronic Equipment

MIL-STD-200K, Electron Tubes, Selection of

AMCP 706-124, Engineering Design Handbook, *Reliable Military Electronics*

AMCP 706-125, Engineering Design Handbook, *Electrical Wire and Cable*

DARCOM-P 706-315, Engineering Design Handbook, *Dielectric Embedding* of *Electrical or Electronic Components*

AMCP 706-211, Engineering Design Handbook, *Fuzes, Proximity, Electrical, Part One*

AMCP 706-212, Engineering Design Handbook, *Fuz.es, Proximity, Electrical, Part Two (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-213, Engineering Design Handbook, *Fuzes, Proximity, Electrical, Part Three (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-214, Engineering Design Handbook, *Fuzes, Proximity, Electrical, Part Four (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-215, Engineering Design Handbook, *Fuzes, Proximity, Electrical, Part Five*

AMCP 706-411, Engineering Design Handbook, *Vulnerability of Communication, Electronic and Electro-Optical Systems (Except Guided Missiles) to Electronic Warfare, Part One, Introduction and General Approach to Electronic Warfare Vulnerability (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-412, Engineering Design Handbook, *Part Two, Electronic Warfare Vulnerability* of *Tactical Communications (U)* (THIS DOCUMENT IS CLASSIFIED CONFIDENTIAL.)

AMCP 706-413, Engineering Design Handbook, *Part Three, Electronic Warfare Vulnerability of Ground-Based and Airborne Surveillance and Target Acquisition Radars (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-414, Engineering Design Handbook, *Part Four, Electronic Warfare Vulnerability of Avionics (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-415, Engineering Design Handbook, *Part Five, Optical/Electronic Warfare Vulnerability of Electro-Optic Systems (U)* (THIS DOCUMENT IS CLASSIFIED SECRET,)

AMCP 706-416, Engineering Design Handbook, *Part Six, Electronic Warfare Vulnerability of Satellite Communications (U)(THIS* DOCUMENT IS CLASSIFIED SECRET.)

AMCP 706-417, Engineering Design Handbook, *Vulnerability of Guided Missile Systems to Electronic Warfare (U)* (THIS DOCUMENT IS CLASSIFIED SECRET.)

Walter H. Buchsbaum, *Complete Handbook of Practical Electronics, Reference Data,* Prentice Hall, Englewood Cliffs, NJ, 1978

L. J. Giacoletto, *Electronic Designers Handbook,* McGraw-Hill, Inc., 1221 Avenue of the Americas, New York, NY 10020, 1977.

A-8.2 JOURNALS AND PERIODICALS

Electronic Warfare/Defense Electronics, Monthly, E. W. Communications, Inc., 3975 East Bayshore Road, Palo Alto, CA 94303

Electronic Packaging and Production, Monthly, Electronic Packaging and Production, 222 West Adams Street, Chicago, IL 60606

Electrical World, Bi-Weekly, McGraw-Hill, Inc., 1221 Avenue of the Americas, New York, NY 10020

Spectrum, Monthly, Institute of Electrical and Electronics Engineers, 345 East 47th Street, New York, NY 10017.

A-8.3 DOCUMENTATION AND INFORMATION ANALYSIS CENTERS

A-8.3.1 Thermophysical and Electronic Properties Information Analysis Center (TEPIAC)

A-8.3.1.1 General

TEPIAC—A DoD Information Analysis Center administratively managed and funded by DLA, Cameron Station, Alexandria, VA 223 14—is sponsored by the AMMRC, Arsenal Street, Watertown, MA 02172. Southwest Research Institute, 8500 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78284, operates the TEPIAC under a Government contract.

TEPIAC collects and disseminates information relative to thermal conductivity, thermal contact resistance, accommodation coefficient, viscosity, emissivity, absorptivity, reflectivity, transmissivity, absorptance/emittance, specific heat, thermal diffusivity, Prandtl number, linear coefficient of thermal expansion, and volumetric coefficient of thermal expansion. The materials covered include inorganic compounds, alloys, intermetallics, glasses, ceramics, cermets, applied coatings, and polymers.

The electronic properties covered include absorption coefficient, dielectric constant, dielectric strength, effective mass, electric hysteresis, electrical resistivity, Hall coefficient, mobility, energy bands, energy gap, energy levels, magnetic hysteresis, magnetic susceptibility, refractive index, and work function. Additionally, the following property groups are covered: electron emission properties, luminescence properties, magnetoelectric properties, photoelectronic properties, piezoelectric properties, thermoelectric properties and magnetomechanical properties.

A-8.3.1.2 Data Acquisition

Both Government and industry may request information directly from this center. Routinely available information will be provided without charge. Those inquiries requiring special studies are done for a fee. For additional information contact TEPIAC, Southwest Research Institute, 8500 Culebra Road, P.O. Drawer 28510, San Antonio, TX 78284.

A-8.3.2 Reliability Analysis Center (RAC)

A-8.3.2.1 General

The RAC disseminates reliability information concerning integrated circuits, hybrid devices, discrete devices (transistors, diodes), and selected nonelectronic parts employed in military, space, and commercial applications. The RAC analyzes and disseminates information that is generated during all phases of device fabrication, testing, equipment assembly, and operation. RAC data files are continually updated through information collected by research and development, testing laboratories, device and equipment manufacturers, Government agencies, and field installations.

A-8.3.2.2 Data Acquisition

Requests for technical assistance and information related to available RAC services and publications may be directed to RAC, Rome Air Development Center, Griffiss Air Force Base, NY 13441.

A-9 PROPELLANTS AND EXPLOSIVES, OPTICS, CERAMICS, AND TEXTILE INFORMATION SOURCES

A-9.1 TECHNICAL BOOKS

A-9.1.1 Propellants and Explosives

AMCP 706-140, Engineering Design Handbook, *Trajectories, Differential Effects, and Data for Projectiles*

AMCP 706-150, Engineering Design Handbook, *interior Ballistics of Guns*

AMCP 706-165, Engineering Design Handbook, *Liquid-Filled Projectile Design*

AMCP 706-175, Engineering Design Handbook, *Solid Propellants, Part One*

AMCP 706-177, Engineering Design Handbook, *Properties of Explosives of Military Interest*

AMCP 706-179, Engineering Design Handbook, *Explosive Trains*

AMCP 706-180, Engineering Design Handbook, *Principles of Explosive Behavior*

AMCP 706-181, Engineering Design Handbook, *Explosions in Air, Part One*

AMCP 706-185, Engineering Design Handbook, *Military Pyrotechnics, Part* One, *Theory and Applications*

AMCP 706-186, Engineering Design Handbook, *Military Pyrotechnics, Part Two, Safety, Procedures and Glossary*

AMCP 706-187, Engineering Design Handbook, *Military Pyrotechnics, Part Three, Properties of Materials Used in Pyrotechnic Compositions*

AMCP 706-188, Engineering Design Handbook, *Military Pyrotechnics, Part Four, Design of Ammunition for Pyrotechnic Effects*

AMCP 706-189, Engineering Design Handbook, *Military Pyrotechnics, Part Five, Bibliography*

AMCP 706-242, Engineering Design Handbook, *Design for Control of Projectile Flight Characteristics*

AMCP 706-244, Engineering Design Handbook, *Ammunition, Section 1, Artillery Ammunition—General, With Table of Contents, Glossary, and Index for Series*

AMCP 706-245, Engineering Design Handbook, *Ammunition, Section 2, Design for Terminal Effects*

AMCP 706-247, Engineering Design Handbook, *Ammunition, Section 4, Design for Projection*

AMCP 706-248, Engineering Design Handbook, *Ammunition, Section 5, Inspection Aspects of Artillery Ammunition Design*

AMCP 706-249, Engineering Design Handbook, *Ammunition, Section 6, Manufacture of Metallic Components of Artillery Ammunition*

AMCP 706-270, Engineering Design Handbook, *Propellant Actuated Devices*

AMCP 706-280, Engineering Design Handbook, *Design of Aerodynamically Stabilized Free Rockets*

AMCP 706-285, Engineering Design Handbook, *Elements of Aircrajt and Missile Propulsion*

AMCP 706-445, Engineering Design Handbook, *Sabot Technology Engineering*

A-9.1.2 Optics

D. F. Home, *Optical Production Technology,* Hayden & Son, Inc., 247 South 41st Street, Philadelphia, PA 19104, 1972

A-9.1.3 Ceramics

The Ceramic Data Book, Cahners Publishing Co., Division of Reed Publishing Corp., 5 South Wabash Avenue, Chicago, IL 60603, 1978

R. Nathan Katz, *Recent Developments in High Performance Ceramics*, US Army Materials and Mechanics Research Center, Watertown, MA, 1975

W. D. Kingery, *Introduction to Ceramics*, John Wiley and Sons, Inc., New York, NY, 2nd edition 1976

Standards of the Alumina Ceramic Manufacturers Association, Alumina Ceramic Manufacturers Association, 331 Madison Avenue, New York, NY 10017

J. Burke, A. Gorham, R. Katz, *Ceramics for High Performance Applications*, Brookhill Press, Chestnut Hill, MA, 1974.

A-9.1.4 Textiles

Man-Made Fibers Fact Book, Man-Made Fiber Producers Association, Inc., 1150 Seventeenth Street NW, Washington, DC 20036

Federal Standard 75 la, *Stitches, Seams, and Stitching*, General Services Administration, Business Service Center, Washington, DC 20407

MIL-HDBK-741, *Fabric Design*

A-9.2 JOURNALS AND PERIODICALS

A-9.2.1 Propellants and Explosives

Pyrotechnics Bulletin, Monthly, American Pyrotechnics Association, 407 Campus Avenue, Chestertown, MD 21620.

A-9.2.2 Optics

Applied Optics, Monthly, Optical Society of America, Inc., 2000 L Street NW, Washington, DC 20036.

A-9.2.3 Ceramics

Ceramics Trade Journal, Monthly, National Ceramic Association, Box 39, Glen Burnie, MD 21061.

A-9.2.4 Textiles

International Apparel Digest, Quarterly, American Apparel Manufacturers Association, 1611 North Kent Street, Arlington, VA 22209.

A-9.3 PROFESSIONAL AND TRADE ASSOCIATIONS

A-9.3.1 Propellants and Explosives

Institute of Makers of Explosives
420 Lexington Avenue
New York, NY 10017.

A-9.3.2 Optics

Optical Manufacturers Association, Inc.
2000 L Street, NW
Washington, DC 20036.

A-9.3.3 Ceramics

American Ceramic Society, Inc.
65 Ceramic Drive
Columbus, OH 43214.

A-9.3.4 Textiles

Man-Made Fiber Producers Association, Inc.
1150 Seventeenth Street, NW
Washington, DC 20036

American Apparel Manufacturers Association, Inc.
1611 North Kent Street
Arlington, VA 22209.

A-9.4 METALS AND CERAMICS INFORMATION CENTER (MCIC)

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