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MILITARY HANDBOOK

POLYAMIDE (NYLON) PLASTICS: PROPERTIES, PROCESSING, PERFORMANCE, AND MILITARY APPLICATIONS



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FOREWORD

1. This military handbook is approved for use by all Activities and Agencies of the Department of the Army and is available for use by all Departments and Agencies of the Department of Defense.

2. Beneficial comments (recommendations, additions, and deletions) and any pertinent data that may be of use in improving this document should be addressed to Commander, US Army Armament Research, Development, and Engineering Center, ATTN: SMCAR-BAC-S, Picatinny Arsenal, NJ 07806-5000, by using the Standardization Document Improvement Proposal (DD Form 1426) appearing at the end of this document or by letter.

3. Nylon is an engineering material that is widely used in armaments and other applications. The information in this handbook is focused for the design engineer who might not be familiar with the properties of nylon. This handbook was developed under the auspices of the US Army Materiel Command's Engineering Design Handbook Program, which is under the direction of the US Army Industrial Engineering Activity. Research Triangle Institute (RTI) was the prime contractor for the preparation of this handbook.

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LIST OF ABBREVIATIONS AND ACRONYMS

ABS = acrylonitrile butadiene styrene	PEK = polyether ketone
APDS-T = armor-piercing, discarding-sabot tracer	PET = polyethylene terephthalate
APFSDS-T = armor-piercing, fin-stabilized, discarding-sabot tracer	Pip = piperazine
AR = assault rifle	PTFE = polytetrafluoroethylene
ASTM = American Society for Testing and Materials	PV = pressure x velocity
CLP = clamp-limiting pressure	PVC = polyvinyl chloride
DAM = dry as molded	RH = relative humidity
DoD = Department of Defense	rpm = rotations per minute
2,5-DiMePip = 2,5-dimethylpiperazine	RTD = resistance temperature device
DS2 = decontaminating solution No. 2	SA = semiautomatic
ERA = extended range ammunition	SAN = styrene acrylonitrile
FS = factor of safety	SAW = squad automatic weapon
GD = soman	SE-2 = self-extinguishing class 2
HD = distilled mustard	STB = supertropical bleach
I = isophthalic acid	T = terephthalic acid
ID = inner diameter	TFE = tetrafluoroethylene
MC/AAAC = medium caliber/automatic antiarmor cannon	TMD = trimethylhexamethylene-diamine
MPD = <i>meta</i> -phenylenediamine	TMDT = Trogamid T [®]
MXD = <i>meta</i> -xylylenediamine	TP = polyester
OD = outer diameter	U.S. = United States
PBT = polybutylene terephthalate	US = United States
PCT = poly-1-4-cyclohexylene dimethylene terephthalate	UV = ultraviolet
	WP = white phosphorus

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CHAPTER 1

INTRODUCTION

This chapter summarizes the purpose of this handbook, states the general scope of the document, and reviews, in some detail, the history of the development and uses of nylons.

1-1 PURPOSE

This handbook provides up-to-date information on polyamides, which are commonly referred to as nylon resins. This document is intended for use by the Department of Defense (DoD), industry, and academic engineers and scientists. Others who will find it useful are draftsmen, technicians, and designers who must have access to information on nylon properties, processing, and performance. Guidelines are given for (1) nylon 6/6 and its many variants, (2) the properties of nylon resins, and (3) the use of nylon resins, particularly within the context of end products, which must meet stringent service conditions.

Details are given on the use of nylons in both military and commercial applications, and successes and failures are noted.

The users of the handbook will benefit by gaining a better understanding of nylons, their diversity, advantages, limitations, and properties pertinent to design and end-item use.

1-2 SCOPE

This handbook provides a summary of nylon technology and technical information for these important plastic materials. The handbook contains tables and figures available in the open literature and in suppliers' bulletins. The focus is on the molding and extrusion grades of nylons. This handbook does cover, but not to any great extent, nylon formulations that are processed by blow molding, rotational molding, or fluidized-bed coating. Processing of fibrous nylons is not included.

1-3 HISTORY

1-3.1 NYLON DEVELOPMENT MILESTONES

The primary impetus for the birth and early development of nylon was the work of Wallace Hume Carothers, who initiated studies on certain condensation polymerizations in 1928 (Refs. 1 and 2). This general type of polymerization joins at least two different molecules to form a plastic material via the loss of a small molecule such as water.

In 1935 Carothers and his co-workers of the E. I. Du Pont de Nemours Co. prepared a high-molecular-weight polyamide by condensing hexamethylene diamine with adipic acid to form nylon 6/6. Du Pont led the development of nylon for many years.

Several milestones in the early development of nylon are important. In 1938 Du Pont announced the development of fibers from nylon 6/6. In 1940 Du Pont opened the first plant for the production of nylon 6/6. During 1938-1940, Du Pont marketed such products as nylon bristles (stretched) and brushes. Those items, using heavy nylon filaments, were considered plastic, not fibers. In 1941 Du Pont marketed nylon powder for molding. In 1954 Allied Chemical Co. began marketing extracted polycaprolactam that was designated nylon 6. Nylon 6, used for many years in Europe prior to 1954, is essentially with some exceptions an offset to nylon 6/6. Both nylons have a nearly equivalent pricing structure.

As of 1948 Du Pont supplied six grades of nylon 6/6 molding and extrusion resins. In 1968 the Du Pont product line included about sixty nylon formulations. Since then, the number of nylon types and grades has increased. Diversified and improved nylons are available, and certain older formulations have been discontinued.

There are two general classes of nylons: those made from the reaction of dibasic acids with dibasic amines and those synthesized from hydrolyzed lactams. The first class includes nylon 6/6, 6/10, and 6/12; the second class includes nylon 6, 11, and 12. All six types are available in grades for molding or extrusion.

1-3.2 NYLON—THE FIRST ENGINEERING THERMOPLASTIC

Dr. Carothers' development of 6/6 polyamide was called nylon*. This plastic had unique characteristics not available in any other plastic at that time and made possible wide and increased use of nylons over the years.

Nylon was the first crystalline plastic. Such structured physical characteristics established a reasonably precise transition from solid phase to melt phase, i.e., a fairly sharp melting point. Other "noncrystalline" plastics, such as polystyrene or polymethyl methacrylate (both well-entrenched prior to the 1935-38 birth of nylon), give a solid-to-liquid transition range that is inherently broad.

Nylon 6/6 exhibited a significantly higher service temperature, i.e., beyond the values known for the accepted early thermoplastics of limited engineering use. It exhibited enhanced properties of toughness, rigidity, and natural lubricity, which are useful for bearings, gears, and support structures. Before nylon 6/6 became available, such items

*This word became a generic term for the various polyamide resins; at no time did Du Pont use this as a trademark.

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were made of metals or certain woods, bone, or other natural polymers; no plastics were suitable for such use.

Nylons are quality materials that have many uses. For fifty-plus years the superior toughness and stiffness of nylon have been evident. In many, but not all, cases, their use established superior replacement and application for the commonly known and "well-entrenched" metals and their alloys. Such proven performance gave nylon, within a short time, the designation of the first engineering plastic.

1-3.3 NYLON—MANY COMPOUNDS FOR PROPERTY VARIATIONS

Since 1948 useful nylon resins have grown from a dozen or so to several hundred basic and modified compounds. The principal types are nylons 6/6, 6, 6/10, 6/12, 11, and 12. As of 1991 there were 16 major domestic producers of nylon plastics (Ref. 3). This number may increase with the eventual further penetration of the American market by European and Asiatic companies oriented toward maintaining nylon production facilities in the U.S. or, more broadly, on the North and South American continents. Several of the 16 major domestic producers in 1991 were affiliates of large West European companies.

There are definite reasons for development of the hundreds of commercially available nylon compounds or formulations. Nylon can be modified with relative ease. Different diacids and diamines can be used to give a variety of polyamide homopolymer and copolymer plastics. In general, polycondensation polymerizations are simpler to use and manipulate than typical chain reaction routes to syntheses of plastics (Ref. 4).

For example, these chain polymerizations are the major routes to polystyrene, polyethylene, methyl methacrylate, and other plastic-precursor monomers. Each of the six or more marketed types of nylons can be customized via compound formulation and/or base-resin modifications via syntheses of many variants, physical modification (such as tempering and/or nucleating) for a more finely tuned crystalline structure, and other processes. Such "customization" can be used to enhance or even to suppress certain properties that are very important to meeting fairly critical service usage.

Unfilled nylon 6/6 resins from a number of major American sources can be physically or chemically modified, as shown in Table 1-1. The variants listed are designed primarily for injection molding. Most of these modifications are reasonably delineated in the patent literature; some clues can be postulated from the open literature and technical bulletins, e.g., company bulletins and data sheets (Ref. 3). Many relevant techniques, however, are highly proprietary and/or are alluded to in general terms.

The important properties of nylons are basic economy of use; toughness at high and low temperatures; resistance to repeated impacts; retention of stiffness and tensile properties and dimensional stability at high temperatures; resistance to abrasion; resistance to organic solvents, oils, and gasoline; capability of being fabricated into thin, tough, strong shapes; natural lubricity; and long-term service at high temperatures. Chapter 2 contains information regarding advantages and disadvantages.

Nylons have many military applications. Nylon 6/6 is used in bearings, bushings, cams, gears, hydraulic fluid lines, hoses, petroleum piping, compressed-air lines, and panelings for various equipment. Cartridge cases for practice rounds have also been made of nylon 6/6, and a toughened, reinforced nylon 6/6 is being used in improved bayonets. Nylon 6 is used in sliding parts, runners, casters, and parts subject to high-impact service. Nylons 6/10 and 6/12 are used for electrical components; these types have also been used as sabots, obturating bands, and rotating bands. Nylons 11 and 12 are used in electrical insulation, corrosion-resistant coatings, and parts requiring dimensional stability.

1-4 OVERVIEW

Nylons are widely used in the plastics industry, particularly nylon 6/6 and nylon 6.

Information is given in Chapter 2 on characteristics of nylons. Advantages and disadvantages of the six marketed types of nylons are given. Reactions, preparation, and properties are discussed. Detailed data on properties of various nonreinforced, unmodified resins are given. Modified and reinforced nylons are discussed in Chapter 3. Tabulated data are shown.

The processing methods of injection molding and extrusion are discussed in Chapter 4. Molding defects and corrective measures are given. Annealing and accelerated moisture conditioning to relieve molded-in stresses are covered.

Fabrication and design factors are discussed in Chapter 5. The stress-strain curve, tolerances, structure and prototype construction are detailed. Quality control methods are discussed.

Assembly methods are reviewed and permanent and temporary joining techniques are given.

The effects of natural and induced environmental factors that affect nylon properties are discussed in Chapter 6. Information is given in Chapter 7 concerning the safety aspects of nylon. Flammability, toxicological, and ecological safety considerations are provided.

The relationship between applications and nylon properties is discussed in Chapter 8. Illustrative military applications are given.

TABLE 1-1. NYLON 6/6 RESINS FOR INJECTION MOLDING

Nylon 6/6 has a melting point of 255°C (491°F), it is stiff and strong over a range of temperatures, and it has good toughness and chemical resistance.

DESCRIPTION	TYPE MODIFICATION	CHARACTERISTICS
General-purpose, unlubricated	None	Basic 6/6: stiff, strong over wide temperature range, good toughness and chemical resistance
General-purpose, lubricated	Physical, coated pellets for interface bloom on processing	Improved machine feed and release from molds, widely used. Use: mechanical parts and consumer appliances
General-purpose, internally lubricated	Physical, possibly some chemical modification	Enhanced machine feed and mold-release properties
General-purpose, internally lubricated, color stabilized	Physical, chemical modification, possibility of use of improved pigments and/or dyes	Very good color retention even though vigorous mixing is required
Fast molding, externally and/or internally lubricated	Physical, possibly some minimal chemical modification	Nucleated form increases production rates. Cooling time from "liquid" to "solid" state significantly reduced via controlled crystallization, which gives fast setups
Heat stabilized, lubricated	Physical, some chemical modification possible	Reduced embrittlement at elevated service temperature, good electrical properties for standard purposes, better machine feed and mold release
Weather resistant, grey to black in color	Physical	With about 2% or less high surface area, well-dispersed carbon black(s) for quenching of free-radical oxidizers, increased resistance to environmental degradation
Hydrolysis resistant, i.e., "spine" polymer cleavage via reaction with water	Physical, possibly some chemical	Stabilized against hydrolytic and oxidative degradation, lubricated. Withstands long-term exposure to hot water
Toughened, increased impact resistance and flexibility	Physical, use of additives, some are copolymers.	Similar to basic 6/6, but with modifications, such as dispersed additives, to suppress crack initiation and propagation

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CHAPTER 2

CHARACTERISTICS OF NYLONS

This chapter discusses the general market status of nylon resins, the system used to identify the nylon types, and the basic synthetic methods used to produce the major and minor types. The advantages and limitations of nylon resins as engineering materials and the comparative properties of the nylon types are discussed. The interpretations of some major properties are described, and tabulations are given on the properties of nylons 6, 6/6, 6/10, 6/12, 11, and 12.

2-0 LIST OF SYMBOLS

- m = number of repeating groups
- n = number of repeating groups
- R = any alkyl group
- R' = any alkyl group different from R
- x = number of CH₂ groups

2-1 STATUS OF NYLONS AS ENGINEERING PLASTICS

The growth of nylon production in the United States (U.S.) averaged 13% per year from 1960 to 1979; performance since then, however, has been erratic (Ref. 1). The 1979 volume was 144×10^6 kg (317×10^6 lb). Production has been rising consistently since 1982 and was 192×10^6 kg (424×10^6 lb) in 1986. In the United States in 1983 61% of the nylon pro-

duction was nylon 6/6, and 26% was nylon 6. There is slightly greater use of nylon 6 worldwide, but there has been a trend since 1980 toward greater usage of nylon 6/6. Worldwide usage of the other nylons has been about 8.5%. Use of nylons is expected to grow well in the 1990s along with use of other engineering thermoplastics. Engineering plastics are broadly defined (Ref. 2) as plastics with or without fillers or reinforcements that have mechanical, chemical, and thermal properties and are suitable for use in construction, machine components, and chemical processing equipment.

Information concerning US plastic sales for 1989 and 1990 of various plastics, including nylon, is given in Table 2-1. The market consumption for nylon resins for 1989 and 1990 is given in Table 2-2. The comparative prices in mid-December 1990 for nylon and other resins are given in Table 2-3.

TABLE 2-1. US PLASTIC SALES IN MILLIONS OF KILOGRAMS (POUNDS) (Ref. 3)

MATERIAL	1989		1990	
(ABS) Acrylonitrile-butadiene-styrene	561	(1,237)	550	(1,212)
Acrylic	335	(739)	341	(751)
Alkyd	147	(325)	145	(320)
Cellulosics	41	(91)	23	(50)
Epoxy	219	(483)	206	(454)
Nylon	263	(580)	259	(570)
Phenolic	1,282	(2,826)	1,282	(2,827)
Polyacetal	65	(143)	65	(143)
Polycarbonate	283	(624)	281	(620)
Polyester, thermoplastic (PBT, PCT, PET)	951	(2,097)	1,287	(2,837)
Polyester, unsaturated*	598	(1,319)	557	(1,227)
Polyethylene, high-density	3,707	(8,173)	3,858	(8,505)
Polyethylene, low-density**	4,900	(10,803)	5,386	(11,875)
Polyphenylene-based alloys	89	(196)	90	(199)
Polypropylene and copolymers	3,312	(7,303)	3,858	(8,505)
Polystyrene	2,327	(5,131)	2,330	(5,137)
Other styrenics†	535	(1,180)	506	(1,116)
Polyurethane	1,462	(3,224)	1,481	(3,265)
Polyvinyl chloride and copolymers	3,872	(8,536)	4,217	(9,297)
Other vinyls	408	(900)	415	(915)
Styrene-acrylonitrile (SAN)	49	(108)	61	(134)
Thermoplastic elastomers	246	(542)	265	(584)
Urea and melamine	626	(1,381)	653	(1,439)
Others	141	(310)	150	(330)
Total	26,422	(58,251)	27,886	(61,480)

*Resin only

**Includes linear low density polyethylene (LLDPE)

†Excludes ABS and SAN

PBT = polybutylene terephthalate

PCT = poly-1-4-cyclohexylene dimethylene terephthalate

PET = polyethelene terephthalate

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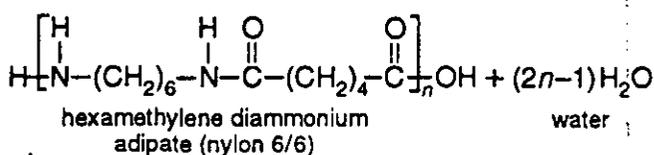
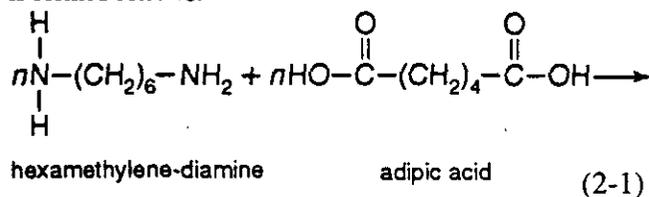
TABLE 2-2. NYLON PATTERN OF CONSUMPTION, MILLIONS OF KILOGRAMS (POUNDS) (Ref. 3)

MARKET	1989		1990	
Extrusion				
Filaments	11	(24)	9	(19)
Film	26	(57)	30	(65)
Sheet, rod, tube	14	(31)	14	(31)
Wire and cable	16	(36)	17	(37)
Total	67	(148)	69	(152)
Molding				
Appliances/power tools	9	(19)	9	(19)
Consumer products	16	(36)	13	(29)
Electrical/electronics	22	(48)	20	(45)
Industrial	20	(45)	20	(45)
Transportation	68	(151)	67	(148)
Total	136	(299)	130	(286)
Export	35	(77)	35	(77)
Other	25	(56)	25	(55)
Grand total	263	(580)	259	(570)

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2-2 NOMENCLATURE

Nylon is the generic term for all long chain polyamides that have recurring amide groups (—CONH—) as an integral part of the main polymer chain. Nylons are synthesized from intermediates, such as dicarboxylic acids, diamines, amino acids, and lactams, and are identified by numbers denoting the number of carbon atoms in the polymer chain derived from specific constituents. Those from diamine are given first. If used, the second number denotes the number of carbon atoms derived from a diacid. For example, nylon 6/6, the first polyamide used in commercial production in the United States, was made from adipic acid and hexamethylene-diamine, both of which contain six carbon atoms. Polymers formed from the condensation of diamines and dibasic acids are called AABB types. A represents amine groups, and B represents carboxyl groups. The reaction in which nylon 6/6 is formed follows:



where

n = number of repeating groups.

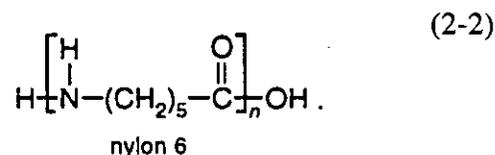
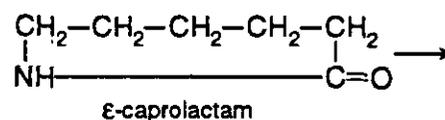
TABLE 2-3. COMPARATIVE MARKET—PRICES MID-DECEMBER 1990 (Ref. 4)

MATERIAL*	cents/in. ^{3**}	cents/cm ^{3**}
Nylon		
Type 6	5.9	0.36
Type 6/6	6.6	0.40
Type 6/9	9.7-10.7	0.59-0.65
Type 6/10	12.1-13.6	0.74-0.83
Type 6/12	11.4-13.2	0.70-0.81
Type 11	13.6-14.1	0.83-0.86
Type 12	12.1-13.0	0.74-0.79
ABS		
Medium impact	3.6	0.22
High impact	3.9	0.24
Extra high impact	4.1	0.25
Acetal		
Homopolymer	6.1-6.5	0.37-0.40
Copolymer	6.1-6.5	0.37-0.40
Polyamide-imide		
Modified	95.0	5.80
Unmodified	97.0	5.92
Polycarbonate	6.7	0.41
Polyester (TP) PBT	6.9	0.42
Polyurethane		
Ester	7.5-9.3	0.46-0.57
Ether	10.0-10.5	0.61-0.64
Polysulfone	17.5	1.07
Polyether-sulfone	22.0	1.34
Polyarylsulfone	21.8	1.33
Polyether-imide	21.5	1.31
Polyether ketone (PEK)	130.1	7.94

*unfilled natural color

**based on sampling of processors indicating direction of price change into 1991

The nylons designated with a single number, such as nylons 6, 11, and 12, are those polymerized by addition reactions of ring compounds that contain both acid and amide groups on the monomer. For example, nylon 6 is polymerized from ϵ -caprolactam (6 carbon atoms) as follows:



These polymers are referred to as AB polymers. Numerous combinations of diacids, diamines, and amino acids have been interacted, and copolymers containing various proportions of

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two or more diacids, diamines, and amino acids have been prepared. To represent copolymers, the major component is named first and is followed by the minor components in order of decreasing percentages. For example, if hexamethylene-diamine (6 carbon atoms), adipic acid (6 carbon atoms), and sebacic acid (10 carbon atoms) were copolymerized, the resultant product would be named 6/66/10 (95:5) when the 6/6 and 6/10 components are present in the copolymer in the proportion 95:5. In other cases chains between functional groups in the reactants may comprise linear or branched aliphatic hydrocarbons or alicyclic or aromatic rings; they may contain hetero atoms, such as oxygen, sulfur, and nitrogen (e.g., piperazine or even hydrazine).

Secondary diamines lead to the formation of N-substituted polyamides. Polyfunctional reactants, in which the sum of the functional groups in the polyfunctional amine and acid is

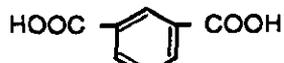
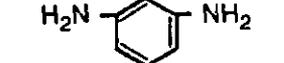
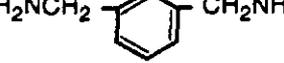
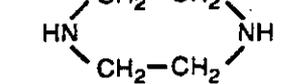
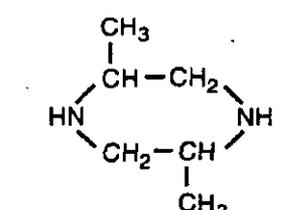
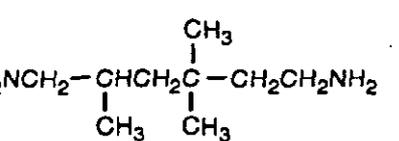
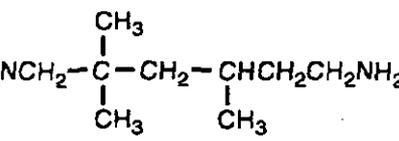
greater than four, lead to the formation of cross-linked, or network, polymers. Thus it is apparent that it is theoretically possible to synthesize a large number and variety of polyamides. Of these, only a few combinations, primarily the linear polyamides, have been chosen for commercial exploitation because of their lower cost, availability of intermediates, and generally satisfactory physical and chemical properties.

Those reactants involving rings and side groups employed in making nylons have no rules governing how they are designated. Abbreviations of the chemical names of the reactants are commonly resorted to, and some of these are listed in Table 2-4. Thus 2,5-DiMePipT, pronounced

tü fiv di-meth-el pip tē,

is the polymer from 2,5-dimethylpiperazine and terephthalic

TABLE 2-4. ABBREVIATIONS FOR NYLON INGREDIENTS (Ref. 5)

FORMULA	NAME	ABBREVIATION
	Terephthalic acid	T
	Isophthalic acid	I
	<i>meta</i> -phenylene-diamine	MPD
	<i>meta</i> -xylylene-diamine	MXD
	Piperazine	Pip
	2,5-dimethylpiperazine	2,5-DiMePip
	2,4,4-trimethylhexa- methylene-diamine	} TMD (50/50 mixture)
	2,2,4-trimethylhexa- methylene-diamine	

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acid. In complex nomenclature of this type it is sometimes helpful to separate the amine and acid descriptions with a hyphen. The nylons from diamines and diacids are most often named as polyamides. The name of a nylon from an amino acid or lactam is usually based on the monomer. The more common nylons include

1. Nylon 6, polycaprolactam: $\text{—NH(CH}_2\text{)}_5\text{CO—}$
2. Nylon 6/6, poly(hexamethylene-adipamide):
 $\text{—NH(CH}_2\text{)}_6\text{NHCO(CH}_2\text{)}_4\text{CO—}$
3. Nylon 6/66 and Nylon 66/6: copolyamides of hexamethylene-diamine, adipic acid, and caprolactam
4. Nylon 6/10, poly(hexamethylene-sebacamide):
 $\text{—NH(CH}_2\text{)}_6\text{NHCO(CH}_2\text{)}_8\text{CO—}$
5. Nylon 6/12, poly(hexamethylene-dodecanoamide):
 $\text{—NH(CH}_2\text{)}_6\text{NHCO(CH}_2\text{)}_{10}\text{CO—}$
6. Nylon 11, poly(11-aminoundecanoic acid):
 $\text{—NH(CH}_2\text{)}_{10}\text{CO—}$
7. Nylon 12, poly(12-aminododecanoic acid):
 $\text{—NH(CH}_2\text{)}_{11}\text{CO—}$

2-3 SYNTHESIS AND CHEMISTRY— MAJOR AND MINOR TYPES

2-3.1 INTRODUCTION

This discussion on the synthetic routes to commercial nylon plastics is primarily concerned with the major types, i.e., nylons 6/6 and 6. As the most important nylon plastics, these have received the most study. The synthetic and polymerization techniques for nylons 6/6 and 6, however, are also applicable to the minor types, i.e., 6/10, 6/12, 11, and 12, and the syntheses of these types are summarized.

In general, the thermoplastic nylons are produced by polymerization (or polycondensation) in the molten state (Ref. 6). The respective monomers are heated in the presence of various quantities of water at 200 to 300°C (392 to 572°F) at normal or elevated pressure, depending on the specific application. The final degree of polymerization is determined by the polycondensation equilibrium; excess water and water formed in the reaction must be evaporated during the process in a controlled manner. At the end of the process the molten polymer is extruded into strands that are collected and cut into chips.

2-3.2 BASIC METHODS OF SYNTHESIS

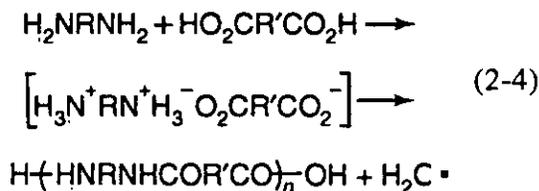
Polyamides have been prepared or synthesized by many routes. The classical and most popular routes for preparation of the commercially available general types, however, include direct amidation and ring-opening polymerization of the lactams (Ref. 7).

2-3.2.1 Direct Amidation (Nylons 6/6, 6/10, 6/12, and 11)

Direct amidation is the reaction of amine groups with carboxyl groups accompanied by elimination of water. This method has been studied most extensively. The groups may be in a single molecule for self-condensation, e.g., an amino acid,



or they may be different molecules, e.g., the reaction of diamines with dicarboxylic acids. When polycondensation of diamines with dicarboxylic acids is used, balance of the reactive ends is usually obtained by prior isolation and purification of the polymeric salt:



where

$\text{R}' = \text{any alkyl group different from R.}$

In general, amide-forming derivatives of the dibasic acid, such as diester, dihalide, or diamide, could also be used, but the acid itself is normally preferred.

The amino acid self-condensation of Eq. 2-3 is used to synthesize nylon 11, and the polycondensation of diamines with dicarboxylic acids of Eq. 2-4 is the route used to synthesize nylons 6/6, 6/10, and 6/12.

As shown by Eq. 2-1, nylon 6/6 is formed by the polycondensation of hexamethylene-diamine and adipic acid or the amide-forming derivative of the acid, but the acid itself is normally preferred. Cyclohexane and phenol are the raw materials for adipic acid; butadiene and acrylonitrile are the raw materials for hexamethylene-diamine.

Nylon generation processes that use free acid as one of the ingredients produce the salt hexamethylene diammonium adipate as an intermediate product. The correct stoichiometric proportions of the ingredients are indicated by the pH of the salt solution being the "equivalence" value. The equivalence value is determined by titrating the salt solution with a strong acid or base while closely monitoring the pH of the solution. The correct equivalence value is the pH of the solution when the pH changes most rapidly with addition of a measured amount of the titrating solution. For 1 to 10% solutions of nylon 6/6, 6/10, or 6/12 salts, the equivalence pH is approximately 7.6. The difference between the measured value and the equivalence value is indicative of the disparity in the molal proportions of the ingredients, which limits the molecular weight of the product that can be produced. A 1.25 mole percent disparity limits the maximum molecular weight to 18,000 and makes the requirements for moisture levels more stringent. Allowances for differences in the volatility of the ingredients must be made so that the correct stoichiometric proportions are maintained after evaporative loss of material. (Ref. 8)

A purified form of the salt may be produced by mixing solvent-based solutions of the reactants, (e.g., methanol based), and collecting the pure, precipitated salt. It may also be formed in the aqueous solution needed for production of

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nylon by combining diamine dissolved in water with a stirred dispersion of the acid. Since this solution contains reacted ingredients, additional purification with activated charcoal may be necessary.

The nylon 6/6 polymer may be generated in batch processes by first concentrating the aqueous solution in evaporators until the solution is 75% solid nylon and then transferring the solution to heated pressure vessels purged of oxygen. The solution is heated until the temperature reaches 210°C (410°F) or the pressure reaches 1.7 MPa (17 atmospheres). Water-vapor is removed while pressure is maintained, and the temperature is gradually increased. Finally, the pressure is reduced to atmospheric, and the temperature is increased to 280°C (535°F), slightly above the melting point for dry nylon of 269°C (516°F). Since the melting point of dry nylon increases as the moisture is removed, the pressure and temperature profiles are designed to maintain the material in a molten state. The final moisture content determines the degree of polymerization, which determines the final molecular weight. For more complete moisture removal a vacuum may be applied to produce a high molecular weight material. Also, extruding the melt through a device equipped with an extraction zone purged with an inert gas will produce a higher molecular weight material. If lower molecular weights are desired, several options are available including incomplete extraction of the moisture, using excess adipic acid or hexamethylene-tetramine, or adding acetic acid.

The molten polymer is forced out of the pressure vessel, quenched, dried, cut into chips, and packaged in hermetically sealed containers. Packages are usually 11.3-kg (25-lb) cans or 22.7-kg (50-lb) bags, but polyolefin-lined drums and cartons of 113.4- to 544.3-kg (250- to 1200-lb) capacity are also used.

A continuous process may be used to produce nylon 6/6 instead of the batch process described in the preceding paragraphs. The process facility, however, must be carefully designed to minimize the effect of transient occurrences on the molecular weight of the product. Suitable equipment has been described primarily in the patent literature.

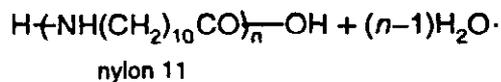
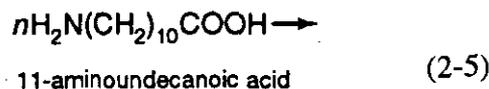
Nylons 6/10 and 6/12 are obtained in an essentially analogous manner and mostly by this discontinuous process. The dicarboxylic acids required are sebacic acid (from castor oil) and dodecanoic acid (from butadiene), respectively.

Although catalysts are not necessary for the production of nylon 6/6, processes for other nylon compositions may require catalytic materials, such as oxides, carbonates, and halogen salts of polyvalent metals, strong acids, litharge, and organotin compounds. Also unnecessary for nylon 6/6 but occasionally useful is polymerization in the presence of fluids with high boiling points that may or may not be solvents for the nylons.

General descriptions of this process are given in various sources such as Refs. 9 and 10. Details of the processes, however, are either proprietary or available only in patent literature.

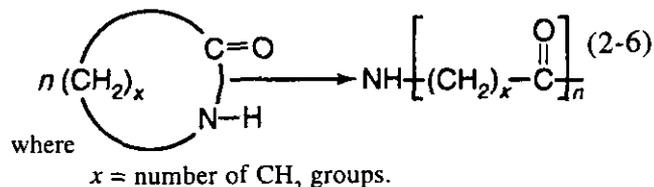
Solid-phase reactions of an amine and an acid have been used to produce an amide at temperatures below the melting point. Differences between solid-phase and melt-phase polymerized nylons are minimal after the product has been melted. (Ref. 11)

Nylon 11 is manufactured by self-condensation of 11-aminoundecanoic acid (whose feedstock is castor oil), and the reaction is



2-3.2.2 Ring-Opening Polymerization (Nylons 6 and 12)

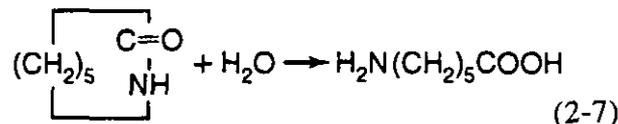
Nylons 6 and 12 are formed by ring-opening polymerization (either hydrolytic or anionic) of lactams by the general equation



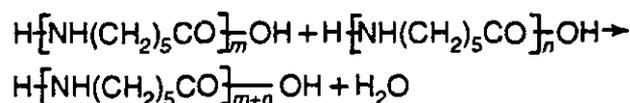
Caprolactam is the predominant commercial lactam monomer used because of its cost and resultant polymer (nylon 6) properties. The raw materials for caprolactam are cyclohexane, toluene, and phenol.

The synthesis of nylon 6 from caprolactam is carried out in a batch process similar to the process used for 6/6, except that caprolactam is the only active ingredient. Thus the concern for stoichiometric proportions is removed (Ref. 12). The caprolactam monomer contains both the acidic and basic functional groups, although the residual amounts of amine and acid groups are not necessarily equal. Dry caprolactam does not polymerize, but in water at 200°C (392°F) the following reactions occur (Refs. 13 through 16):

1. Hydrolysis:



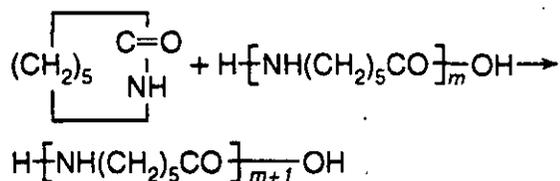
2. Condensation:



(cont'd on next page)

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3. Addition:



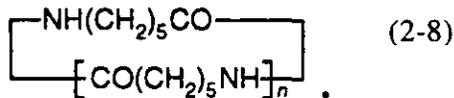
where

m = number of repeating groups.

The hydrolysis and addition reactions and possibly the condensation reaction are acid catalyzed (Ref. 17). The condensation reaction is the primary reaction for production of nylon 6/6, whereas the addition reaction is the major growth reaction for nylon 6. Because of the significance of the addition reaction, polymerization is expedited by adding aminocaproic acid at the beginning of the process. Hexamethylene-tetramine adipate (or a similar amine-acid combination) can also be used, but the product will be a 66/6 copolymer whose composition depends on the amount of 6/6 salt used. Rapid, smooth polymerization occurs if the amount of acid added to a 20% solution is sufficient to yield a pH of 5.7.

The melting point of polycaprolactam used for nylon 6 is 40 deg C (72 deg F) lower than that of nylon 6/6, but the polymerization temperatures for the two nylon materials, 6 and 6/6, are normally not very different because of the need to heat until adequate melt flow and reasonable rates of reaction are achieved. As is true for nylon 6/6, the molecular weight of nylon 6 may be controlled by adding amine or acid to cause an imbalance in the amine-acid ratio or by adding a monofunctional reactant such as acetic acid. Also the residual moisture content during manufacture affects the molecular weight. Thus the moisture must be extracted under careful control, and the final product must be hermetically packaged.

Immediately after manufacture, about 10% of nylon 6 is 10% extractable material, which acts as a plasticizer and is preferably removed for most applications. The extractables include monomer and cyclic oligomers

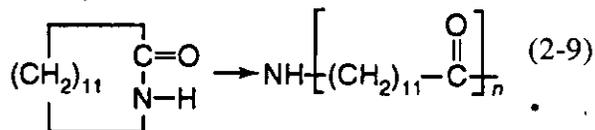


The monomer is removed with a vacuum of 0.67 to 1.33 kPa (5 to 10 mm Hg), but removal of oligomers requires prolonged heating at low atmospheric pressure, i.e., less than 0.13 kPa (1 mm Hg).

The production of nylon 6 by polymerization of caprolactam is rapidly adaptable to a continuous process because the relative volatility of two different reactants is not a factor. Continuous processes have been described in the literature (Refs. 18 through 22). One description describes a technique for more complete removal of water from the melt by intermittent injection of inert gas. Another suggests limiting initial conversion to 45% with a vacuum finish to reduce the

residual cyclic oligomers to less than 2% to eliminate the requirement for prolonged heating at less than 0.67 kPa (5 mm Hg).

In processes similar to those for nylon 6, nylon 12 is manufactured by the hydrolytic polymerization of lauric lactam (dodecanoic lactam) or cyclododecalactam (whose feedstock is butadiene):



In contrast to the requirements for nylon 6, higher polymerization temperatures (about 300°C (575°F)) are required, residual monomer concentration is low, and the extraction process is eliminated for nylon 12.

Nylon 6 can also be synthesized by the anhydrous polymerization of caprolactam by using a strong base (anionic) or a strong acid (cationic) as a catalyst. The cationic procedure has not provided a polymer of useful molecular weight, but anionic polymerization leads to a very high molecular weight in a matter of minutes, or even seconds, particularly if a suitable cocatalyst is added. The cocatalyst can be any of a wide variety of N-substituted lactams (or their precursors) for which the substituent on the nitrogen atom is of the electron-withdrawing type. Anionic polymerization is used in monomer casting. The polymer made anionically is not as thermally stable as that made in the presence of water and is not directly applicable to injection molding or extrusion. The anionic, or monomer, casting process, however, provides the designer great latitude in areas of application that may be too difficult or too expensive by extrusion or molding methods. Although not generally economical for small, thin parts weighing less than 0.45 kg (1 lb), this process is very practical in a range up to several hundred pounds.

2-4 ADVANTAGES AND LIMITATIONS—GENERAL

2-4.1 ADVANTAGES

The two most important advantages of nylons are their toughness and ability to withstand repeated impacts over a wide temperature range. These properties are particularly important in military applications such as rotating and centering bands, cartridge cases, and obturators in both small and large caliber weapon systems. Other desirable properties include those that follow:

1. The combination of excellent abrasion resistance and an exceptionally low coefficient of friction makes nylons very useful for gears, cams, and bearing surfaces. Their resiliency permits the load to be spread over large surface areas. Nylons can be used without lubrication, which is a desirable characteristic for food-handling equipment and textile and home appliance applications.

2. Nylons are particularly resistant to detergents, fuels, greases, and oils, including animal and vegetable oils.

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They are extremely resistant to aromatic and chlorinated hydrocarbons and ketone and ester solvents, and they are not affected by alkalies or dilute acids. Nylons are also resistant to military decontaminants, such as decontaminating solution No. 2 (DS2) (a strong alkali environment) and supertropical bleach (STB), used to neutralize chemical warfare agents on military hardware.

3. Nylons are excellent barriers to many common gases and organic liquids. Permeation tests with chemical warfare agents, such as blister and nerve agents, showed no permeation or visual surface effects.

4. Most nylons are compatible with explosives, even when stored in long-term, direct contact with the explosives at slightly elevated temperatures.

5. Nylon grades can be molded and extruded without difficulty.

6. Spin welding, vibration welding, and ultrasonic welding can be used as assembly techniques.

7. All nylons have low flammability and generate very little smoke or noxious fumes. Some are classified as self-extinguishing.

8. Nylons can be modified to meet specific requirements or needs. Modified nylons include copolymers, compositions containing additives to impart specific properties, filled and reinforced materials, and chemically modified nylons. The preparation of a copolymer requires only that the *desired ingredients be added to the polymerization vessel*. Modifiers such as antioxidants, nucleating agents, plasticizers, and carbon black can be added directly to the polymerizer.

9. Nylons are cost competitive with other engineering thermoplastics, especially nylon 6/6 and 6, which are in the middle of the cost spectrum per unit volume.

2-4.2 LIMITATIONS

Nylons are good engineering plastics, but their limitations include the following:

1. Nylon is a hygroscopic material. Moisture is slowly absorbed from the atmosphere and acts as a plasticizer. Thus tensile strength and stiffness are reduced, and elongation is increased. Moisture, however, increases the general energy absorption characteristics of the resin, including its impact strength. The absorbed moisture also causes dimensional changes that must be considered during design. Although not indicated by physical property and moisture data, nylon does have fairly good dimensional stability (Ref. 23). *Nylon moldings pick up moisture from the moment they are taken from the mold. The moisture does two things: It causes the nylon to swell, and it causes stress relief, of which shrinkage is a result. The expansion of the part due to moisture pickup is counteracted by the contraction caused by stress relief, so the net result can be a very small change in dimensions. Moisture also degrades the electrical properties. Excess moisture (in excess of 0.3%) in molding powders can also lead to splay marks and blisters on the molded object and to "drooling" of the resin from the injection molding*

machine between injection cycles.

2. Because nylon absorbs water, nylon parts stain easily.

3. The electrical properties of nylon are not outstanding and are affected by water. The electrical properties are adequate at ordinary power frequencies, but nylon should not be used where static charge buildup is potentially dangerous. Because of its other physical properties, however, nylon is often used in electromechanical applications, such as coil forms, wire jackets, cable clamps, and switches. It is generally used below 500 V and 400 Hz.

4. When exposed to elevated temperatures, unmodified nylons undergo molecular weight degradation, which results in loss of mechanical properties. Unstabilized nylons can withstand continuous exposure to 65°C (149°F), but incorporation of a heat stabilizer system permits long-term performance at elevated temperatures up to 140°C (284°F).

5. Nylons have poor ultraviolet (UV) and weathering characteristics. Discoloration and embrittlement occur upon extended exposure. The effect of radiation can be reduced by the use of UV absorbers and other additives, which extend the useful life of the nylons.

6. Nylons are not resistant to strong acids, hydrogen peroxide, and phenol. They are also attacked hydrolytically by hot water.

7. Most nylons are not compatible with double- and triple-base propellants when stored in direct contact with each other at slightly elevated temperatures, 65.5°C (150°F), and in extended storage, 1 yr.

8. Because of the crystallinity and sharp melting points of nylons, their melting behavior requires special consideration in the mold design, especially the design of hot runners, the heated passageways in the mold that convey the melt from the injector to the mold cavity. High crystallinity also results in high mold shrinkage and thus makes close tolerances more difficult to achieve.

9. Nylons are notch sensitive.

10. Nylons have a low melt viscosity; therefore, blow molding of nylons is very difficult. They require much attention in order to achieve the right temperature. The best results can be obtained by using additives that strengthen the parisons.

2-5 COMPARATIVE PROPERTIES— NYLON TYPES

2-5.1 INTRODUCTION

The comparative properties, advantages, and limitations of the various nylons are summarized in this paragraph. All nylons exhibit many similar properties, so the choice is often dictated by economic and processing conditions. All of the commercially available major and minor types are thermoplastic. Nylon 6/6 possesses the greatest hardness and rigidity and the highest resistance to abrasion and heat deformation.

With respect to toughness, nylon 6/6 is the least tough, and

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nylon 12, the most tough. The rising order of progression is 6/6, 6, 6/10, 6/12, 11, and 12. Generally, the more carbon atoms or the lower the concentration of amide groups, the greater the toughness, impact strength, thermal expansion, and stress-crack resistance, and the lower the water absorption (which gives better dimensional stability) and melting point. Nylons in which the amides are separated by an even number of carbon atoms melt at higher temperatures than those of similar amide concentration with an odd number of carbon atoms. On the other hand, the highly crystalline (40 to 50% crystalline) polyamides, such as nylons 6/6, 6/10, and 6, having regular structures permit good chain alignment and a high degree of hydrogen bonding in the plane of the molecular chains and hence exhibit excellent mechanical behavior with high tensile and yield strengths, high elastic and shear moduli, high hardness, and excellent abrasion resistance.

2-5.2 MAJOR AND MINOR TYPES

Some of the limitations and outstanding properties of the major and minor nylon types follow:

1. *Nylon 6/6* (polyhexamethylene adipamide), melting point of 260°C (500°F). Nylon 6/6 is the most widely used nylon type. It is the strongest of the most popular types and has the highest tensile strength, flexural modulus, and heat resistance over the widest temperature range of the unfilled nylon types. Along with type 6, it is the cheapest of all nylon types, but it absorbs less moisture than nylon 6 and is about 25% stiffer. Nylon 6/6 also has the lowest permeability rate of the nylons to petroleum, mineral oil, and fluorocarbon refrigerants. It is the most sensitive of all nylon types to ultraviolet and oxidative degradation, but it has good weatherability when pigmented with carbon black. It also has lower resistance to weak acids than types 6/10, 6/12, 11, and 12. Type 6/6 parts made to high precision or close tolerances are difficult to mold because of high mold shrinkage.

2. *Nylon 6* (polycaprolactam), melting point of 220°C (428°F). Nylon 6 is as structurally sound as nylon 6/6 at room temperature but has the highest moisture absorption of any type with the attendant dimensional stability and undesirable changes in electrical and mechanical properties. It also loses strength more rapidly than nylon 6/6 as the temperature increases. Nylon 6 is less crystalline than nylon 6/6. Thus mold shrinkage is lower, and closer tolerances are possible. Nylon 6 is the best nylon choice for parts that must be shockproof even at subzero temperatures. Nylon 6 can also be self-plasticized with its monomer to yield a tougher, softer, and more ductile material than nylon 6/6 is. Such modification, however, results in higher water absorption. When dry, nylon 6 has low impact strength and ductility. Its resistance to weak acids is low compared to nylons 6/10, 6/12, 11, and 12.

3. *Nylon 6/10* (polyhexamethylene-sebacamide), melting point of 215°C (419°F). Nylon 6/10 absorbs about one-half as much water as nylon 6/6 and one-third as much as nylon 6 and therefore has smaller property and dimensional changes and better electrical properties over a wide humidity

range. It is less crystalline than nylon 6/6, so it is more flexible and has a very low embrittlement temperature. It is a good material for molding precision engineering parts.

4. *Nylon 6/12* (polyhexamethylene-dodecanoamide), melting point of 212°C (414°F). Nylon 6/12, like 6/10, retains its physical and electrical properties over a wide humidity range. It is about 12% stiffer, shows better heat resistance, and is lower in cost than type 6/10, which it is gradually replacing. Its properties are between those of types 6/6 and 6, and it has slightly better creep properties under moist conditions. Nylon 6/12 is also a good material for molding precision engineering parts.

5. *Nylon 11* (11-aminoundecanoic acid), melting point of 190°C (374°F). Nylon 11 has very low water absorption, a low specific gravity (density) of 1.03, and relatively high impact strength. When fully plasticized, it is especially shock resistant and for most practical purposes is unbreakable. However, it has inferior mechanical properties compared to other nylons but superior electrical properties and dimensional stability. It also maintains its hardness and abrasion resistance over useful temperature ranges. The properties of nylon 11 are intermediate between those of nylon 6 and polyethylene, and its cost is higher than that of nylons 6/10 and 6/12.

6. *Nylon 12* (poly(11-aminododecanoic acid)), melting point of 175°C (347°F). Nylon 12 is similar to nylon 11. It has the lowest specific gravity (density), i.e., 1.01, water absorption, and melting point of the commercially available nylons. It has properties that are similar to those of the olefins, e.g., low-temperature flexibility. There is no embrittlement at -78.9°C (-110°F). Because of its low water absorption, it has good electrical and dimensional stability. It has lower strength than types 6/10, 6/12, and 11, and its maximum service temperature is lower than that for types 6/6, 6/10, and 6/12. The cost of nylon 12 is higher than that of types 6/10 and 6/12 and slightly less than that of type 11.

2-5.3 OTHER COMMERCIALY AVAILABLE TYPES

2-5.3.1 Cast Nylon 6

By using cast nylon 6, complex parts with large sections can be processed economically in small batches. The nylon-monomer casting process provides the designer great latitude in applications that may be too difficult or too expensive by extrusion or molding methods. Cast nylon 6 also offers some property advantages over extruded and molded nylon 6. These advantages are a result of its higher molecular weight and crystallinity and include higher modulus of elasticity, higher deflection temperature, improved solvent resistance, lower moisture absorption, and better dimensional stability. (See par. 2-7 for comparisons.) Cast nylon 6, however, shows the lowest ductility of the unfilled types, and the high crystallinity results in such high shrinkage that the dimensional tolerances are inferior to those of injection-molded parts. The casting process also introduces high internal stresses that must be relieved before machining the part or placing it in use.

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Additives, such as pigments and various insoluble fillers, present a processing problem because it is difficult to achieve a homogeneous dispersion during manufacturing. Many commercial dyes or colorants cannot be used because they are soluble in the melt, have little resistance to chemical attack, are unstable at the operating temperatures involved, or because they have adverse effects on the polymerization cycle.

2-5.3.2 Copolymers

Copolymerization is a familiar route to a lower melting point, a lower modulus, and increased solubility, e.g., types 6/6 and 6 copolymers have higher elongation and impact strength than general-purpose types 6/6 and 6. These copolymers also cost less than types 6/10, 6/12, 11, and 12. The types 6/6 and 6 flexible copolymers, however, are less resistant to weak acids than types 6/6 and 6. These copolymer types and nylon 12 show lower maximum service temperatures than those shown for 6/6, 6, 6/10, and 6/12, and they are not self-extinguishing. The most commercially significant copolymers are nylons 6/66 and 6/610.

2-5.3.3 Transparent Nylons

Transparent nylons process readily; show lower shrinkage values than other nylons; exhibit good impact, stress-crack, and crazing resistance; and are rigid. Moisture absorption is low and comparable to the values for types 6/10 and 6/12. These nylons possess good dimensional stability and electrical properties when compared with other nylons; however, they exhibit lower deflection temperatures, scratch resistance, and abrasion resistance. Transparent nylons are priced slightly below nylons 11 and 12.

2-5.3.4 Supertough Nylon

The impact strength of supertough nylon is dramatically higher than that of current modified, alloyed, and unmodified nylons 6/6 and 6. The impact performance of toughened nylon 6/6, unlike that of the other nylons, is unaffected by orientation, thickness, notch radius, or type of impact test. This nylon also exhibits ductile-type breaks rather than brittle fracture and has extremely low notch sensitivity. It has good chemical and heat resistance, processibility, and greater flexibility but has lower tensile strength than unmodified nylon 6/6.

2-5.3.5 Filled or Reinforced Grades

Filled or reinforced grades of nylon have greatly improved heat resistance, stiffness, yield strength, and creep resistance over their unmodified types. However, they exhibit lower impact strengths, brittle fracture, and in most cases higher specific gravities than their unfilled types. Also they lose much of their self-extinguishing properties. Good surface finishes on molded parts can be difficult to obtain with filled or reinforced nylon grades.

2-5.3.6 Pressed and Sintered Parts

Parts of controlled density and pore size can be produced from powder by the press and sinter process. The porosity, or density, of the part is controlled by the pressure used to com-

press the nylon powder. Parts produced by this process tend to be highly crystalline and to have good dimensional stability but less tensile and impact strengths than parts produced by standard injection molding. Impact-resistant varieties, however, are available, and their compressive strengths are in the same range as those of unmodified, injection-molded nylons. Sintered nylon parts are used in applications such as bearings, bushings, cams, and wear plates and provide performance superior to that of standard nylons because of the control over porosity, the ability to hold up to 50% by volume of lubricants, and the improved creep resistance and frictional characteristics provided by special fillers.

2-5.4 MISCELLANEOUS AND NEWER-TYPE NYLONS

A very large number of polyamides have been synthesized since Carothers first synthesized nylons 6/6 and 6/10, but very few of these have been evaluated as plastic materials. Also failure to specify test conditions, particularly the moisture content of the polymer, limits the usefulness of available data. The high cost of the raw material may also limit the use of a given polymer with desired properties. Miscellaneous nylons based on aliphatic-base units, those based on aromatic (ring) units, and other transparent nylons are summarized in the subparagraphs that follow.

2-5.4.1 Nylons Based on Aliphatic-Base Units

Nylons based on aliphatic-base units include

1. *Nylon 3* (polypropiolactam), melting point $> 320^{\circ}\text{C}$ (608°F). This is a type of nylon that has been prepared and explored experimentally but has not yet been used commercially.
2. *Nylon 4* (polypyrrolidone), melting point of 260°C (500°F). This is a polymer of 2-pyrrolidone. Early attempts to commercialize nylon 4 failed because much of the material was of low molecular weight and decomposed at a relatively low temperature; thus it was unsuitable for melt spinning. The polymer resulting from improved catalyst systems has a molecular weight of about 400,000 and a melting point of 265°C (509°F). The newer nylon 4s have good heat stability, but their moisture absorption is higher than that of nylons 6 and 6/6. Nylon 4 can be molded and extruded.
3. *Nylon 7* (polyenanthalactam), melting point of 235°C (455°F). This type of nylon is known commercially in the Commonwealth of Independent States as "Enant", and it is not yet produced in commercial quantities in the U.S. Production can be by the polymerization of enantholactam or by the melt polycondensation of 7-aminoheptanoic acid. Its properties are similar to those of nylon 6, but it has better heat resistance and lower monomer content.
4. *Nylon 8* (polycapryllactam), melting point of 200°C (392°F). This type of nylon is made by polymerization of capryllactam. Its low melting temperature and high cost of raw material have limited its usefulness. Nylon 8 should not be confused with a type of nylon marketed as "Type 8", which is actually a chemically modified nylon 6/6.

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5. *Nylon 9* (polypelargonamide), melting point of 209°C (408°F). This nylon is made by melt condensation of aminopelargonic acid or by more recent techniques derived from 9-aminononanoic acid. Nylon 9 has attractive properties. It offers tensile yield and flexural strengths approaching those of nylon 6 and has low water absorption, which closely approaches that of nylons 11 and 12. It is, however, in limited use.

6. *Nylon 10*, melting point of 188°C (370.4°F). This is an experimental polymer prepared from aminodecanoic acid. Research on this polymer has been limited due to difficulties in preparing the monomer.

7. *Nylon 6/9*, melting point of 215°C (419°F). This type is synthesized analogously to nylon 6/6, i.e., mostly by a discontinuous process. The dicarboxylic acid required is azeloic acid, which is from oleic acid.

8. *Nylon 13/13*, melting point of 174°C (345°F). Nylon 13/13 is synthesized by the batch process described for nylon 6/6. The dicarboxylic acid required is brassylic acid derived from crambe seed oil, and the 13-carbon diamine is made from brassylic acid (tridecanedioic acid).

2-5.4.2 Nylons Based on Aromatic (Ring)-Base Units

Departing from the traditional nylons that were based on aliphatic-base units and referred to with numbers indicating the number of carbon atoms, Dynamit Nobel introduced a transparent polyamide based on aromatic (ring)-base units in the early 1970s. The first such nylon, Trogamid T™* (TMDT), is made by polycondensation of terephthalic acid with a (1:1) mixture of 2,4,4- and 2,2,4-trimethylhexamethylene-1,6-diamine. This crystal-clear, amorphous polyamide has low mold shrinkage, good retention of properties in water up to 80°C (176°F), excellent resistance to stress cracking, and a glass transition temperature comparable to that of polycarbonates. Abrasion resistance and solvent resistance, however, are reduced below those of other nylon plastics.

Other aromatic nylons consist of the xylylene-diamines, MXD6 (from *meta*-xylylene-diamine and adipic acid) and HPXD8 (from *trans*-hexahydro-*para*-xylylene-diamine), which are potentially available at low cost, and attempts to capitalize on this situation are reasonable. MXD6 can be either transparent and amorphous or opaque and crystalline, depending on molding conditions and subsequent annealing. Inclusion of a ring in the polymer chain adds rigidity and thus raises the glass transition temperature, but it also results in increased melt viscosity, which can impair melt fabrication.

A crystal-clear polyamide reportedly based on terephthalic acid with the isomeric bisaminomethylboranes and up to 70% ϵ -caprolactam is available from Hoechst Celanese, and a Phillips Petroleum version copolyamide, PACP 9/6, is made from a 60:40 mixture of azeloic acid and adipic acid with the diamine. Atochem, Inc., has developed an amorphous poly-

amide, Rilsan N™*, believed to be a modification of nylon 11.

2-6 DISCUSSION OF PROPERTIES OF NYLONS

This paragraph discusses general physical properties prior to presentation of the detailed quantitative values for the various nylons given in par. 2-7. Primarily the discussion uses the properties of nylon 6/6. Information is given on mechanical properties, durability, and electrical, thermal, and optical properties.

2-6.1 MECHANICAL PROPERTIES AND DURABILITY

2-6.1.1 Introduction

The basic strength measures of a material including tensile, compressive, bending, and shear strengths must be understood by the designer before using any engineering material in an application. For plastics, especially nylon, it is essential to remember that most of the material characteristics change to some degree based on environmental factors, especially moisture content (Ref. 24). Factors that must be considered in application of nylons (or any other material) are listed in Table 2-5. These factors must be considered to the degree appropriate for the property and the intended application and as permitted by available information. The mechanical properties—whether in tension, compression, flexure, or shear—are time dependent. A second set of measured properties that incorporate this time dependence is used to characterize the material, e.g., creep, tear resistance, etc.

2-6.1.2 Strength and Stiffness

The strength and stiffness properties of nylon resins are different than those of other engineering materials. The level of strength that can be withstood depends on the length of

TABLE 2-5. FACTORS AFFECTING MECHANICAL BEHAVIOR OF NYLON (Ref. 5)

Material Factors

- Chemical structure
- Molecular weight
- Presence of modifiers
- Moisture content
- Physical structure (crystallinity, morphology, and orientation)

Environmental Factors

- Temperature
- Relative humidity
- Solvents or other chemicals

Stress Factors

- Nature of stress (tension, compression, flexure, or shear)
- Rate of loading
- Duration of stress

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time the force is applied and the past environmental conditions to which the material was exposed.

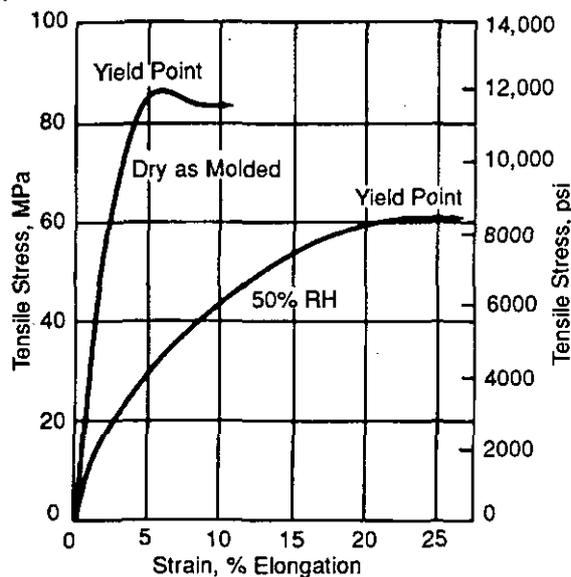
The most widely quoted mechanical property is tensile strength, but it is a single value of varying significance that can correspond to either yield or fracture. The tensile strength is a single-point approximation for the actual nonlinear stress-strain curve. As such, it is a poor substitute for the complete curve.

2-6.1.2.1 Stress-Strain Behavior of Nylon 6/6

Humidity and temperature affect the strength and stiffness of nylon. Fig. 2-1 illustrates the effects of moisture on nylon 6/6. Complete stress-strain curves are shown at 0 and 100% relative humidities (RH). Figs. 2-2 and 2-3 show water absorption and moisture content data for typical nylon 6/6. In general, increasing humidity increases the flexibility of nylon (lowers the modulus of elasticity) and toughness but reduces the yield and tensile strengths.

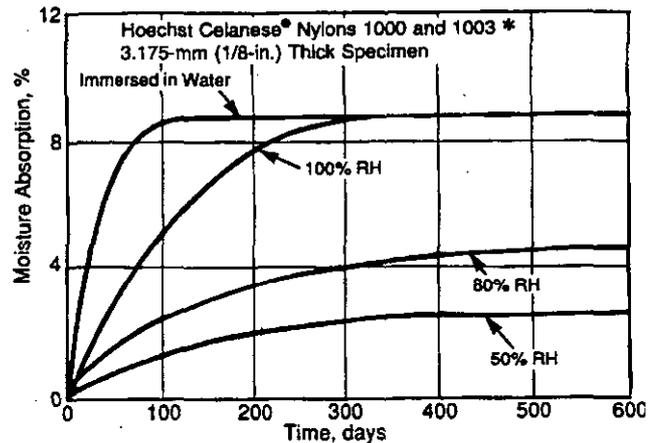
Fig. 2-4 shows the temperature effects on the stress-strain characteristics of a modified dry nylon 6/6. Fig. 2-5 shows similar temperature data for unmodified nylon 6/6 at 50% RH. Fig. 2-6 shows the effect of temperature on tensile yield strength. Higher temperatures result in lower tensile yield strength values as well as lower yield stress values. Yield stress is more important in design than tensile strength is since dimensional stability is usually required. Once a part undergoes permanent deformation, failure is usually implied. Fig. 2-7 shows the effects of temperature and moisture content on the yield point of nylon 6/6.

The rate at which nylon is stressed may have a significant effect upon its strength. Fig. 2-8 shows that the yield strength of nylon 6/6 increases slightly with the rate of loading (Ref. 24).



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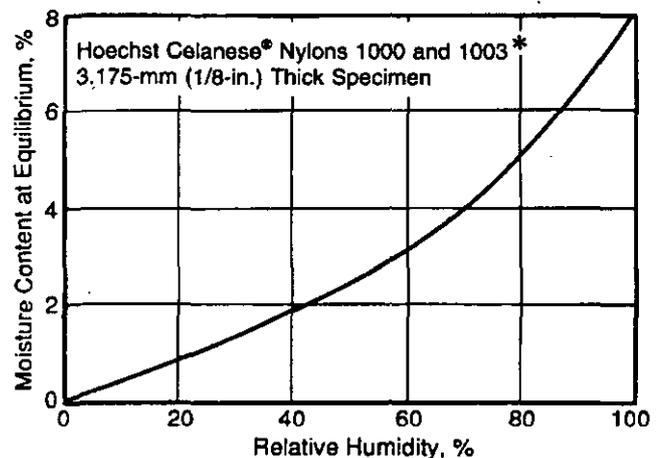
Figure 2-1. Tensile Stress-Strain Data for Zytel® 101 (Nylon 6/6) at 23°C (73°F) (Ref. 24)



* Nylon 6/6, Regular and Heat-Stabilized

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Figure 2-2. Rate of Water Absorption for Nylon 6/6 at 23°C (73°F) (Ref. 25)

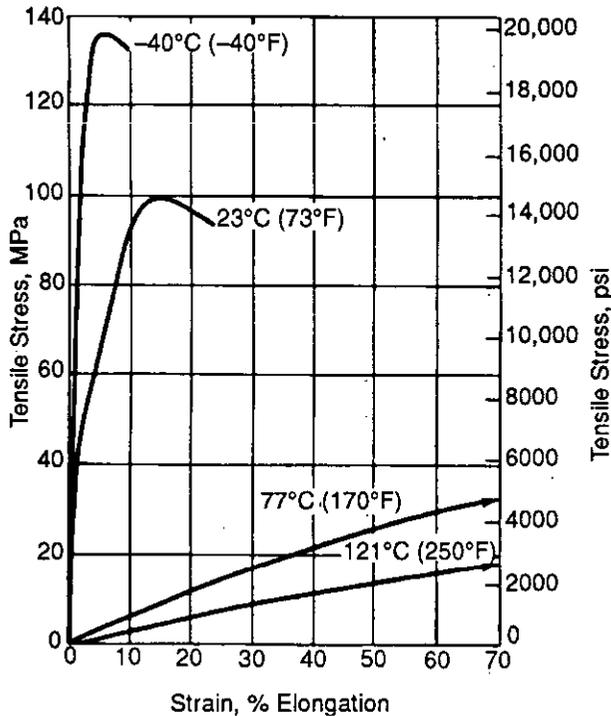


* Nylon 6/6, Regular and Heat-Stabilized

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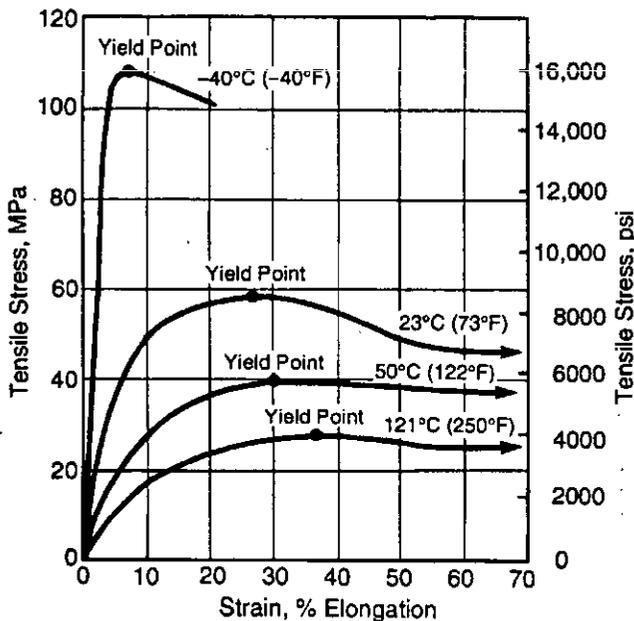
Figure 2-3. Equilibrium Moisture Content vs Relative Humidity for Nylon 6/6 at 23°C (73°F) (Ref. 25)

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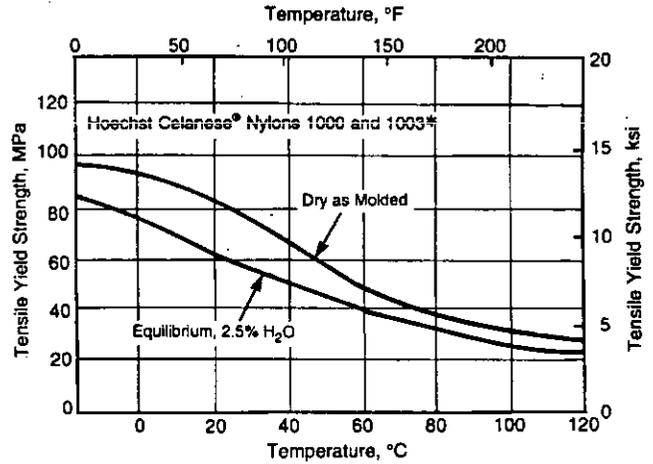
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Figure 2-4. Tensile Stress-Strain Data for Zytel® 133L (Nylon 6/6, Lubricated and Highly Nucleated) Dry as Molded (Ref. 24)



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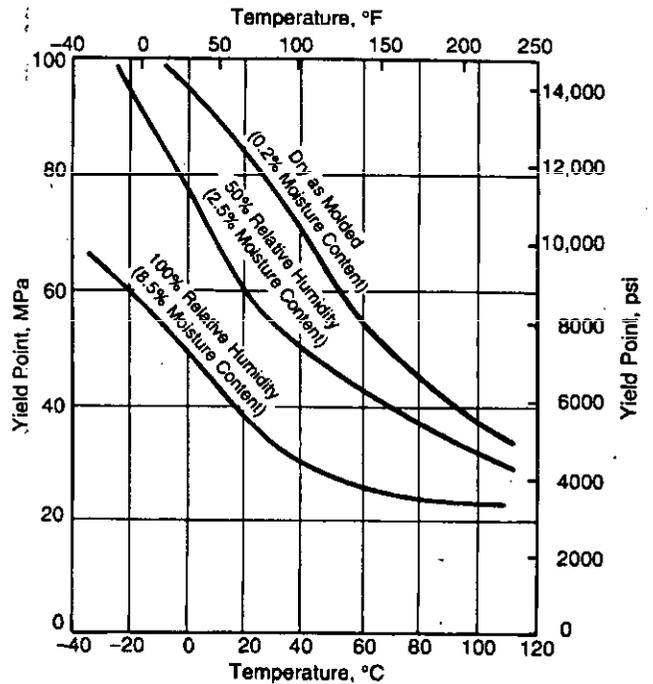
Figure 2-5. Tensile Stress-Strain Data for Zytel® 101 (Nylon 6/6, Not Heat Stabilized) at 50% RH at Four Temperatures (Ref. 24)



* Nylon 6/6, Regular and Heat-Stabilized

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Figure 2-6. Effect of Temperature on Tensile Yield Strength of Nylon 6/6 (Ref. 25)



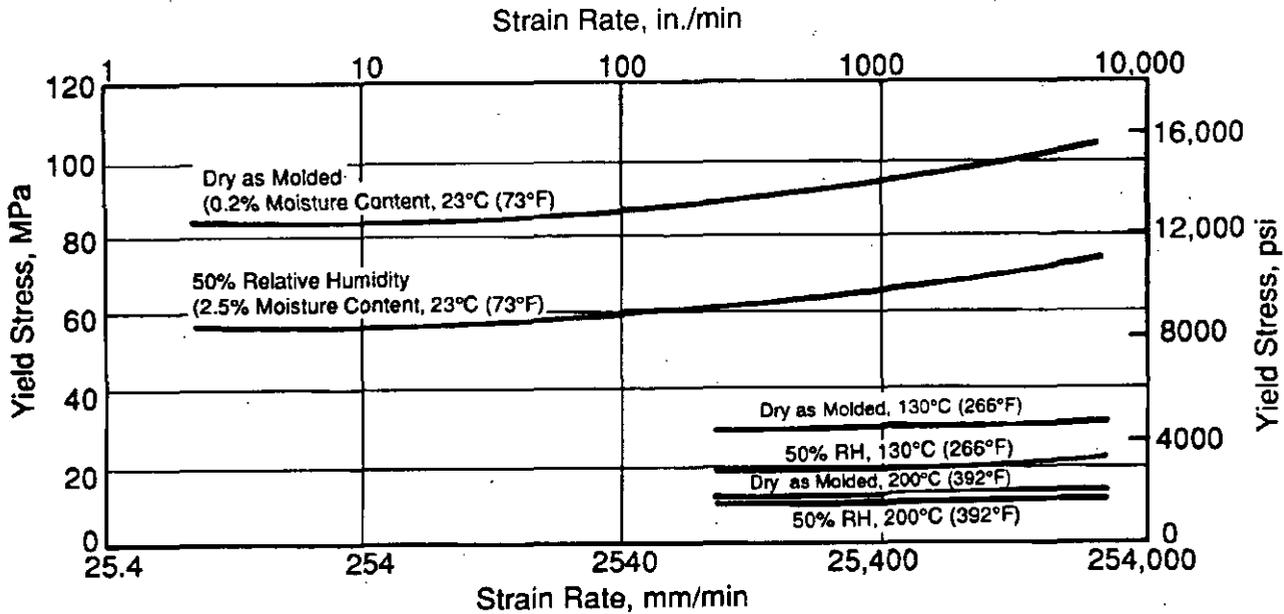
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Figure 2-7. Yield Point of Zytel® 101 (Nylon 6/6) vs Temperature and Moisture Content (Ref. 24)

2-6.1.2.2 Tension and Compression

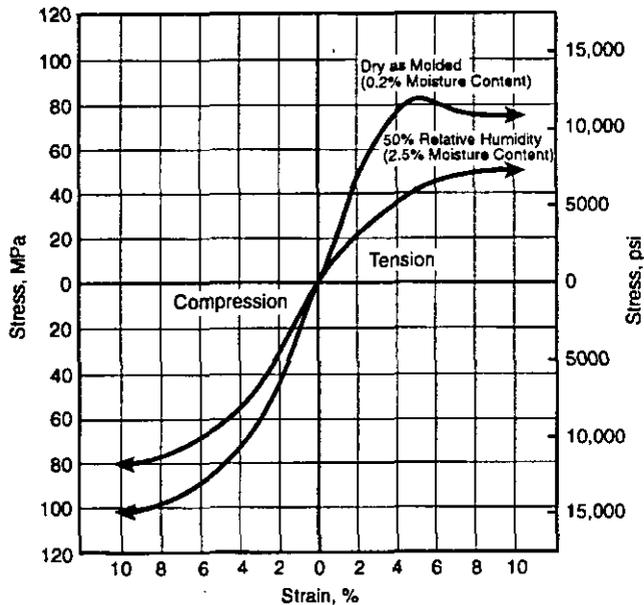
The stress-strain behavior of nylon in tension is different from what it is in compression. The data in the preceding subparagraph are for tension. Fig. 2-9 shows the stress-strain relationship for nylon 6/6 resin at 23°C (73°F) in both posi-

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Figure 2-8. Yield Stress Data for Zytel® 101 (Nylon 6/6) vs Strain Rate and Temperature (Ref. 24)



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Figure 2-9. Stress-Strain in Tension and Compression of Zytel® 101 (Nylon 6/6) at 23°C (73°F) (Ref. 24)

tive and negative tension. At high stress levels the strain in compression is less than it is in tension. For all practical purposes, however, the tensile and compressive stress-strain curves are identical at low stress levels. Therefore, at low strain the compressive modulus is equal to the tensile modulus. At higher stress levels the designer must consider whether the stress in his application is compressive or tensile.

2-6.1.2.3 Modulus of Elasticity

The elastic modulus of nylon may be specified for tension, compression, and flexure but is more commonly specified for flexure because of the greater likelihood of a bending stress during use. The elastic modulus in tension is about equal to its value in compression, especially at low stress levels. The flexural modulus may be about 20% lower because the flexural test emphasizes the flexural behavior of an object and is more dependent on the properties of the material at the surface than at the core of the object. The surface of nylon is less crystalline than the core and therefore has a lower modulus.

Data on the modulus of elasticity under the specific environmental conditions of moisture and temperature are given for nylon 6/6 in Fig. 2-10.

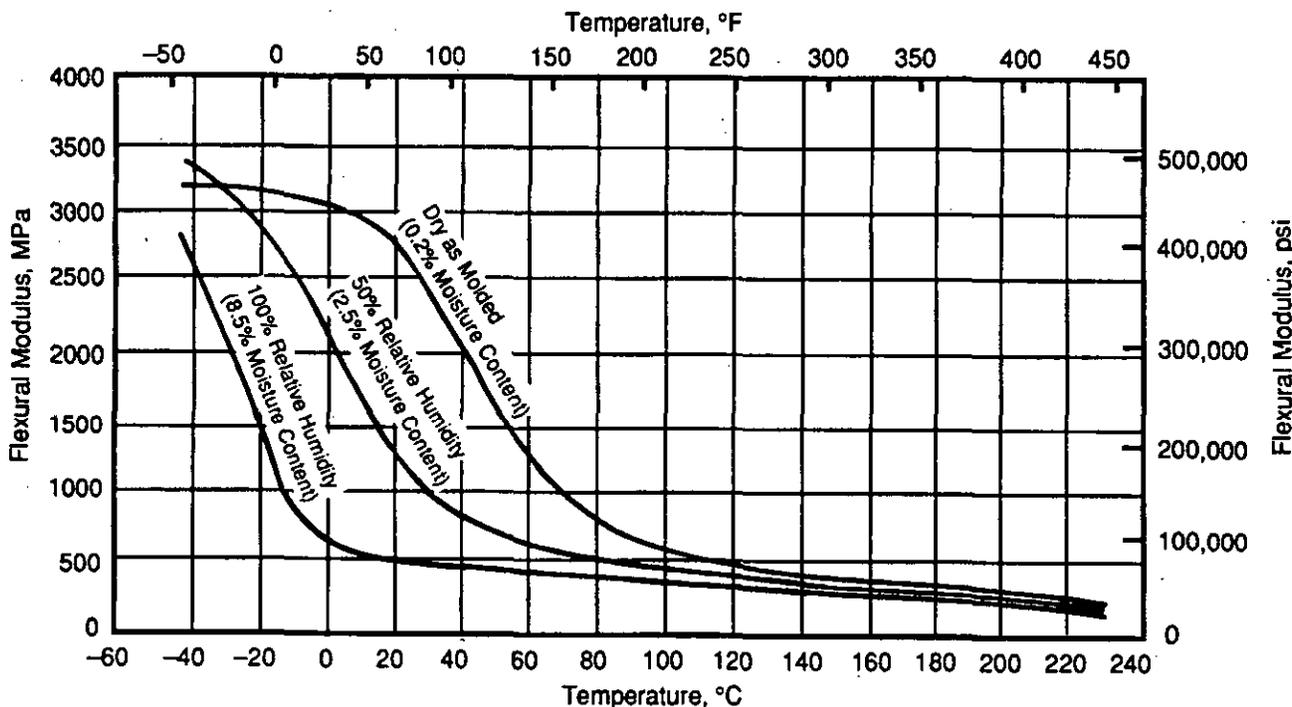
2-6.1.3 Fatigue Resistance

Repetitious application and release of stress usually cause failure of a material at stress levels below the normal tensile strength, and this failure is referred to as fatigue. The fatigue failure phenomenon has been well studied and characterized for metals, but the same considerations apply to plastics. In plastics, fatigue failure occurs in gears or in parts subject to vibration, cyclic loading, or flexure (Ref. 26).

Nylon fatigue characteristics are affected by environmental conditions. Thus, during design, proper consideration must be given to environmental conditions and to the nature of the stress in the application. Actual or realistically simulated end-use testing of a part in service is the best method by which to evaluate material performance for a specific application.

Fatigue characteristics for nylon can be obtained by using a Sonntag-Universal machine. A cylindrical test sample with a formed neck-down region is mounted in the machine between two clamping fixtures. An axial, oscillating force with

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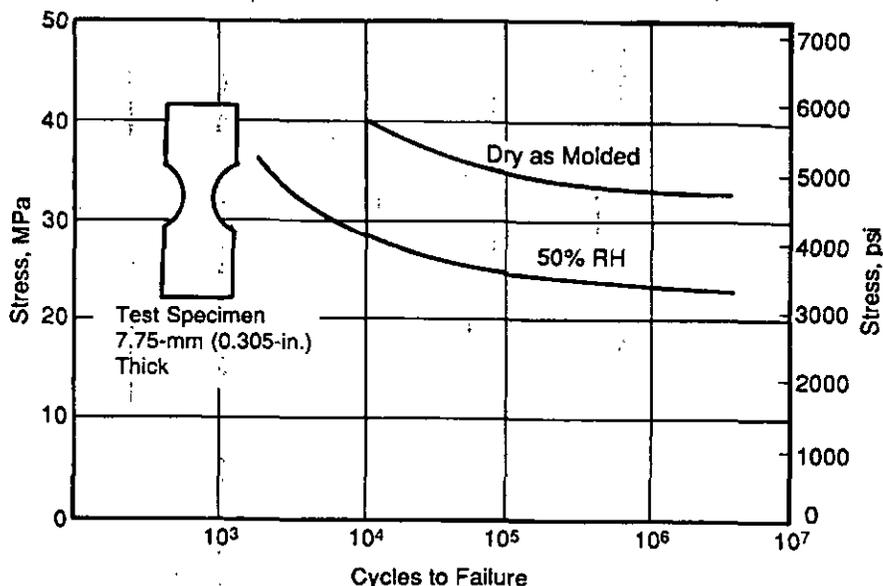


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Figure 2-10. Flexural Modulus of Zytel® 101 (Nylon 6/6) vs Temperature at Various Moisture Contents (Ref. 24)

a frequency of 30 Hz is applied to the sample through the clamps. This oscillatory force may be biased to test the sample under compression, under tension, or for a more severe test to alternate between compression and tension at the 30-Hz cyclic test rate. The samples are tested until failure occurs. The recorded data include the environmental conditions of the test, the applied stress level and type (compressive, ten-

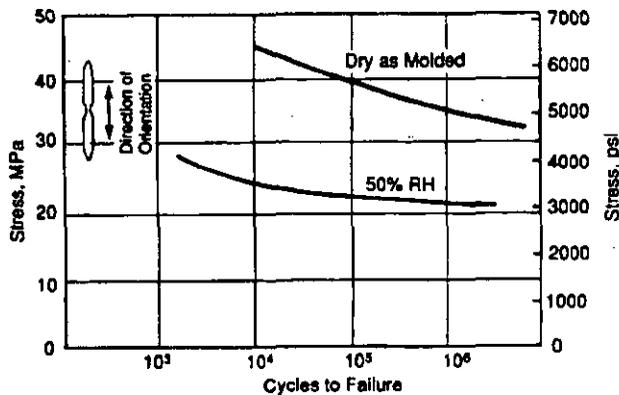
sile, or alternating), and the number of stress cycles the sample withstands before failure. Fig. 2-11 shows the results of a series of tests on nylon 6/6 at different stress levels for both dry and 50% RH conditions. Note the higher stress level that can be withstood by the dry samples. Fig. 2-12 provides similar data for nylon 6/6 resin under cyclic axial stress alternating between tension and compression.



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Figure 2-11. Flexural Fatigue Data for Zytel® 101 (Nylon 6/6) Using Sonntag Machine at Constant Stress and 1800 cycles per minute at 23°C (73°F) (Ref. 31)

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Figure 2-12. Axial Fatigue of Zytel® 101 (Nylon 6/6) With Alternate Tension and Compression Using Sonntag Machine at 1800 cycles per minute and 23°C (73°F) (Ref. 31)

Fatigue endurance data give the designer insight into the useful life expected of a material subjected to repeated loading (Ref. 27). The data are generally expressed for plastics as the stress level at which failure occurs after one million cycles, but they may be extrapolated to determine the number of cycles that can be withstood for any specified stress level.

Materials used in military vehicles, weapons, engineer equipment, and machinery must exhibit good fatigue endurance behavior at elevated temperatures and in the presence of such materials as oils, greases, gasoline, and detergents. The fatigue endurance limits of nylon 6/6 do not change significantly over the temperature range of 23 to 100°C (73 to 212°F). Tests on samples of nylon 6/6 conditioned in a variety of detergents showed that no loss of fatigue endurance resulted from these exposures. Prolonged conditioning of nylon 6/6 in gasoline vapors has no harmful effect on its fatigue endurance (Ref. 24).

For moderate repetition rates the fatigue endurance of nylon 6/6 does not depend on the cycle rate.

Experimental work has revealed that cyclic application of stress below 1800 cycles per minute has little effect on the fatigue properties. At higher rates, however, heat generated from the energy loss in the material might affect the properties of the material.

Nylons are superior to metals for applications in which low-level vibrations dominate. Metals can withstand higher repeated stresses than nylons, but because metals are stiffer and less yielding, failure can occur at very small repeated strains. Under the same amount of strain, nylon will have at a much lower stress and will perform satisfactorily. If designed correctly, nylon can be a more durable material for gears, tubing, and parts of vibrating machinery than metals.

2-6.1.4 Impact Resistance—Single Blow

Impact resistance is a measure of the toughness of a material or the ability of a part to absorb the force of impact. The

impact resistance of a molded part is difficult to predict because the shape of the part affects the distribution of stress and strain throughout the part. Consequently, good physical design, especially in terms of generous radii for all sharp corners, and appropriate material selection are important in high-impact applications.

Designing flexibility into the part greatly improves impact resistance. Thin-walled, flexible pieces such as round coil structures represent proper design for impact resistance because they are difficult to break on impact. Conversely, designs incorporating rigid corners are not as tough because they concentrate stresses and cannot “give” with the blow.

The impact resistance of materials can be determined by a variety of test procedures. Factors such as rate of loading and physical configuration (notch effect) have important effects on measured impact resistance. The tensile-impact-energy-to-break test is described in American Society for Testing and Materials (ASTM) D 1822 (Ref. 28). This procedure determines the energy required to break a flat test specimen by using a calibrated pendulum while subjecting the test specimen to a tensile stress at a high strain rate. Either a short specimen (for greater reproducibility) or a long specimen (for better material differentiation) can be used. A possible problem with the procedure is that it is machine dependent, i.e., the results of tests run on a large capacity machine may differ from those run on a low capacity machine. Tensile impact values of both long and short specimens of nylon 6/6 that are dry and moisture conditioned at 23°C (73°F) are shown in Table 2-6.

The impact resistance of nylons increases with increasing temperature and moisture concentration. Moisture makes the nylon part more flexible; consequently, the conditioned part will absorb more energy before breaking. Also the flexibility of nylon increases as the temperature increases from room temperature to 66°C (150°F). At room temperature and below, down to -40°C (-40°F), the impact resistance of nylons does not change significantly.

“Brittleness temperature”, as measured by ASTM D 746 (Ref. 29), is the temperature at which 50% of test specimens

TABLE 2-6. TENSILE IMPACT STRENGTH OF NYLON 6/6 (ASTM D 1822) (Ref. 24)

CONDITION AND SPECIMEN	TENSILE IMPACT STRENGTH, kJ/m ² at 23°C (ft·lb/in. ² at 73°F)	
Dry as molded		
L*	504	(240)
S**	158	(75)
At 50% RH		
L*	1470	(700)
S**	231	(110)

*L = long

**S = short

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fail when subjected to a specified impact. It is an indicator of the low-temperature performance of the material but is not necessarily the lowest temperature at which the material may be used. The test has been used extensively for tough, flexible materials such as nylon. The brittleness temperature of nylon 6/6 is shown in the dry-as-molded (DAM) state and in the moisture-conditioned state in Table 2-7.

"Izod impact", as measured by ASTM D 256 (Ref. 30), determines the energy required to break a precisely formed, notched specimen. The notch has a 0.25-mm (0.010-in.) radius at the bottom of the groove and is placed on the opposite side from impact and thus causes the notched side to be under tension during impact. The energy necessary to fracture bar-type material specimens depends on the surface condition of the sample, i.e., the presence of cracks, which tend to concentrate the stress. The addition of a "standard" notch for concentration of stresses improves the repeatability of the tests. Compared with a conventional impact test, the Izod impact value is indicative of the reduction in toughness that can be caused by part design, e.g., by failure to provide a generous fillet for a corner. Although this test has been a common physical test in the plastics industry, its value for actually measuring impact toughness is questionable. Because notched specimens are used, the test measures mainly notch sensitivity rather than the ability to withstand impact.

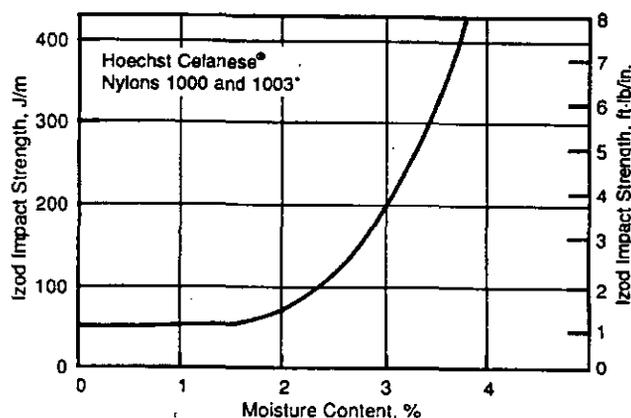
Table 2-8 presents the Izod impact values of nylon 6/6 for dry-as-molded and for conditioned bars. The effects of moisture content and temperature on the Izod impact strength of nylon 6/6 are shown in Figs. 2-13 and 2-14.

TABLE 2-7. BRITTLENESS TEMPERATURE OF NYLON 6/6 (ASTM D 746) (Ref. 24)

SPECIMEN CONDITION	LOW-TEMPERATURE BRITTLENESS,	
	°C	(°F)
Dry as molded	-80	(-112)
At 50% RH	-65	(-85)

TABLE 2-8. IZOD IMPACT OF ZYTEL® 101 AT 23°C (73°F) (ASTM D 256) (Ref. 24)

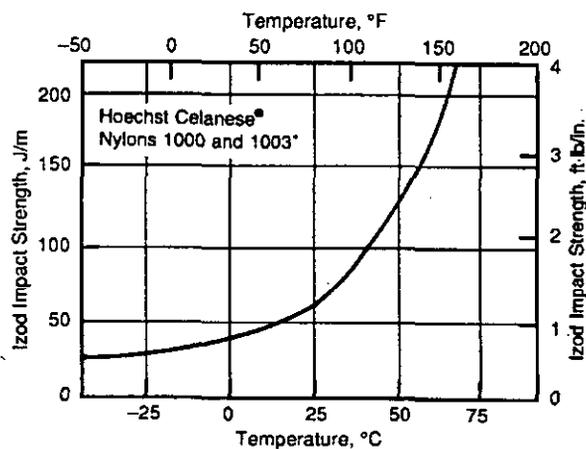
SPECIMEN CONDITION	IZOD IMPACT STRENGTH,	
	J/m	(ft-lb/in.)
Dry as molded	53	(1.0)
50% RH	112	(2.1)



Nylon 6/6, Regular and Heat-Stabilized

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Figure 2-13: Effect of Moisture Content on Notched Izod Impact Strength of Nylon 6/6 at 23°C (73°F) (Ref. 25)



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Figure 2-14: Effect of Temperature on Notched Izod Impact Strength of Dry-as-Molded Nylon 6/6 (Ref. 25)

2-6.1.5 Impact Resistance—Repeated Blows

Material data on resistance to repeated impacts are more meaningful than data on single-impact strength when selecting materials for many end-uses, such as striker plates in automobiles and appliances, boot heels, cams, and gear teeth. Repeated-impact data are more representative of actual service conditions than are data from the single-impact type of test, such as the Izod. As shown in Table 2-9, cellulose acetate butyrate has a high Izod value and good toughness in the single-impact roller test and thus would seem to be pre-

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**TABLE 2-9. REPEATED-IMPACT TEST
ON NYLON 6/6 AND CELLULOSE
ACETATE BUTYRATE (Ref. 24)**

MATERIAL	DISTANCE OF FALL				J/m (ft-lb/in.)	
	ONE BLOW, mm (in.)	REPEATED, mm (in.)	IZOD IMPACT, mm (in.)			
Zytel® 101	890 (35)	760 (30)	107	(2)		
Cellulose acetate butyrate	990 (39)	180 (7)	320	(6)		

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ferred over nylon 6/6 for high-impact applications, but under repeated impact nylon 6/6 is markedly superior to cellulose acetate butyrate. These tests were conducted using pipe-shaped test specimens, 18-mm (0.7-in.) outside diameter by 9-mm (0.35-in.) inside diameter, that were hit on the outer surface by a free-falling, 1.22-kg (2.7-lb) weight. The weight was dropped from various heights until the height was found that would cause a visible crack in one blow or 10 blows for repeated tests. The test was run in a room at 50% RH, but the actual moisture content of the nylon was 0.35%. (Ref. 24)

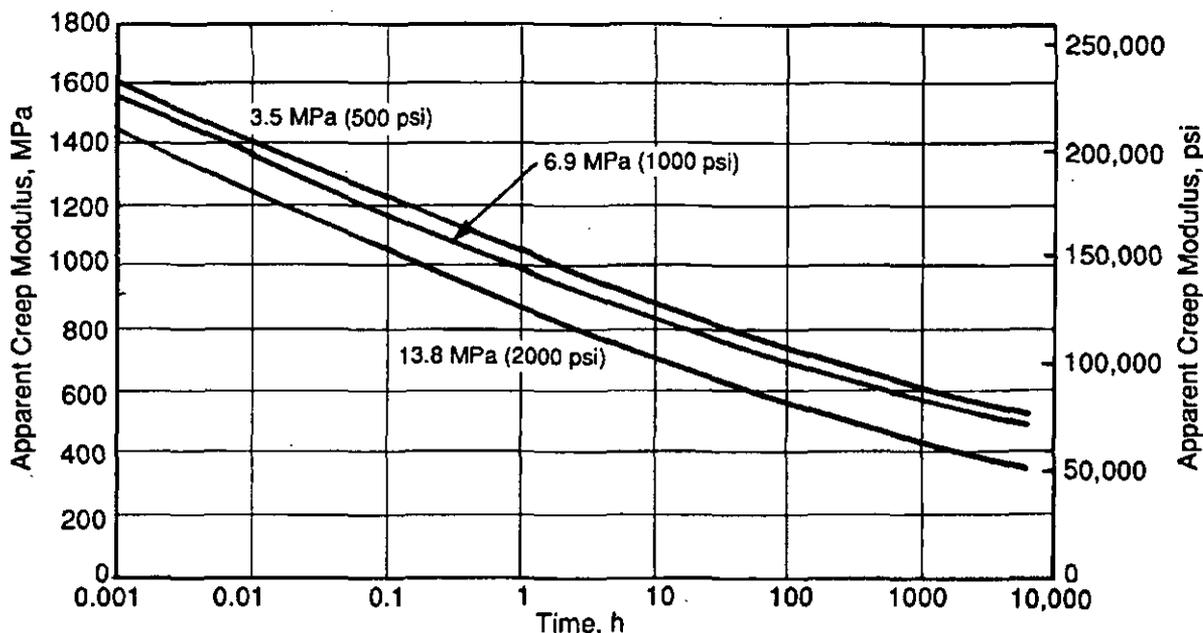
2-6.1.6 Creep: Long-Term Loads

When placed under load, all plastic materials initially deform some amount because of the elasticity of the material. With the continued application of constant loading, the material continues to deform with time. The sum of both deformations is called *creep*. Nylon composition, ambient temperature, stress level, and moisture content all affect the creep rate. The anticipated creep behavior of the particular nylon under the expected environmental conditions must be considered in the physical design.

Creep data can be graphed in a variety of ways. One popular format is the isochronous (equal time duration) stress vs strain, a family of curves, each curve of which relates the stress vs strain for a specified time interval. An alternate presentation is the graph of strain vs time for a specified level of loading.

Creep data for nylon 6/6 are shown in Figs. 2-15 through 2-19. All creep data presented in these figures were determined on test specimens 12.7 mm (0.5 in.) wide by 3.2 mm (0.125 in.) thick, freely supported at the ends on a 102-mm (4-in.) span and loaded in flexure at the center span.

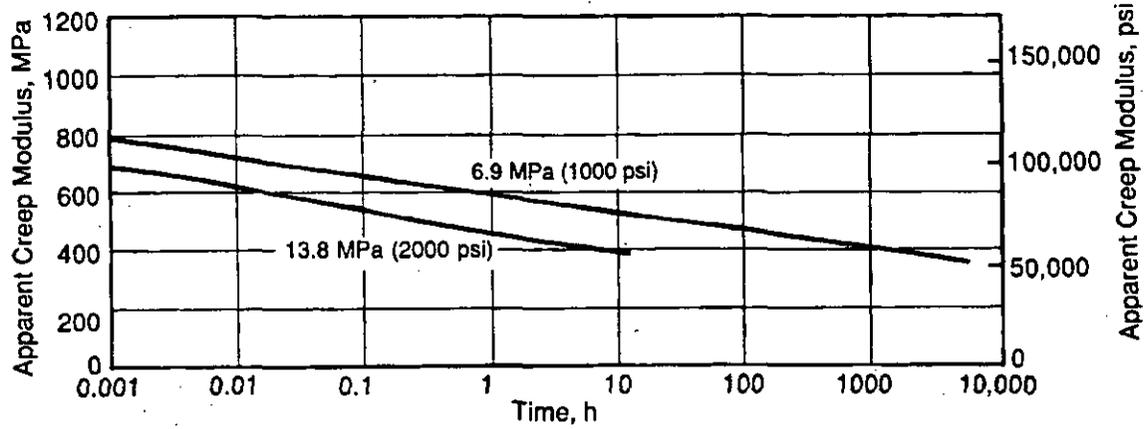
As stated, creep is the combination of the initial deformation (as predicted by Young's modulus) and the subsequent deformation that occurs from the continuously applied stress. The amount of initial deformation is dependent on the environmental conditioning of the material. Fig. 2-20 shows the change in the modulus with time of nylon that has equilibrated at 50% humidity and of nylon that is saturated with moisture.



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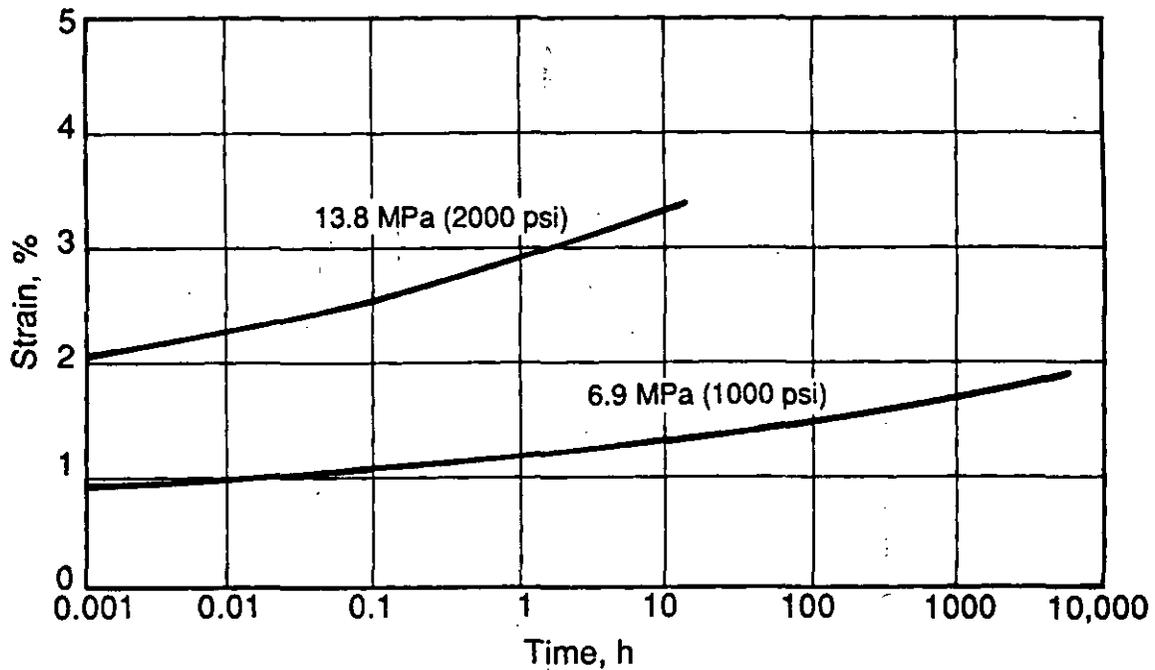
Figure 2-15. Creep in Flexure of Zytel® 101 (Nylon 6/6) at 23°C (73°F) (Ref. 24)

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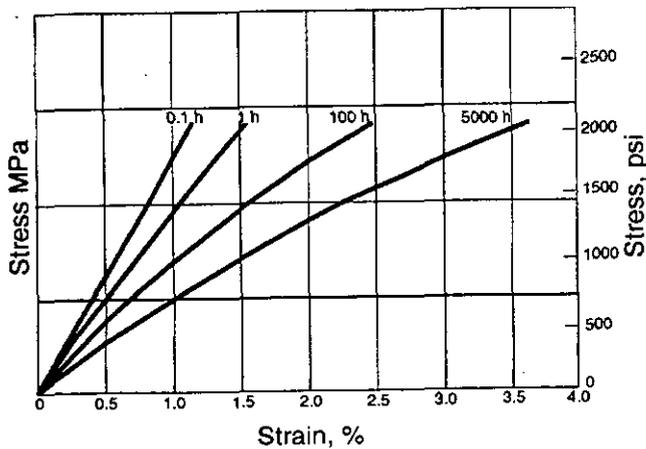
Figure 2-16. Creep in Flexure of Zytel® 101 (Nylon 6/6) at 60°C (140°F) and 50% RH (Ref. 24)



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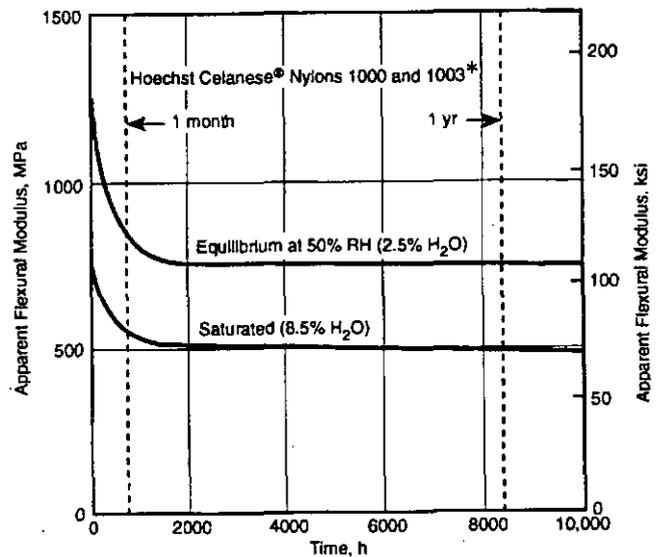
Figure 2-17. Strain in Flexure of Zytel® 101 (Nylon 6/6) at 60°C (140°F) and 50% RH (Ref. 24)

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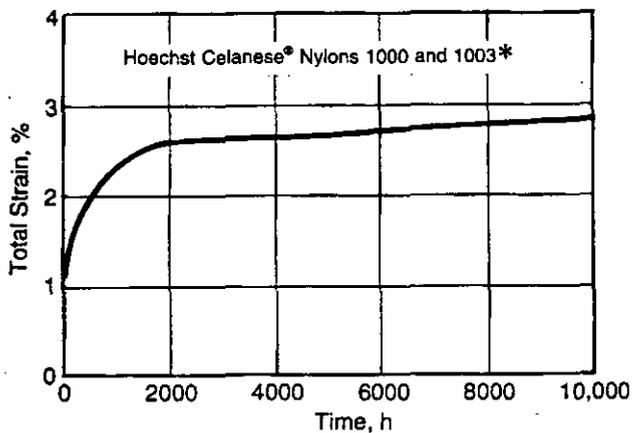
Figure 2-18. Isochronous Stress vs Strain in Flexure of Zytel® 101 (Nylon 6/6) at 23°C (73°F) and 50% RH (Ref. 24)



*Nylon 6/6, Regular and Heat-Stabilized

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Figure 2-20. Nylon 6/6 Apparent Modulus vs Time at 23°C (73°F) (Ref. 25)



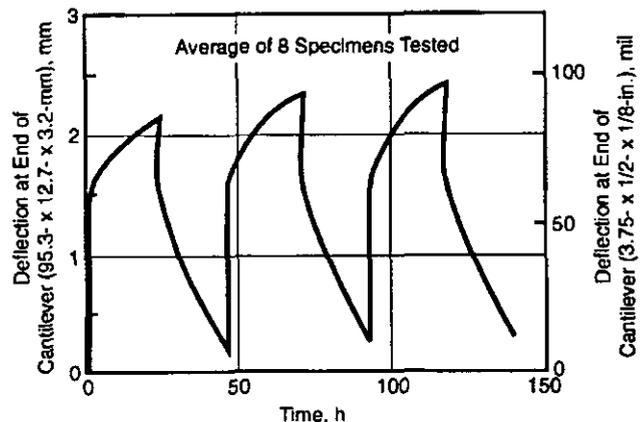
* Nylon 6/6, Regular and Heat-Stabilized.

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Figure 2-19. Tensile Creep of Nylon 6/6 at 20.7 MPa (3000 psi), 23°C (73°F), and 50% RH (Ref. 25)

2-6.1.7 Recovery From Cyclic Loading

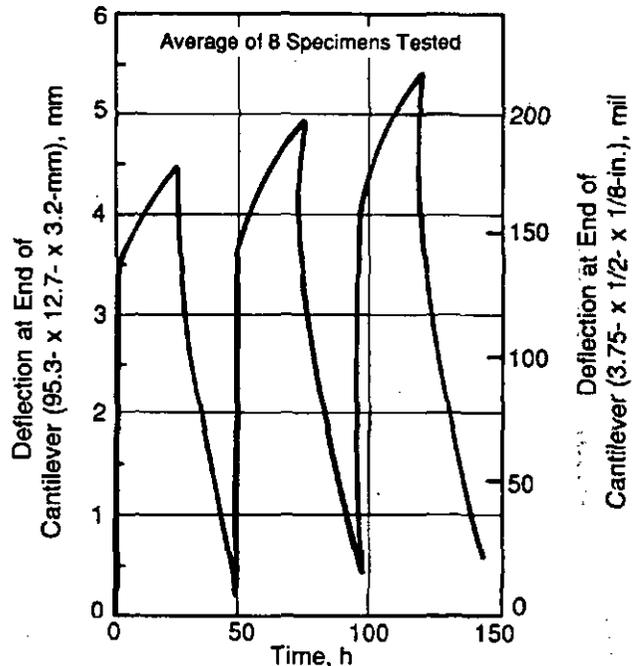
When a load is applied to nylon and then removed, there is an immediate, partial, elastic recovery followed by a time-dependent recovery. For small stresses, i.e., those well below the yield point, the amount of recovery is affected by the time under load, the stress level, the temperature, the nature of the environment, and the time allowed for recovery. Figs. 2-21 and 2-22 show the behavior of nylon 6/6 under cyclic loads at room temperature.



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Figure 2-21. Cyclic Loading and Recovery of Zytel® 101 (Nylon 6/6) With Short-Term Loads—6.9 MPa (1000 psi)—at 23°C (73°F) (Ref. 24)

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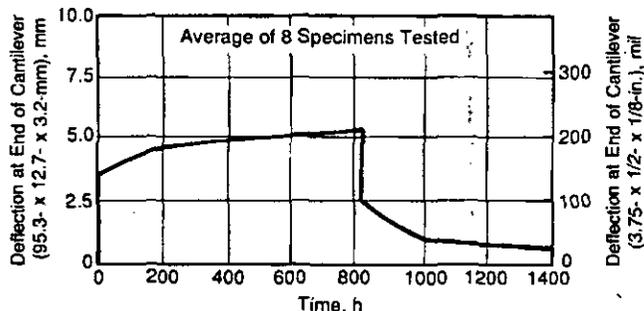
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Figure 2-22. Cyclic Loading and Recovery of Zytel® 101 (Nylon 6/6) With Short-Term Loads—13.8 MPa (2000 psi)—at 23°C (73°F) (Ref. 24)

The long-term decay of stress due to creep in a beam subjected to a fixed deflection is illustrated in Figs. 2-23 and 2-24. This distress decay is important in applications that use the force exerted by the resiliency of the material, such as preloaded springs, self-tapping screws, and press fits.

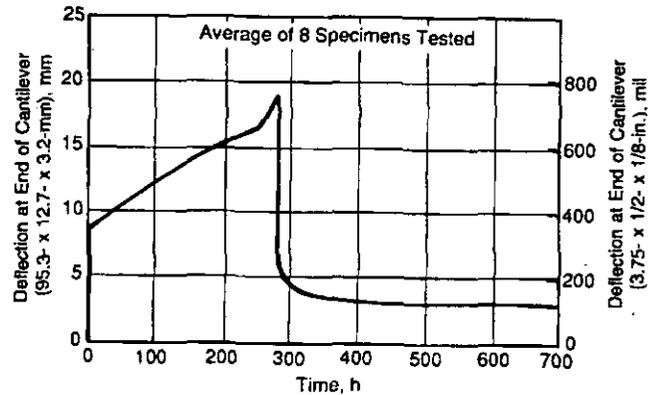
2-6.1.8 Hardness

As the term implies, hardness is a measure of the rigidity of the material surfaces and is specified by the permanent



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Figure 2-23. Cyclic Loading and Recovery of Zytel® 101 (Nylon 6/6) With Long-Term Loading—10.3 MPa (1500 psi)—at 23°C (73°F) (Ref. 24)



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Figure 2-24. Cyclic Loading and Recovery of Zytel® 101 (Nylon 6/6) With Long-Term Loading—20.7 MPa (3000 psi)—at 23°C (73°F) (Ref. 24)

deformation produced by an applied localized stress. A means of measuring and specifying hardness is the Rockwell hardness, which is the measure of surface penetration by a 12.7-mm (0.5-in.) diameter ball under a specified load. The Rockwell hardness correlates with the tensile modulus and is the hardness value most frequently used to describe nylon. Another measure of hardness sometimes reported is Durometer, which is a measure of indentation with a hardened steel indenter. Hardness data in both forms are presented in Table 2-10 for nylon 6/6. Hardness values are given for dry-as-molded samples and for samples equilibrated to 50% RH at 23°C (73°F). These data confirm that the increasing moisture content of the specimens reduces hardness values. Increasing temperature also decreases the hardness of nylon 6/6.

2-6.1.9 Abrasion Resistance

Its resistance to abrasion makes nylon 6/6 an engineering material that will outlast metals in a variety of applications. Because of its resiliency, nylon 6/6 can deform when a load is applied and later return to its original dimensions without wear. In a paint mixer steel worm gear teeth were worn to

TABLE 2-10. HARDNESS VALUES FOR NYLON 6/6 RESIN (ROCKWELL HARDNESS ASTM D 785, DUROMETER HARDNESS ASTM D 676) (Ref. 24)

MATERIAL	ROCKWELL HARDNESS		DUROMETER HARDNESS (D scale)	
	Dry	50% RH	Dry	50% RH
Zytel® 101	R121	R108	89	82

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knife-edges in three to six months, whereas nylon replacement gears lasted 18 months with only negligible wear. (Ref. 24)

Normalized results of physical tests that evaluate the abrasion resistance of various plastic materials are given in Table 2-11. Each entry in the table is the proportional amount of material lost or the depth of a groove cut into the material compared to the results of the same test on nylon. For example, nine to 26 times more material was removed from polystyrene than from nylon in Taber tests conducted under similar conditions, and the second best performer, cellulose acetate butyrate, lost two to five times more material than nylon. All tests clearly showed that nylon has the superior abrasion resistance. The material loss of nylon 6/6 is only one-half to one-tenth as much as the loss of other plastics. In ball-milling tests the weight loss of nylon was less than one-tenth that of hard rubber, cast aluminum, or mild steel. In wire drag tests nylon 6/6 outperformed polystyrene by a factor of 35 and two other plastics by factors of 15 and 20, respectively. In caster wheel tests nylon 6/6 outperformed a thermoset, phenolic material, phenol-formaldehyde. In the street marker tests disks of nylon 6/6 subjected to street traffic showed durability up to 25 to 60 times better than similar disks made from either a copolymer of styrene and acrylonitrile or cellulose acetate butyrate.

The tests in Table 2-11 were conducted as follows:

1. Taber abrasion tests were conducted with a CS-17 wheel and a 1000-g load at 23°C (73°F). The pieces were conditioned at 23°C (73°F) and 50% RH.

2. Ball-mill abrasion tests were conducted with 51- × 38- × 3.2-mm (2- × 1.5- × 0.125-in.) bars in a 127-mm (5-in.) Abbe ball mill with 25 "Borundum" balls and 500 mL of water. In various instances molded objects were substi-

tuted for test bars, the "Borundum" balls were replaced by steel balls, and the water was omitted without substantial change of the relative results.

3. Wire drag abrasion tests were conducted by pulling a continuous loop of fine resistance wire (spirally wrapped on a cord) over a cylindrical test piece. The cord was held at a constant tension and pulled over the test piece at about 0.36 m/s (70 ft/min). The depth of the groove was measured after 30 min.

4. Caster wheels 38 mm (1.5 in.) in diameter with an 8.7-mm (0.34-in.) tread were molded and mounted in pairs in standard caster frames. The phenolic wheels tested were those wheels normally supplied with the casters. The chairs on which the test wheels were mounted were used on cement floors, and tests were carried out over a period of months.

5. Street marker disks 51 mm (2 in.) in diameter by 12.7 mm (0.5 in.) thick were secured by a center bolt in a traffic lane. Much of the abrasion was between the street and the disk.

2-6.1.10 Frictional Properties

The frictional and wear characteristics of nylon resins make them an appropriate selection for bearings, gears, and sliding parts. Nylons can be used in applications in which other materials would require lubricants to meet performance or durability requirements. For applications in which lubricants would cause contamination or would collect dirt, nylon bearing surfaces represent a logical design solution. Although nylon can be used without lubrication, continuous or initial lubrication of the bearing surface further reduces friction and extends life (Ref. 32).

The measured coefficient of friction depends upon many variables including equipment, temperature, clearance, ma-

TABLE 2-11. COMPARISON OF THE WEIGHT LOSS OF VARIOUS MATERIALS RELATIVE TO NYLON 6/6 IN DIFFERENT ABRASION TESTS (Ref. 31, updated by Ref. 24)

MATERIAL	TABER	BALL MILL	WIRE DRAG	CASTER WHEEL	STREET MARKER
Zytel® 101 (Nylon 6/6)	1	1	1	1	1
Polystyrene (several types)	9-20	15-20	35	NA*	NA
Terpolymer of styrene, butadiene, and acrylonitrile (ABS)	9	10-20	NA	NA	NA
Copolymer of styrene and acrylonitrile (SAN)	NA	NA	NA	NA	25
Cellulose acetate	9-10	NA	NA	NA	NA
Cellulose acetate butyrate	9-15	10-20	15	NA	60
Methyl methacrylate	2-15	10-20	20	NA	NA
Melamine formaldehyde (molded)	NA	15-20	NA	NA	NA
Phenol formaldehyde (moldings)	4-12	NA	NA	16-50	NA
Hard rubber	NA	10	NA	NA	NA
Die-cast aluminum	NA	11	NA	NA	NA
Mild steel	NA	15-20	NA	NA	NA

*NA = not available

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terial, and finish of the mating surface. The values are also dependent on pressure and velocity.

Coefficients of friction between nylon and nylon, steel, brass, and an acetal homopolymer, are given in Tables 2-12 and 2-13 for lubricated and dry uses. There is little change in the coefficient of friction over a temperature range of 23 to 121°C (73 to 250°F) and speed changes from 0.04 to 2 m/s (8 to 400 ft/min).

TABLE 2-12. RANGE OF COEFFICIENTS OF FRICTION OF ZYTEL® 101 (NYLON 6/6) (Ref. 24)

		COEFFICIENT OF FRICTION, dimensionless	
Zytel® 101* on Zytel® 101*			
No lubricant	Static	Dynamic	
Maximum	0.46	0.19	
Minimum	0.36	0.11	
Zytel® 101* on acetal homopolymer			
No lubricant	Static	Dynamic	
Maximum	0.20	0.11	
Minimum	0.13	0.08	
Zytel® 101* on steel			
No lubricant	Static	Dynamic	
Maximum	0.74	0.43	
Minimum	0.31	0.17	

Normal pressure: 0.14 MPa (20 lb/in.²)

Sliding speed: 0.48 m/s (95 ft/min)

Temperature: 23°C (73°F)

Test method: Thrust washer

*Nylon 6/6 at 2.5% moisture

NOTE: The low thermal conductivity of plastic-on-plastic unlubricated pairs reduces the pressure and velocity limit.

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TABLE 2-13. COEFFICIENT OF FRICTION OF ZYTEL® 101 (NYLON 6/6) (Ref. 24)

LUBRICANT	OTHER SURFACE	LOAD, MPa (lb/in. ²)	COEFFICIENT OF FRICTION, dimensionless
Dry	Zytel® 101*	7.2 (1050)	0.05 to 0.13
Water	Zytel® 101*	7.2 (1050)	0.08 to 0.14
Oil	Zytel® 101*	7.2 (1050)	0.07 to 0.18
Water	Steel	7.2 (1050)	0.3 to 0.5
Oil	Steel	10.7 (1550)	0.02 to 0.11
Water	Brass	7.2 (1050)	0.3 to 0.5
Oil	Brass	10.7 (1550)	0.08 to 0.14

Battelle Memorial Institute; Neely, or boundary film, testing machine; surface speed 0.8 m/s (156 ft/min)

*Nylon 6/6

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2-6.1.11 Wear

As mentioned in subpar. 2-6.1.10, lubrication reduces the friction between nylon and many other materials and therefore decreases the rate of wear. Initial lubrication provides longer life compared to unlubricated conditions. Continuous boundary, or thin-film, lubrication by a wide range of conventional lubricants typically reduces the wear rate tenfold. Continuous hydrodynamic, or thick-film, lubrication can virtually eliminate wear (Ref. 24).

Water is not a desirable boundary film lubricant. Lubrication with water can reduce friction at higher pressure and velocity operation, but it usually causes higher wear rates than no lubrication and may affect the properties of the nylon.

The rate of wear in any application is dependent on a large number of factors and is difficult to predict. Prediction of wear rates is best accomplished by testing under simulated operating conditions.

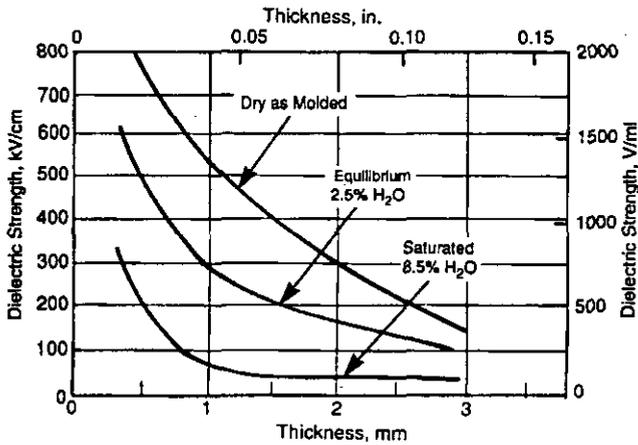
2-6.2 ELECTRICAL PROPERTIES

Nylons are widely used in electronic and electromechanical applications because of their excellent mechanical properties, chemical resistance, and heat resistance and their satisfactory electrical properties. Typical electrical applications include coil forms, connectors, strain-relief grommets, terminal blocks, and tough overcoatings on wire insulation. Nylon does have greater electrical loss at high frequencies compared to materials typically used for high-frequency insulation, so nylon is typically used where the electrical characteristics are not as critical, i.e., low-frequency and low-voltage applications. Use of nylon where high levels of electromagnetic radiation may result in dielectric heating, which may affect the physical properties of the nylon and result in power loss, is not recommended. (Ref. 33) The dielectric strength, volume resistivity, dielectric constant, and dissipation factor of nylons are affected by temperature and moisture content.

Thickness, moisture content, and temperature all affect the short-time dielectric strength as measured by ASTM D 149 (Ref. 34). Fig. 2-25 shows the relationship between dielectric strength and material thickness for different levels of moisture content. (Note that the dielectric strength is the electric field strength per unit thickness that can be withstood by the material without dielectric breakdown. Thicker dielectrics have a lower dielectric strength but are able to withstand a higher applied electrical field.) As the temperature increases, the dielectric strength decreases, as shown on Fig. 2-26.

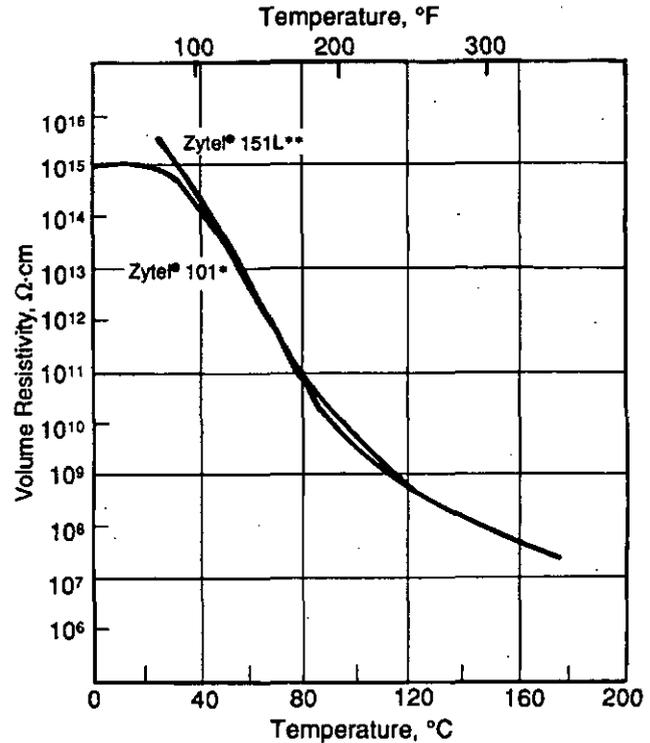
Volume resistivity, an indicator of leakage currents that can flow through insulation material, is affected by both temperature and moisture content. When temperature increases, volume resistivity decreases, as shown on Fig. 2-27. Fig. 2-28 shows that the volume resistivity decreases with increasing moisture content. Nylon 6/12 reaches moisture saturation at a lower level than nylon 6/6 and retains a higher volume resistivity. Volume resistivity measurements are made in accordance with ASTM D 257 (Ref. 35).

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Figures excerpted from Bulletin NY-1A, "Celanese® Nylon 6/6 Properties and Processing", Copyright 1992 by Hoechst Celanese Corporation.

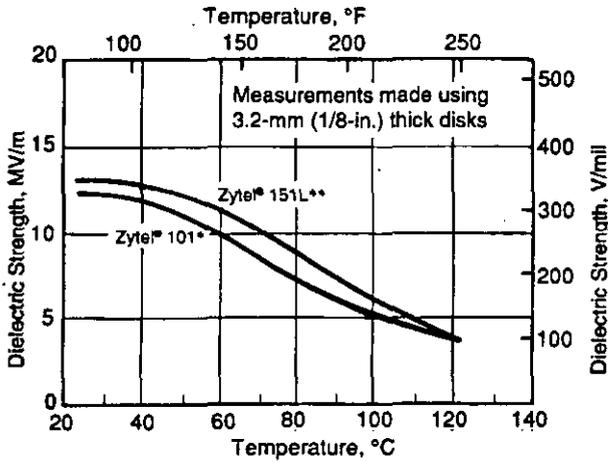
Figure 2-25. Short-Time Dielectric Strength of Nylon 6/6 (Celanese® Nylon 1000) vs Thickness at 23°C (73°F) (Ref. 25)



*Zytel® 101 = Nylon 6/6
**Zytel® 151L = Nylon 6/12 Lubricated

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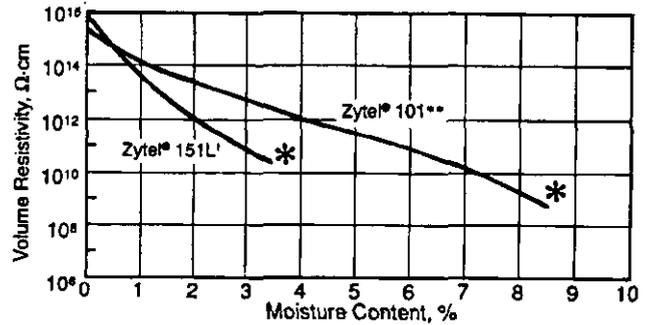
Figure 2-27. Volume Resistivity vs Temperature for Dry-as-Molded Nylon at 25°C (77°F) (Ref. 24)



* Zytel® 101 = Nylon 6/6
** Zytel® 151 = Nylon 6/12 Lubricated

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Figure 2-26. Effect of Temperature on Dielectric Strength of Nylon 6/6 (Ref. 24)



* Indicates saturation at 100% RH
**Zytel® 101 = Nylon 6/6
Zytel® 151L = Nylon 6/12 Lubricated

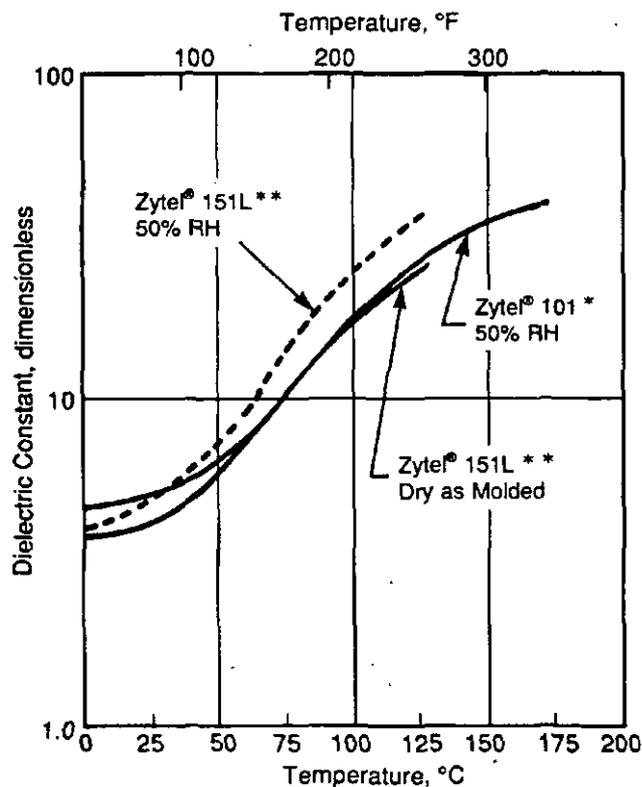
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Figure 2-28. Effect of Moisture Content on Volume Resistivity of Nylon at 23°C (73°F) (Ref. 24)

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The dielectric constant, sometimes referred to as relative permittivity, of nylon increases rapidly with increasing temperature and moisture content, as shown on Figs. 2-29 and 2-30, respectively. The dielectric constant measurements on these figures were made in accordance with ASTM D 150 (Ref. 36). Since maintaining constant moisture and temperature conditions over the test period is difficult, the curves represent only general values for these conditions.

The dissipation factor is a measure of the electrical losses in the material and is related to the portion of field energy passing through the medium that would be converted to heat. For high-voltage applications in which the insulation material is the only load on a line energized by a sinusoidal voltage, the dissipation factor is numerically equal to the power factor, which is related to the phase difference between the applied voltage and the current. (If a perfect insulator is used as the dielectric of a capacitor that has no other losses and ac voltage is impressed across the capacitor, the current through the capacitor will lead the voltage by exactly 90 deg. Any loss in the dielectric will result in a phase angle different than 90 deg. The loss dissipation factor is the cosine of the phase

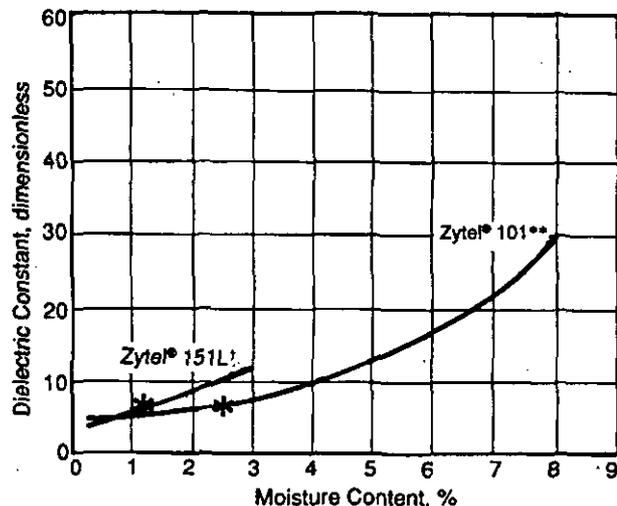


*Zytel[®] 101 = Nylon 6/6

**Zytel[®] 151L = Nylon 6/12 Lubricated

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Figure 2-29. Dielectric Constant vs Temperature, Samples Conditioned as Indicated (Ref. 24)



* Indicates moisture content when material is equilibrated to 50% RH

**Zytel[®] 101 = Nylon 6/6

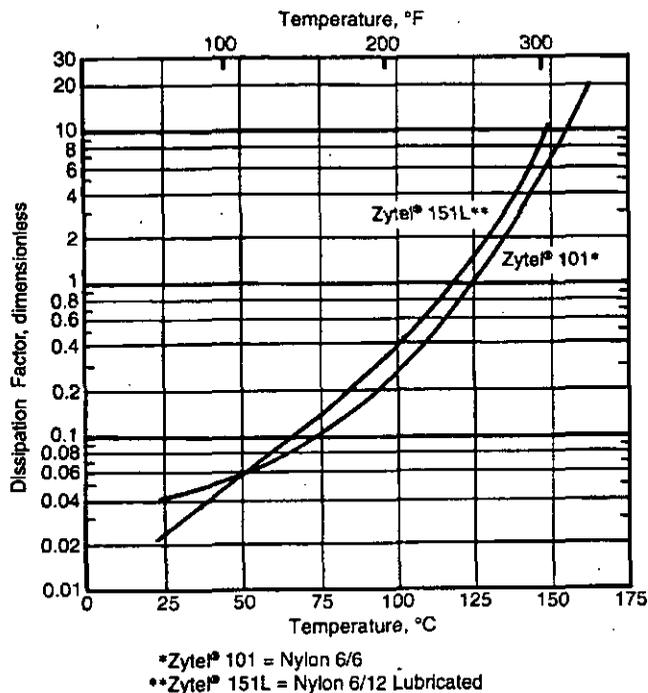
*Zytel[®] 151L = Nylon 6/12 Lubricated

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Figure 2-30. Effect of Moisture on Dielectric Constant Measured at 100 Hz Using 3.3-mm (0.129-in.) Thick Plaques at 23°C (73°F) (Ref. 24)

angle and is zero for lossless materials.) The dissipation factor of nylons increases with increasing temperature and moisture. Measurements of dissipation factor showing this dependency were made in accordance with ASTM D 150 and are shown in Figs. 2-31 and 2-32. Fig. 2-32 illustrates that nylon 6/12 shows less variation in these properties because it absorbs less moisture than nylon 6/6. The moderate dissipation factor of nylon is not generally a concern at low frequencies but can affect the performance and efficiency of high-frequency circuits. Nylon is not a suitable insulation material in components for which dimensional stability and stability of electrical characteristics are critical because the dielectric heating raises the temperature of the dielectric and thus affects its electrical and physical characteristics. Nylon serves admirably, however, in low-frequency applications, such as connector and wire insulation covering for power systems.

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Figure 2-31. Dissipation Factor vs Temperature With Samples Conditioned at 50% RH and 23°C (73°F) (Ref. 24)

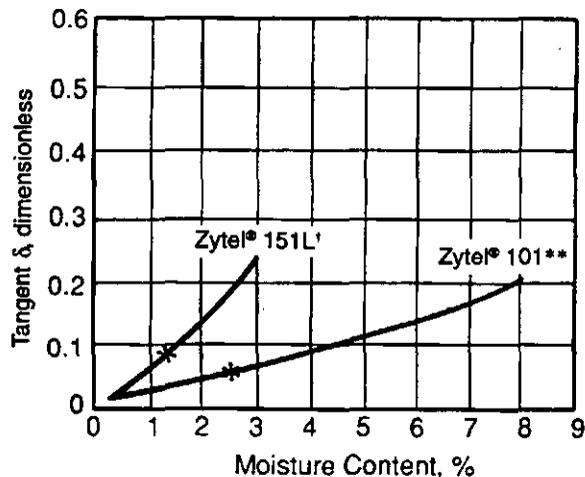
2-6.3 THERMAL PROPERTIES

The thermal expansion coefficients of several nylons at different temperatures are given in Table 2-14. The values shown are based upon dry-as-molded specimens and will change as moisture content increases. For example, at 23°C (73°F) dry Zytel® 101 has a coefficient of $8.1 \times 10^{-5} \text{ m/m/}^\circ\text{C}$ ($4.5 \times 10^{-5} \text{ in./in./}^\circ\text{F}$), but at saturation it has a coefficient of $11.7 \times 10^{-5} \text{ m/m/}^\circ\text{C}$ ($6.5 \times 10^{-5} \text{ in./in./}^\circ\text{F}$).

Specific heat and thermal conductivity data for nylon 6/6 and 6/12 are given in Table 2-15.

The heat deflection temperature, as defined in ASTM D 648 (Ref. 37), is the temperature at which a bar of standard dimensions deflects 0.25 mm (0.01 in.) under a stated stress level of either 455 or 1820 kPa (66 or 264 lb/in.²). Environmental differences during the tests and internal stresses lead to differences in the reported heat deflection temperatures. The heat deflection data in Table 2-16 are for dry-as-molded specimens that have been annealed in oil at 59 deg C (90 deg F) below their melting temperature. The heat deflection temperatures convey the temperature characteristic of the material but do not correspond to a melting or upper use temperature.

Nylon becomes more plastic as the temperature increases. The modulus is reduced, and the material will deflect an additional amount under load. Most of this deflection is recoverable when the load is removed. Amorphous plastics, however, do not show this recovery when the load is removed.



* Indicates equilibration to moisture at 50% RH

**Zytel® 101 = Nylon 6/6

'Zytel® 151L = Nylon 6/12 Lubricated

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Figure 2-32. Effect of Moisture on Dissipation Factor at 100 Hz, Samples at 23°C (73°F) (Ref. 24)

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TABLE 2-14. COEFFICIENT OF LINEAR THERMAL EXPANSION (Ref. 24)

TEMPERATURE, °C	m/m/°C		
	ZYTEL® 101*	ZYTEL® 151L**	ZYTEL® 101 MODIFIED†
-40	6.3×10^{-5}	7.2×10^{-5}	6.1×10^{-5}
0	7.2×10^{-5}	8.1×10^{-5}	6.5×10^{-5}
23	8.1×10^{-5}	9.0×10^{-5}	7.2×10^{-5}
77	9.0×10^{-5}	10.8×10^{-5}	9.0×10^{-5}

TEMPERATURE, °F	in./in./°F		
	ZYTEL® 101*	ZYTEL® 151L	ZYTEL® 101 MODIFIED
-40	3.5×10^{-5}	4.0×10^{-5}	3.4×10^{-5}
32	4.0×10^{-5}	4.5×10^{-5}	3.6×10^{-5}
73	4.5×10^{-5}	5.0×10^{-5}	4.0×10^{-5}
170	5.0×10^{-5}	6.0×10^{-5}	5.0×10^{-5}

*Nylon 6/6

**Nylon 6/12

†Nylon 6/6 with superior toughness and moldability (designated Zytel® 408)

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TABLE 2-15. SPECIFIC HEAT AND THERMAL CONDUCTIVITY (Ref. 24)

SPECIFIC HEAT*	ZYTEL® 101**	ZYTEL® 151L†
Below 0°C (32°F)	0.30	0.30
0-49°C (32-120°F)	0.35	0.40
49-99°C (120-210°F)	0.45	0.50
99-204°C (210-400°F)	0.55	0.60

THERMAL CONDUCTIVITY	ZYTEL® 101	ZYTEL® 151L
W/(m·°C)	0.25	0.22
(Btu/h/ft ² /°F/in.)	(1.7)	(1.5)

*Specific heat is dimensionless. It is defined as the heat capacity, J/(kg·°C), relative to water at 15°C (59°F).

**Nylon 6/6

†Nylon 6/12

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TABLE 2-16. DEFLECTION TEMPERATURE UNDER LOAD (Ref. 24)

MATERIAL	0.46 MPa (66 lb/in. ²)	1.8 MPa (264 lb/in. ²)
Zytel® 211*	171°C (340°F)	54°C (129°F)
Zytel® 101**	235°C (455°F)	90°C (194°F)
Zytel® 151L†	180°C (356°F)	90°C (194°F)

* Du Pont Co. trademark for general-purpose, unextracted nylon 6

** Du Pont Co. trademark for general-purpose nylon 6/6

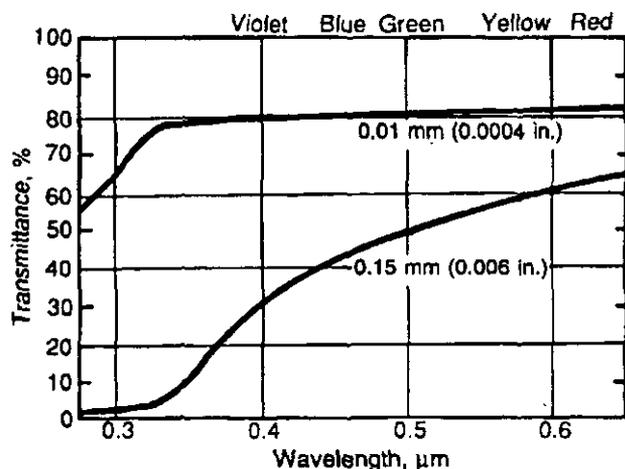
† Du Pont Co. trademark for general-purpose, lubricated nylon 6/12

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2-6.4 OPTICAL PROPERTIES

Pure nylons are relatively translucent in thin sections (less than or equal to 3.2 mm (0.125 in.)) and have been used extensively where diffuse light transmission is required, e.g., for dome and courtesy lights in automotive and aircraft applications. Nylon 6/12 is even more translucent than nylon 6/6. The nucleated versions of nylon 6/6 are less translucent and accordingly are not used when maximum light transmission is important.

Light is scattered at the boundaries of spherulites, i.e., crystalline aggregates, which are normally present in nylon. This scattering makes the material translucent but not transparent. Rapid cooling of thin nylon films of about 0.025 mm (one mil) of thickness reduces the amount of crystalline structure and produces an essentially transparent amorphous material.



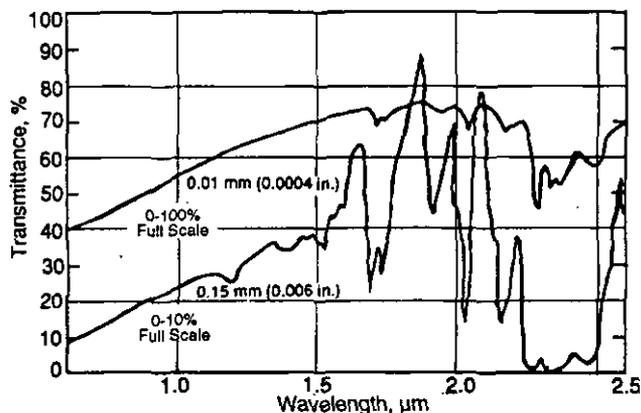
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Figure 2-33. Spectral Transmittance Curve of Zytel® 101 (Nylon 6/6) Resin in Ultraviolet and Visible Regions, Cary Model 14 With Integrating Sphere (Ref. 31)

Additions of nucleating agents increase the crystallinity and produce a material that is more opaque. Figs. 2-33 and 2-34 show the spectral distribution of transmitted light through 0.01- and 0.15-mm samples of nylon 6/6.

2-7 TABULATED DATA ON PROPERTIES OF NYLONS

Tables 2-17 through 2-20 give data on types of nylons 6, 6/6, 6/10, 6/12, 11, and 12. Table 2-17 gives the processing and miscellaneous properties of the nylons, and Table 2-18 gives the mechanical and durability properties of the nylons. Table 2-19 shows the electrical properties, and Table 2-20, the thermal properties of the nylons. Table 2-21 gives the comparative properties of types of injection-molded nylon 6 and cast nylon 6.



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Figure 2-34. Spectral Transmittance Curve of Zytel® 101 (Nylon 6/6) Resin in Near-Infrared Region, Cary Model 14 Without Integrating Sphere (Ref. 31)

TABLE 2-17. PROCESSING AND MISCELLANEOUS PROPERTIES (Ref. 38)

PROPERTIES	ASTM METHOD	GENERAL-PURPOSE NYLON TYPES						
		6	6/6	6/10	6/12	11	12	
Melting temperature (Crystalline)	°C (°F)	NA	210-220 (410-428)	255-265 (491-509)	220 (428)	195-219 (383-426)	191-194 (376-381)	160-209 (320-408)
Processing temperature range	°C (°F)	NA	*I:227-288 (440-550)	I:260-327 (500-620)	I:229-252 (445-485)	I:232-288 (450-550)	I:199-271 (390-520)	I:180-274 (356-525)
	°C (°F)		**E:227-274 (440-525)		E:249-260 (480-500)	E:240-243 (464-469)	E:199-246 (390-475)	E:177-260 (350-500)
Molding pressure range	MPa (lb/in. ² × 10 ³)	NA	6.9-138 (1-20)	6.9-172 (1-25)	6.9-131 (1-19)	6.9-103 (1-15)	6.9-103 (1-15)	6.9-103 (1-15)
Mold (linear) shrinkage	mm/mm (in./in.)	D 955	0.003- 0.015	0.007- 0.018	0.005- 0.015	0.011	0.012	0.003- 0.015
Specific gravity		D 792	1.12-1.14	1.13-1.15	N/A	1.06-1.10	1.03-1.05	1.01-1.02
Water absorption, %	24-h saturation	D 570	1.3-1.9	1.0-2.8	1.4	0.4-1.0	0.3	0.25-0.30
		D 570	3.5-10.0	8.5	3.3	2.5-3.0	NA	0.75-0.9

*I = injection molding

**E = extrusion

TABLE 2-18. MECHANICAL AND DURABILITY PROPERTIES OF NYLON TYPES (Refs. 10, 24, 25, and 38)

PROPERTIES		ASTM METHOD	NYLON TYPES											
			6		6/6		6/10		6/12		11		12	
			DAM*	50% RH	DAM	50% RH	DAM	50% RH						
Tensile Strength														
-40°C (-40°F)	MPa	D 638	110.3	90.3	113.8	110.3	82.7	NA	93.8	93.1	68.3	NA	NA	NA
	(lb/in. ² × 10 ³)		(16.0)	(13.1)	(16.5)	(16.0)	(12.0)	NA	(13.6)	(13.5)	(9.9)	NA	NA	NA
23°C (73°F)	MPa		64.8	60.3	82.7	77.2	58.6	NA	60.7	60.7	58.6	NA	33-63	NA
	(lb/in. ² × 10 ³)		(9.4)	(8.7)	(12.0)	(11.2)	(8.5)	NA	(8.8)	(8.8)	(8.5)	NA	(4.8-9.2)	NA
77°C (170°F)	MPa		41.4	37.2	62.1	40.7	36.5	NA	40.7	36.5	42.1	NA	NA	NA
	(lb/in. ² × 10 ³)		(6.0)	(5.4)	(9.0)	(5.9)	(5.3)	NA	(5.9)	(5.3)	(6.1)	NA	NA	NA
121°C (250°F)	MPa		33.1	30.3	42.7	37.9	NA	NA	NA	NA	NA	NA	NA	NA
	(lb/in. ² × 10 ³)		(4.8)	(4.4)	(6.2)	(5.5)	NA	NA	NA	NA	NA	NA	NA	NA
Yield Stress														
-40°C (-40°F)	MPa	D 638	110.3	90.3	113.8	110.3	82.7	NA	93.8	93.1	NA	NA	79.2	NA
	(lb/in. ² × 10 ³)		(16.0)	(13.1)	(16.5)	(16.0)	(12.0)	NA	(13.6)	(13.5)	NA	NA	(11.5)	NA
23°C (73°F)	MPa		51.0	40.7	82.7	58.6	58.6	NA	60.7	51.0	NA	NA	41-54	NA
	(lb/in. ² × 10 ³)		(7.4)	(5.9)	(12.0)	(8.5)	(8.5)	NA	(8.8)	(7.4)	NA	NA	(6.0-7.8)	NA
77°C (170°F)	MPa		34.5	26.2	44.8	40.7	29.0	NA	29.6	35.2	NA	NA	24.0	NA
	(lb/in. ² × 10 ³)		(5.0)	(3.8)	(6.5)	(5.9)	(4.2)	NA	(4.3)	(5.1)	NA	NA	(3.5)	NA
121°C (250°F)	MPa		17.2	17.2	33.1	27.6	NA	NA	NA	NA	NA	NA	NA	NA
	(lb/in. ² × 10 ³)		(2.5)	(2.5)	(4.8)	(4.0)	NA	NA	NA	NA	NA	NA	NA	NA
Elongation at break, %														
-40°C (-40°F)		D 638	25	35	15	20	20	NA	15	30	37	NA	150-300	NA
23°C (73°F)			290	295	60	≥300	30	NA	150	≥300	329	NA	NA	NA
77°C (170°F)			250	270	≥300	≥300	300	NA	≥300	≥300	400	NA	NA	NA
121°C (250°F)			250	260	≥300	≥300	NA	NA	NA	NA	NA	NA	NA	NA
Elongation at yield, %														
-40°C (-40°F)		D 638	10	8	4	NA	10	NA	8	14	NA	NA	5.8	NA
23°C (73°F)			20	30	5	25	10	NA	7	40	NA	NA	NA	NA
77°C (170°F)			40	NA	30	30	30	NA	30	40	NA	NA	NA	NA
121°C (250°F)			45	NA	45	40	NA	NA	NA	NA	NA	NA	NA	NA
Tensile Modulus														
23°C (73°F)	MPa	D 638	26-30	NA	28.9	NA	19.3	NA	NA	NA	12.3-12.8	NA	11.7-14.5	NA
	(lb/in. ² × 10 ³)		(3.8-4.4)	NA	(4.2)	NA	(2.8)	NA	NA	NA	(1.78-1.85)	NA	(1.7-2.1)	NA

*DAM = dry as molded

(cont'd on next page)

TABLE 2-18. (cont'd)

PROPERTIES		ASTM METHOD	NYLON TYPES											
			6		6/6		6/10		6/12		11		12	
			DAM*	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH
Flexural Modulus														
-40°C (-40°F)	MPa	D 790	NA	NA	3241	3447	NA	NA	2344	2758	NA	NA	NA	NA
	(lb/in. ² × 10 ³)		NA	NA	(470)	(500)	NA	NA	(340)	(400)	NA	NA	NA	NA
23°C (73°F)	MPa		1034	745	2827	1207	1931	NA	2034	1241	1041	NA	1172-1558	NA
	(lb/in. ² × 10 ³)		(150)	(108)	(410)	(175)	(280)	NA	(295)	(180)	(151)	NA	(170-226)	NA
77°C (170°F)	MPa		414	414	661	565	NA	NA	414	379	NA	NA	NA	NA
	(lb/in. ² × 10 ³)		(60)	(60)	(95.8)	(82)	NA	NA	(60)	(55)	NA	NA	NA	NA
121°C (250°F)	MPa		345	345	538	414	NA	NA	331	303	NA	NA	NA	NA
	(lb/in. ² × 10 ³)		(50)	(50)	(78)	(60)	NA	NA	(48)	(44)	NA	NA	NA	NA
Compressive Stress at 1% Deformation														
	MPa	D 695	NA	NA	33.8	NA	NA	NA	16.6	NA	NA	NA	NA	NA
	(lb/in. ²)		NA	NA	(4900)	NA	NA	NA	(2400)	NA	NA	NA	NA	NA
Shear Strength														
	MPa	D 732	62.7	NA	66.2	NA	58.6	NA	59.3	56.4	NA	NA	NA	NA
	(lb/in. ²)		(9100)	NA	(9600)	NA	(8500)	NA	(8600)	(8180)	NA	NA	NA	NA
Izod Impact														
-40°C (-40°F)	J/m	D 256	16	21	32	27	NA	NA	48	32	NA	NA	NA	NA
	(ft-lb/in.)		(0.3)	(0.4)	(0.6)	(0.5)	NA	NA	(0.9)	(0.6)	NA	NA	NA	NA
23°C (73°F)	J/m		80	NA	53	112	32-85	NA	53	75	26.7-40.0	NA	37.4-64	NA
	(ft-lb/in.)		(1.5)	NA	(1.0)	(2.1)	(0.6-1.6)	NA	(1.0)	(1.4)	(0.5-0.75)	NA	(0.7-1.2)	NA
Tensile Impact														
Long specimens	kJ/m ²	D 1822	525	NA	504	1470	NA	NA	611	945	NA	NA	NA	NA
	(ft-lb/in. ²)		(250)	NA	(240)	(700)	NA	NA	(291)	(450)	NA	NA	NA	NA
Short specimens	kJ/m													
	(ft-lb/in. ²)													
Hardness (Rockwell)														
	R	D 785	104	81	121	108	111	NA	114	108	100-108	NA	106	NA
	M		45	29	79	59	NA	NA	NA	NA	NA	NA	NA	NA

*DAM = dry as molded

(cont'd on next page)

TABLE 2-18. (cont'd)

PROPERTIES	ASTM METHOD	NYLON TYPES											
		6		6/6		6/10		6/12		11		12	
		DAM*	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH	DAM	50% RH
Deformation Under Load, %													
at 14 MPa (2000 lb/in. ²) and 50°C (122°F)	D 621	1.6-1.7		2.1-1.4		4.2		1.6		NA		NA	
at 28 MPa (4000 lb/in. ²) and 50°C (122°F)		1.8		NA		NA		NA		NA		NA	
Abrasion (Taber)													
(CS-17 wheel, 1000-g load) mg/1000 cycles	D 1044	5.0		6-8		5-6		5-7		5.0		NA	
Brittleness Temperature													
°C	D 746	-82.2	NA	-80	-65	-110	NA	-126	-109	-70	NA	NA	NA
(°F)		(-116)	NA	(-112)	(-85)	(-166)	NA	(-195)	(-165)	(-94)	NA	NA	NA

*DAM = dry as molded

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TABLE 2-19. ELECTRICAL PROPERTIES OF NYLON TYPES (Refs. 5 and 24)

NYLON	CONDITION	VOLUME RESISTIVITY, $\Omega\cdot\text{m}$ (ASTM D 257)	DIELECTRIC CONSTANT, dimensionless (ASTM D 150)			DISSIPATION FACTOR, dimensionless (ASTM D 150)		
			(60-100 Hz)	(10 ³ Hz)	(10 ⁶ Hz)	(60-100 Hz)	(10 ³ Hz)	(10 ⁶ Hz)
6/6	Dry	10 ¹³	4.0	3.9	3.6	0.02	0.03	0.02
	50% RH	10 ¹¹	6.0	5.1	4.1	0.04-0.18	0.04-0.16	0.05-0.09
	100% RH	10 ⁷	31	29	18	0.50	0.23	0.28
6	Dry	10 ¹³	3.8	3.7	3.4	0.01	0.02	0.03
	50% RH	10 ¹¹	13	8.3	4.2	0.18	0.20	0.12
	100% RH	10 ⁶	NA	NA	25	NA	NA	NA
6/10	Dry	10 ¹³	4.0	3.9	3.6	0.04	0.04	0.03
	50% RH	10 ¹¹	7.4	6.1	3.7	0.04	0.04	NA
	100% RH	10 ⁹	15	12	4.0	0.03	NA	0.1
6/12	Dry	10 ¹³	4.0	4.0	3.5	0.02	0.02	0.02
	50% RH	10 ¹¹	6.0	5.3	4.0	0.04	0.04	0.03
	100% RH	10 ⁹	14	NA	NA	NA	NA	NA
11	Dry	10 ¹³	NA	NA	NA	NA	NA	NA
	50% RH	10 ¹¹	NA	NA	NA	NA	NA	NA
	100% RH	10 ⁹	NA	NA	NA	0.03	NA	0.06
12	Dry	10 ¹³	4.2	3.8	3.1	0.04	0.05	0.03

TABLE 2-20. THERMAL PROPERTIES OF NYLON TYPES (Ref. 5)

PROPERTIES	ASTM METHOD	GENERAL-PURPOSE NYLON TYPES					
		6	6/6	6/10	6/12	11	12
Thermal Conductivity, W/(m·k) (Btu·ft/h·ft ² ·°F)	C 177	0.020 (1.7)	0.020 (1.7)	0.018 (1.5)	0.018 (1.5)	0.018 (1.5)	0.018 (1.5)
Coefficient of Thermal Expansion, cm/(cm·°C) × 10 ⁻⁵ (in./in.·°F) × 10 ⁻⁵	D 696	8.3 (4.6)	8.1 (4.5)	9.0 (5.0)	9.0 (5.0)	9.9 (5.5)	9.9 (5.5)
Specific Heat*	D 696	0.4	0.35	0.4	0.4	0.3	0.3

*Specific heat is dimensionless. It is defined as the heat capacity in J/(kg·°C) (Btu/(lb·°F)) relative to water at 5°C (41°F).

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TABLE 2-21. COMPARATIVE PROPERTIES OF CAST AND MOLDED NYLON 6 (Ref. 5)

PROPERTIES	UNITS	ASTM METHOD	NYLON 6	
			CAST	MOLDED
Specific gravity	dimensionless	D 792	1.15	1.13
Tensile strength	MPa $\times 10^2$ (lb/in. ² $\times 10^3$)	D 638	0.76-0.97 (11-14)	0.48-0.83 (7-12)
Elongation	%	D 638	10-60	20-300
Tensile modulus	MPa $\times 10^2$ (lb/in. ² $\times 10^3$)	D 638	24.1-32.4 (350-470)	6.9-32.4 (100-470)
Compressive strength	MPa $\times 10^2$ (lb/in. ² $\times 10^3$)	D 695	0.83 (12.0)	0.46-0.90 (6.7-13.0)
Flexural yield strength	MPa $\times 10^2$ (lb/in. ² $\times 10^3$)	D 790	0.48-1.21 (7.0-17.5)	0.48-1.10 (7.0-16.0)
Izod impact strength	J/m (ft·lb/in.)	D 256	42.7-160.2 (0.8-3.0)	42.7-No break (0.8-No break)
Flexural modulus	MPa $\times 10^2$ (lb/in. ² $\times 10^3$)	D 790	5.5-31 (80-450)	5.5-28 (80-400)
Rockwell hardness		D 785	R 110-120	R 100-110
Deflection temperature at 0.46 MPa (66 lb/in. ²)	°C (°F)	D 648	204-218 (400-425)	149-188 (300-370)
at 1.8 MPa (264 lb/in. ²)	°C (°F)		93-218 (200-425)	60-82 (140-180)

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CHAPTER 3

MODIFICATION OF NYLONS

Nylons are readily modified by physical and chemical methods. A wide range of properties is available with nylons depending on their polymeric structures. Within any given type of nylon it is possible to modify the properties by means that include additives, polymer blending, and reinforcement with fibers and fillers. Combinations of these methods may be used together. The changes that can be made would be made by the manufacturer of the resins, not by the user. Nevertheless, the several methods available for making changes are given so that the user can request from the manufacturer any types that may be of interest. The means by which nylons can be modified and some of the properties that can be obtained are discussed.

3-1 PHYSICAL MODIFICATIONS

Nylons can be modified by many means, but by far the easiest ones are to alter the shape of the starting material or to modify the molecular weight of the starting nylon. Both methods are relatively easy for the manufacturer to use at the time of polymer preparation and are widely employed.

3-1.1 FORM

Nylons are offered in many sizes and shapes depending on the fabricating techniques to be employed for the desired end-use product. For example, cylindrical and rectangular granules are offered for injection molding or extrusion. They can be extruded from a melt by the producer and cut to the desired width and length, usually 1.5 to 3.0 mm (0.06 to 0.12 in.). Powders for fluidized bed coatings with diameters of 10 to 100 μm are offered but are more expensive because to obtain the fine particle size, the polymers must be precipitated from solution or ground at a low temperature. Even finer size particles of 0.005 to 0.01 μm diameter can be obtained in stable aqueous dispersions and gels of microcrystalline nylons. Since preparation in this form involves partial hydrolysis, there is some loss of molecular weight for these nylons.

3-1.2 MOLECULAR WEIGHT

Most commercial nylons have number-average molecular weights in the range of 11,000 to 40,000 daltons. The range is this wide because it is necessary to vary the melt viscosity (which varies with molecular weight) depending on the end-use product to be prepared. For blown film, blow molding, or free extrusion of rod and profiles, the melt viscosity should be over about 4000 Pa-s or 40,000 P (0.6 lb-s-in.⁻²); for extrusion of tubing, 2000 to 4000 Pa-s or 20,000 to 40,000 P (0.3 to 0.6 lb-s-in.⁻²); for making flat film, 1000 to 2000 Pa-s or 10,000 to 20,000 P (0.15 to 0.3 lb-s-in.⁻²); and for extrusion coating and monofilament extrusion (spinning) and injection molding, less than 1000 Pa-s or 10,000 P* (0.15 lb-s-in.⁻²).

*The values cited are approximate. The actual values will depend on the size and wall thickness of the product produced. Other important parameters that affect selection of the correct melt viscosity are the processing equipment and the processing temperature.

The molecular weight of nylons, which is critical to processing, is controlled by use of monofunctional additives, by adjustment of the stoichiometry, i.e., by altering the ratio of diacid to diamine for nylons prepared from such monomers, or by variation of the amount of water for nylons made from lactams. The molecular weights of nylons can be increased considerably by solid-state polymerization, i.e., by heating finely divided particles under vacuum for appropriate periods of time.

3-2 CHEMICAL MODIFICATIONS

Nylons have a wide range of properties depending on the structure of the homopolymers (Ref. 1). In general, nylons with short alkylene chains have very high melting points, and those with long alkylene chains have low melting points. The most common variants, nylons 6, 6/6, 6/10, and 6/12, are somewhere in the middle of this wide range. Other nylons that have been considered for development and/or are achieving some commercial success are nylons 4 and 4/6. These and other nylons considerably extend the possibilities of properties that can be used in nylon technology.

A new polyamide, however, is expensive to develop, as is its introduction to the marketplace. The preparation of copolyamides and the blending of various polymers (polyamides and others) with polyamides are much less expensive than the introduction of a new nylon and have been exploited extensively.

3-2.1 COPOLYMERS

It is well-known that copolymerization leads to polymers having lower melting points than the constituent homopolymers, lower crystallinity, lower tensile properties (especially modulus), and increased solubility (which usually results in lower solvent resistance). The minimum polymer rigidity and solvent resistance coincides with a minimum polymer melting point.

For copolymers of two well-known polymers, namely, nylons 6/6 and 6/10 (which share a common diamine), the

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minimum melting point comes at about 60 mol percent of 6/10. This minimum melting point is about 200°C, whereas the minimum melting points of nylon 6/6 and nylon 6/10 are about 270°C and 230°C, respectively. Even for two nylons that are rather similar, i.e., nylons 6 and 6/6, a copolymer of the two has a minimum melting point of about 160°C at about 60 mol percent of nylon 6, which has a melting point circa 230°C.

Not all copolymers result in drastically reduced melting points, however. For example, when one or more monomers show isomorphism, i.e., have about the same chain length when placed in a polymer chain, the melting point versus composition curve may not show a minimum. Thus terephthalic acid can be used to replace a considerable amount of adipic acid when these diacids are polymerized with a diamine having an alkylene chain of six to 12 carbon atoms. If a methylene unit of an aliphatic diamine is replaced by an ether or thioether group, isomorphism can also result.

Copolymerization for polyamides is generally taken to mean either that a single diamine is polymerized with two diacids or that a single diacid is polymerized with two diamines. It is possible, however, to use a multitude of diamines and diacids in a single multimonomer mix. Such usage results in a polymer of very low crystallinity; hence its properties will include a low melting point and low solvent resistance.

Nylons prepared in a melt from diacids and diamines, e.g., nylon 6/6, can be prepared as copolymers having *N*-alkyl groups by replacing a portion of the simple diamine with one having *N*-alkyl groups, e.g., *N,N*-dimethyl hexamethylenediamine. Such a substitution greatly reduces hydrogen bonding in the nylon and leads to a lower melting point and lower tensile properties, especially modulus. Most commonly, the alkyl group would be a methyl group; use of larger groups does not particularly change the properties compared with use of a methyl group.

A homopolymer, e.g., nylon 6/6, can be converted to a copolymer (or to a new homopolymer if the reaction is quantitative) by reacting some of the amide groups with reagents that convert the diamine moieties to *N*-substituted ones. Partial substitution brings about a considerable change because of the possibility of head-to-head and head-to-tail portions in the repeat unit, i.e., an "internal copolymeric" effect.

In addition to *N*-alkyl substituted polyamides, *N*-substitution can be effected by acid-catalyzed addition of formaldehyde and an alcohol to prepare alkoxylated polyamides. Such polymers are soluble in alcohol and can be used to provide protective coatings that can be cross-linked by heating with elimination of the alcohol (usually methanol) used in the preparation of the alkoxylated nylon.

Polyamides can also be reacted with ethylene oxide to give a nylon in which polyethylene oxide side chains are attached to the polyamide. These modified polyamides

show less change in melting point and solubility than polyamides that have *N*-alkyl or *N*-alkoxyalkyl groups. Even for these polymers, however, properties are lowered considerably compared to the parent unmodified nylon.

3-2.2 POLYMER BLENDS

Polymer blends, one component of which is a given nylon homopolymer, can consist of a combination of different nylon homopolymers or some other class of polymer. When another class of polymer is used, it is incompatible with the nylon; thus special techniques must be used to achieve compatibility.

When nylons are mixed in a melt for a sufficiently long period of time, a random copolymer results from transamidation. However, if two different nylon homopolymers are coextruded using a short residence time in the melt, products can be obtained that are partly block copolymers and partly physical blends. Interestingly, for a combination of nylon 6 and nylon 11, the melting point of the high-melting nylon is depressed somewhat, but the low-melting one is relatively unaffected (Ref. 2).

A melt blend of nylon and polyethylene yields compositions that have improved permeability but such physical blends usually yield undesirable tensile properties. Grafting a polyhydrocarbon to nylons yields blends that do not phase separate in the melt and produces molding resins that are quite tough. For example, nylon 6/6 and a polyhydrocarbon can be extruded together to produce free radicals that attack the polyhydrocarbon, which in turn can be reacted with a third component, e.g., maleic anhydride, to produce an intermediate in situ that can react with amine end groups of the nylon to give a chemical bond. Thus bonding of the dissimilar polymer, which normally would phase separate, is achieved. An example of such a blend sold commercially is nylon and polypropylene.

Examples of grafting by high-energy radiation are in the literature. When vinyl monomers are grafted to nylons, it is claimed that improved dyeability, static resistance, light stability, and soil resistance can be achieved; such improvements would be especially advantageous for fibers.

3-3 MODIFICATION BY ADDITIVES

Most changes to polymers, either in structure or by simple use of additives, are made by the manufacturer of the resins. A few changes, such as compounding nylon granules with additives for lubricity or mold release, can be made by the user. Additives used for plastics in general often can be used in nylons as well. (See Refs. 3 and 4 for a general discussion of most of the additives in the following subparagraphs as they apply to most plastics; Ref. 5 discusses some additives specific to polyamides.)

3-3.1 PROCESSING MODIFIERS

Additives that modify processing are desirable to aid the flow of nylon granules, to alter melt viscosity, to accelerate crystallization, to avoid color formation, and to im-

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prove mold release. Foamed structures can be obtained by addition of a foaming agent.

Additives that function as lubricants by coating nylon granules can be very useful in injection molding because they lead to lower injection pressures and/or better filling of mold cavities. Very low amounts, 0.005 to 0.1 weight (wt) %, of additives such as ethylene-bisamides from long chain (12 to 20 carbon atoms) acids are claimed to be effective.

Additives to aid ejection of molded parts and bring about shorter cycle times can be surface coated on nylon granules or added in a melt. Addition of 0.05 to 0.1 wt % of purified sodium stearate is claimed to improve mold release without loss of clarity.

Nylons usually crystallize by development of nuclei that serve as sites for crystal growth. When crystallization is initiated, crystalline aggregates of microscopic size known as spherulites form. Nucleating agents can accelerate crystallization and lead to smaller, more uniform spherulites. Controlled nucleation and spherulite growth can give products having increased modulus, yield stress, and hardness, but the tradeoff is decreased elongation.

Desirable features of nucleating agents are fine particle size, polar surfaces capable of attracting amide groups, nonmelting at the temperature at which the nylon is prepared or used, and no tendency to agglomerate near the melting point of the nylon. Some suitable agents include sodium phenylphosphinate, magnesium oxide, lead acetate, silicas and aluminas, graphite, and molybdenum disulfide.

Nylons may be foamed by any number of familiar foaming systems: volatile solvent, decomposable compounds, and injection of inert gases. However, difficulty in achieving low densities is observed, which most surely is due to the low melt viscosity and the high melting points for most nylons compared to the decomposition temperatures of most blowing agents. Foamed nylon is not commercially significant despite the fact that when saturated with lubricating oil, it can make excellent bearings and bushings.

3-3.2 STABILIZERS

Nylons without stabilizers are subject to considerable degradation by heat and/or light. Over the years a number of very useful compounds have been found, mostly through trial and error. Some reviews have enumerated these stabilizers, which include alkylated phenols, polyphenolics, aromatic amines, and organic phosphites. Some of the compounds listed as useful for heat stability have also been found to be useful for light stability, probably because these compounds suppress free radical mechanisms. It is important to note that some antioxidants which prevent degradation do *not* prevent color formation.

Certain inorganic stabilizers are among the most effective ones, impart little color to nylon, and are cheap. These

include copper halides, manganese and cobalt compounds, and phosphinic acid derivatives. For the ultimate in long-term durability outdoors where exposure to light and air pollutants is likely, carbon black is probably the best additive available.

3-3.3 FIRE RETARDANTS

For some applications, flame- and smoke-retarding additives may be required for nylon resins. It can be postulated that with increasing alkylene chain length, nylons will show poorer resistance to combustion. Consequently, some nylons may require more additives than others. Oxides and halides of various metals, e.g., antimony, and phosphorous compounds are among the most useful additives. The additive used must be carefully chosen so that it does not degrade physical properties, e.g., melting point, too much or interfere with other characteristics, e.g., electrical insulating properties, of the unmodified nylon. Most additives used by manufacturers of resins are trade secrets.

3-3.4 COLORANTS*

Commercial nylon resins of many colors compounded by the manufacturer are available. The colorants are used in small quantities, i.e., 1% or less, and have little or no effect on the properties of the nylon resin. Lightfastness of the colors may vary widely according to the dye or pigment used.

Nylons can be colored with organic dyes, which normally would be soluble in the polymer melt, and with pigments, organic or inorganic, which are generally insoluble in the polymer melt. Some examples of colorants used for nylons are listed in Table 3-1. The organic dyes and very finely divided pigments are suitable for end-uses in which the item is to be translucent. Examples of colorants that yield opaque and translucent nylons are given in Table 3-2.

The dyes and pigments selected for use in nylon resins must be stable and nonvolatile at the melt temperature of the nylon, nonreactive with the polymer, and dispersible and must not reaggregate during processing.

Although it is usual to purchase colored resins from a supplier and/or manufacturer, in some instances it may be desirable to alter the shade of color. When a lighter color than that of the purchased colored resin is desired or a lower cost resin is desired, the colored resin ("master batch") may be blended with an uncolored, i.e., natural, one. For highest color uniformity, tumbling barrels can be used prior to extrusion of the resin. Color blending can be done in screw-injection molding machines. The usual precautions to exclude moisture during melt blending apply.

Natural resin may be blended with a pigment in a rotating blender; blending times at approximately 30 rpm are 15 min or more depending on the ease of dispersion.

*White and black resins, although not considered colored, are available. Titanium oxide is usually used to enhance whiteness, and carbon black, to give a deep black. These variants may have more than the usual 1% or less of additive.

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TABLE 3-1. SOME WIDELY USED COLORANTS FOR NYLONS (Ref. 6)

CLASS	GENERIC NAME	COLOR
Dye	Nigrosine	Wide color range
	Induline	Wide color range
Organic pigment	Anthraquinone	Red
	Phthalocyanine	Blue
	Phthalocyanine	Green
	Carbon black	Black
Inorganic pigment	Titanium dioxide	White
	Zinc sulfide	White
	Lithopone	White
	Zinc oxide	White
	Cadmium sulfoselenide	Maroon, red, orange
	Cadmium mercury	Maroon, red, orange
	Ultramarine	Red
	Ultramarine	Pink
	Ultramarine	Violet
	Chrome-tin	Pink
	Cadmium sulfide	Yellow
	Titanium pigment	Light yellow
	Cobalt aluminate	Blue
	Chrome cobalt aluminate	Turquoise
Ultramarine	Blue	
Ultramarine	Green	
Special	Ceramic black	Black
	Metallic oxides	Browns
	Aluminum plastic grades	Silver
	Bronze plastic grades	Red-gold to yellow-gold

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TABLE 3-2. OPAQUE AND TRANSLUCENT COLORANTS FOR NYLON PLASTICS (Ref. 7)

COLOR	APPROXIMATE WT %	COLORANT	COLORANT SUPPLIER
OPAQUE FORMULATIONS			
White	0.5	Ti-Pure® R960	Pigments Department, Dupont
Yellow	0.5	Cadmium Yellow 1470	Harshaw Chemical Company
Orange	0.5	Cadmium Orange 1510	Harshaw Chemical Company
Red	0.5	Cadmium Red 1540	Harshaw Chemical Company
Blue	0.7	Ultramarine Blue UB9055	Pigments Division, Chemtron Corporation
Turquoise	0.5	Ferro Turquoise V7610	Ferro Corporation
Green	0.25	Ultramarine Blue UB9055	Pigments Division, Chemtron Corporation
Black	0.25	Cadmium Yellow 1470	Harshaw Chemical Company
	0.5	Induline Base 5G	American Cyanamid Company
TRANSLUCENT FORMULATIONS			
Yellow	0.2	Irgacet® Yellow 2GL	Geigy Corporation
Blue	0.1	Monastral® Blue G BT-383D	Pigments Department, Dupont
Green	0.1	Monastral® Green G GT-751D	Pigments Department, Dupont
Pink	0.1	Sulfo Rhodamine B	GAF Corporation

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3-3.5 PLASTICIZERS

Water alone is an effective plasticizer for nylons because it lowers the α -transition. Chemicals that tend to remain in the nylon throughout processing and that disrupt hydrogen bonding are suitable permanent plasticizers. These include carbonamides, sulfonamides, phenolics, aliphatic diols, and phosphite esters.

The choice of plasticizer, if one is needed, depends on factors such as cost, compatibility with the nylon chosen, processing behavior, solvent exposure of the end-use item, and whether the item will be exposed to unusually low (or high) temperatures, which can squeeze out the plasticizer. The plasticizer lowers the melting point of the nylon according to the mole fraction used.

3-3.6 LUBRICATING AIDS

In addition to lubricating aids for processing, there are compounds that aid in imparting higher lubricity to the end-use items. Some such aids include molybdenum disulfide, polytetrafluoroethylene, and graphite. Machined parts containing 0.25 to 4.0% molybdenum disulfide are claimed to have equivalent or better tensile and wear properties than unmodified parts and about one-half of the coefficient of linear thermal expansion. Dry bearings of nylon 6/6 containing this additive can be run at up to 50% higher PV (pressure \times velocity) ratings than those of unmodified resin (Ref. 8), and the wear rate against steel is reduced by about 50%. Dry modulus is increased by some 45%, and both Izod and tensile impact strengths are reduced by up to 35% (Ref. 8). Although nylons containing polytetrafluoroethylene or graphite are commercially available, they always contain glass fiber also.

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3-3.7 ANTISTATIC AGENTS

Use of antistats in nylon plastics is rare because absorption of water under most end-use conditions provides sufficient surface conductivity. A static charge may develop if the polymer is quite dry, but this is seldom the case. Antistatic agents are quite important for fibers, however.

3-4 MODIFICATION BY REINFORCEMENT

The use of fillers and reinforcing agents extends the usefulness of nylon into areas in which very high toughness is desired. Additives that bond the fillers and reinforcing agents to the polymer matrix make them more effective.

3-4.1 FILLERS

Inert inorganic fillers, e.g., talc, kieselguhr, mica, silica, and formerly asbestos (now largely replaced with Kevlar® pulp in many thermoplastics and thermosets), can be used in nylon resins. Silica-filled nylon, e.g., 10 wt % of 17 nm, has considerably higher (about 30%) flexural modulus at room temperature and retains it better (up to 50% at 150°C) with increasing temperature. There is, however, decreased

tensile strength (55.6 vs 61.2 MPa (8070 vs 8870 psi)) and elongation (140 vs 253%). Comparison of glass-fiber-reinforced specimens and a mineral-filled specimen is given in Table 3-3.

3-4.2 GLASS FIBERS

Although asbestos formerly was widely used for reinforcement of nylon, glass fiber is currently the most important fiber reinforcement because of its low cost. Other fibers, e.g., graphite and Kevlar® pulp, are used, and there is potential for other high-modulus fibers, e.g., those based on aromatic polyesters.

A wide range of nylons reinforced with glass fibers is available commercially. Among the variables that determine how a nylon is compounded are level of reinforcement in wt %, degrees of lubricity aids, fire retardants, and other modifiers discussed previously. The most common form of glass fiber used is E-glass, which has the following salient properties prior to use:

Tensile strength*, 345 MPa (5×10^5 psi)

Tensile modulus, 72,000 MPa (10.5×10^6 psi)

TABLE 3-3. PROPERTIES OF GLASS-REINFORCED NYLON 6/6 AND MINERAL-FILLED NYLON 6/6 (Ref. 9)

PROPERTIES	ASTM METHOD	UNITS	30% GLASS-FIBER REINFORCED	40% GLASS-FIBER REINFORCED	40-45% MINERAL-FILLED
Tensile strength at break	D 638	MPa (psi)	193* (28,000)	226* (32,800)	97*; 76** (14,000); (11,000)
Elongation at break	D 638	%	2.5*	2.5*	7-10*; 16**
Tensile modulus	D 638	MPa $\times 10^2$ (ksi)	NA NA	117* (1700)	62.1*; 34.5** (900);(500)
Compressive strength (rupture at yield)	D 695	MPa (psi)	193* (28,000)	260* (37,700)	107-152* (15,500-22,000)
Flexural strength	D 790	MPa (psi)	276* (40,000)	339* (49,100)	152*; 62** (22,000); (9000)
Flexural modulus	D 790	MPa $\times 10^2$ (ksi)	89.7* (1300)	110.3* (1600)	62-72.4*; 27.6** (900-1050); (400)
Izod impact	D 256	J/m (ft-lb/in.)	214* (4.0)	368* (6.9)	48-75*; 208** (0.9-1.4); (3.9)
Deflection temperature under flexural load	D 648	°C (°F)	257 (495)	NA NA	149-225 (300-438)
	D 648	°C (°F)	263 (505)	254 (490)	160-249* (320-480)
Specific gravity	D 792	—	1.4	1.45	1.39-1.5
Water absorption					
24 h	D 570	%	0.9	NA	0.6-0.55
saturation	D 570	%	NA	NA	6.0-6.5

* dry as molded

** conditioned to equilibrium with 50% relative humidity

NA = data not available

*Routine handling reduces this value to about one-half.

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Coefficient of linear thermal expansion, $5.0 \times 10^{-6}/^{\circ}\text{C}$
Specific gravity, 2.54.

The degree of reinforcement can be approximated by the rule of mixtures when the short glass, i.e., chopped fiber, meets some critical aspect ratio (length/diameter). However, because the fibers are discontinuous and not precisely aligned (The only alignment imparted comes from the extrusional flow during molding.), only a portion of the calculated tensile strengths is achieved. For example, for dry nylon 6/6 containing about 33% glass fiber, 80% of theory is approached for tensile strength.

Another very important variable is the fiber finish used to facilitate fiber handling. An inappropriate finish can decrease the tensile strength of a nylon composite considerably compared to a better chosen one. Equally important to choice of finish is the length of the chopped fiber. Over the range of 0.25 to 0.5 mm fiber length, the tensile strength may vary by 20% or more for a good finish.

The optimum concentration of glass fiber in nylon depends on the specific application, which will determine the properties desired, the processing conditions allowed, and

the cost requirement. Although loadings of fiber from 6 to 60 wt % have been offered commercially, the more common range is 20 to 40% glass fiber. Tensile strengths increase monotonically from about 206.8 MPa (3×10^4 psi) over the range 20 to 40% fiber loading and increase only to about 241.3 MPa (3.5×10^4 psi) for 40 to 60% loading. Elongation for dry-as-molded specimens falls from about 3 to 2% between 30 to 50% fiber loading; the drop is about 3.5 to 3% at 100% relative humidity. (The larger values are due to plasticization of the nylon by water and to a lesser degree to the influence of water on glass fiber.) Flexural modulus for dry-as-molded composites varies from 6.9 to 13.8 GPa (1 to 2×10^6 psi) over the range of 30 to 50% fiber loading.

The effect of 30 to 33% glass-fiber loading on several types of nylons, e.g., 6, 6/6, 6/10, 6/12, 11, and 12, with regard to a large number of properties has been summarized, as shown in Table 3-4, by Kohan (Ref. 6). These data tend to show that nylon 6/6 is superior in almost all properties to the other nylons.

One of the important conclusions drawn from data on

TABLE 3-4. PROPERTIES (DRY AS MOLDED) OF SEVERAL GLASS-FIBER-REINFORCED NYLON PLASTICS (Ref. 6)

PROPERTY	ASTM	UNITS	NYLON 6/6 30-33% GLASS	NYLON 6 30% GLASS	NYLON 6/10 30% GLASS	NYLON 6/12 33% GLASS	NYLON 11 30% GLASS	NYLON 12 30% GLASS
Specific gravity	D 792	—	1.37-1.38	1.37	1.31	1.32	1.25	1.23
Melting point	D 789	$^{\circ}\text{C}$ ($^{\circ}\text{F}$)	257 (495)	216 (420)	216 (420)	213 (415)	185 (365)	175 (347)
Mold shrinkage, 0.32-cm (1/8-in.) thick, flow direction	—	$(\Delta L/L) \times 10^{3*}$	3.5-5	3.5	3.5	3	—	1.5
Water absorption, 23 $^{\circ}$ (73 $^{\circ}$ F)/24 h	D 570	%	1.0	1.2	0.2	0.2	0.12	—
Water absorption, saturation	D 570	%	5.7	6.5	2.1	2.0	1.4	1.0
Tensile strength, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 638	MPa (lb-in. $^{-2}$)	179.3-193.1 (26,000-28,000)	162.0 (23,500)	144.8 (21,000)	165.5 (24,000)	96.5 (14,000)	120.0 (17,400)
Tensile elongation, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 638	%	2-4	3-4	3-4	4.5	3-4	3-4
Flexural modulus, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 790	MPa (lb-in. $^{-2}$)	8963 (1,300,000)	8274 (1,200,000)	7584 (1,100,000)	8274 (1,200,000)	6033 (875,000)	6895 (1,000,000)
Flexural strength, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 790	MPa (lb-in. $^{-2}$)	262.0 (38,000)	241.3 (35,000)	220.6 (32,000)	—	137.9 (20,000)	151.7 (22,000)
Shear strength, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 732	MPa (lb-in. $^{-2}$)	86.2 (12,500)	82.7 (12,000)	75.8 (11,000)	75.8 (11,000)	—	—
Compressive strength, 23 $^{\circ}$ C (73 $^{\circ}$ F)	D 695	MPa (lb-in. $^{-2}$)	244.8 (35,500)	158.6 (23,000)	137.9 (20,000)	158.6 (23,000)	89.6 (13,000)	—
Izod impact strength, 23 $^{\circ}$ C (73 $^{\circ}$ F), 0.32-cm (1/8-in.) bar	D 256	J-m $^{-1}$ (ft-lb-in. $^{-1}$)	91-112 (1.7-2.1)	—	—	—	—	—
Izod impact strength, 23 $^{\circ}$ C (73 $^{\circ}$ F), 0.635-cm (1/4-in.) bar	D 256	J-m $^{-1}$ (ft-lb-in. $^{-1}$)	—	123 (2.3)	128 (2.4)	139 (2.6)	117 (2.2)	160 (3.0)
Rockwell hardness	D 785	M-scale	101	92-100	93	(R118)	—	—
Deformation under load, 27.6 MPa (4000 lb-in. $^{-2}$), 50 $^{\circ}$ C (122 $^{\circ}$ F)	D 621	%	0.8	0.9	0.9	—	—	—
Deflection temperature, 1.8 MPa (264 lb-in. $^{-2}$)	D 648	$^{\circ}\text{C}$ ($^{\circ}\text{F}$)	249 (480)	216 (420)	216 (420)	210 (410)	171 (340)	174 (345)
Coefficient of linear thermal expansion	D 696	$(\Delta L/L) \times 10^{6}/^{\circ}\text{C}$ ($^{\circ}\text{F}$)	2.3-2.9 (1.3-1.6)	3.1-3.8 (1.7-2.1)	2.7 (1.5)	2.3 (1.3)	5.4 (3)	13.5 (7.5)
Thermal conductivity	—	kcal-h $^{-1}$ -m $^{-2}$ ($^{\circ}\text{C}/\text{m}$) (Btu-h $^{-1}$ -ft $^{-2}$ ($^{\circ}\text{F}/\text{in.}$))	0.19 (1.5)	0.20-0.41 (1.6-3.3)	0.20-0.43 (1.6-3.5)	—	—	(0.48) (3.9)
Specific heat	—	—	0.3-0.4	0.35	0.34	—	—	—
Dielectric strength, step-by-step	D 149	kV mm $^{-1}$ (V mil $^{-1}$)	16-17 (400-440)	17 (435)	19 (440)	19 (490)	—	—
Volume resistivity	D 257	Ω -cm	5×10^{14} - 5×10^{15}	5×10^{14}	8×10^{13}	10^{15}	—	—
Surface resistivity	D 257	Ω	3×10^{14}	9×10^{13}	10^{15}	10^{15}	—	—
Dielectric constant, 10 3 cycles	D 150	—	4.0-4.5	4.3	3.8	3.7	—	—
Dissipation factor, 10 3 cycles	D 150	—	0.02	0.03	0.015	0.024	—	—

*L = length

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nylon composites reinforced by glass fibers is that the physical properties of these composites are greatly enhanced with regard to absorption of moisture. Thus although absorption of water greatly decreases the modulus of nylon reinforced with glass fiber at all fiber loadings, such composites can have a higher modulus at 100% relative humidity than unmodified dry nylon, 4137 vs 2758 MPa (600,000 vs 400,000 psi), respectively, for a 33% glass-fiber loading vs 0% loading. Fig. 3-1 (Ref. 10) shows data for tensile strength vs time for samples exposed to water at 100°C (212°F). Fig. 3-2 (Ref. 11) shows tensile strength data for a glass-reinforced specimen (molded from

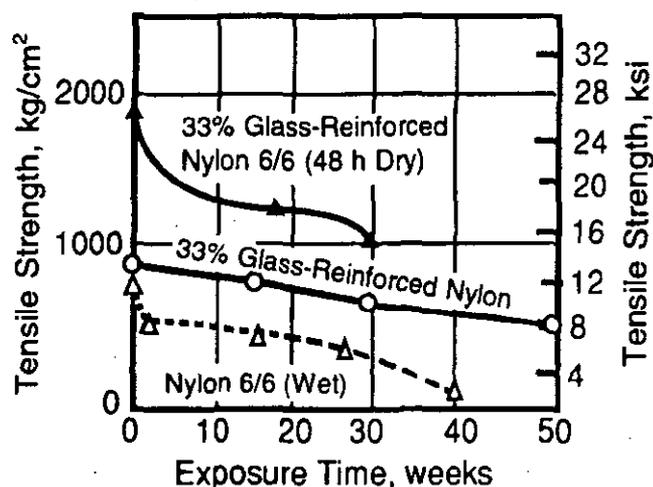
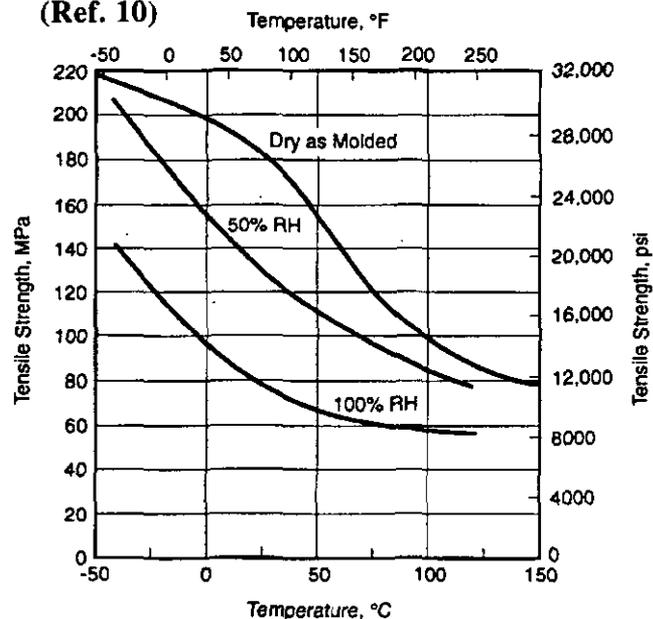


Figure 3-1. Resistance of 33% Glass-Reinforced Nylon 6/6 to the Effects of Water at 100°C (Ref. 10)



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Figure 3-2. Tensile Strength Versus Temperature and Moisture for Zytel® 70 G-33L, Cross-Head Speed 0.2 in./min (Ref. 11)

Zytel® 70G-33L) under hot, moist conditions. Other important properties that are significantly improved are resistance to hydrolysis, weathering, and oxidation.

Commercially compounded compositions are available with long glass fibers and short ones. The short-glass-fiber-reinforced materials are extrusion compounded. The polymer and the chopped fibers are blended together, processed through an extruder, stranded, and pelletized. The long-fiber-reinforced compounds are processed by pultrusion. Thus continuous glass fibers are run through a molten resin bath that wets out the fibers, which are then cooled and chopped into pellets of the desired length. The long-fiber compounds offer better performance than the short-fiber ones, albeit with some loss of ease of processing. The strength, impact resistance, and stiffness of the nylons are improved by the use of longer fibers. The resins containing the long fibers also show improved long-term retention of physical properties at elevated temperature, lower warpage, and differential shrinkage; surface finish also is better.

Because of fiber breakage during both initial mixing with nylon (which occurs during the compounding stage) and after molding of the resin, the average fiber length can decrease considerably from its initial value. For example, the fiber lengths are 0.8 mm, 0.5 mm, and 0.35 mm for fiber in virgin resin, after the first molding, and after the fifth molding, respectively. Increased screw speed or back pressure and lowering of the rear zone temperature also increase fiber breakage. When 100% rework has gone through four successive moldings, i.e., the fifth molding is compared to the first, a nylon 6/6 test specimen showed a 20% decrease in tensile strength, a 15% decrease in flexural modulus, a 40% decrease in Izod impact strength, a 45% decrease in tensile impact strength, a 5% decrease in shear strength, and a marked increase in mold shrinkage.

3-4.3 GLASS SPHERES

Solid glass spheres used in other plastics may also be used in nylon resins. Such glass spheres are made from A-glass instead of the E-glass used for fibers. These spheres, which have an average 325 mesh and a diameter of about 0.03 mm (0.0012 in.), have lower initial properties compared to the virgin strength of E-glass: 4.5% lower modulus, a nearly doubled coefficient of expansion, and a 3% lower density. It should be recalled, however, that during processing of virgin E-glass, the tensile strength may drop as much as 20 to 50%.

The spherical shape of the A-glass particles causes less increase in melt viscosity than glass fibers, which allows higher loadings. Because fiber aligns in the flow direction during molding and spheres do not, properties related to directionality are consequently lower for glass-sphere-filled composites. However, compressive strength is high. A summary of some properties of a nylon 6/6 composite containing glass spheres is given in Table 3-5.

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TABLE 3-5. PROPERTIES OF A NYLON 6/6 COMPOSITE CONTAINING 40% GLASS SPHERES (Ref. 6)*

Specific gravity	1.43
Tensile strength, MPa (lb/in. ²)	97.9 (14,200)
Ultimate elongation, %	2.5 (36,500)
Flexural modulus, GPa (lb/in. ²)	5.04 (731,000)
Compressive strength, MPa (lb/in. ²)	251.7(36,500)
Izod impact strength, J/m (ft-lb/in.)	32 (0.6)
Rockwell hardness	R117
Deformation under load of 27.6 MPa (4000 lb/in. ²) at 50°C (122°F)	0.8
Deflection temperature under load of 264 lb/in. ² , °C (°F)	74 (165)
Coefficient of linear thermal expansion, $\Delta L/L \times 10^5 \text{ }^\circ\text{C}^{-1} (\text{ }^\circ\text{F}^{-1})$	5.2 (2.9)

*Data suggest that measurements were made on dry specimens, although this is not stated specifically in the reference.

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CHAPTER 4

PROCESSING METHODS

The various molding and processing techniques used for nylon resins, with emphasis on the injection molding and extrusion processes, are discussed in this chapter. The topics covered include materials handling, drying, molding machines, and injection molding and extrusion operations. Blow molding, casting, and methods based on powdered nylon resins, such as fluidized-bed coating, electrostatic coating, pressing and sintering, and rotational molding, are also described. A discussion is presented on annealing and moisture conditioning of molded parts to reduce internal stresses. A table outlining military applications fabricated by the techniques discussed is included.

4-1 INJECTION MOLDING

Since about 1948 injection molding has been used to produce nylon parts. The nylon industry has grown from a modest beginning to one that produces a diversity of products having a wide range of physical properties and using a variety of processes for their fabrication. The growth of the nylon and other thermoplastics industries has caused the injection molding industry to grow also. Injection molding is a process of heating a thermoplastic such as nylon to liquid form and putting this liquid into a relatively cold mold where it solidifies at the liquid/mold interface and takes the shape of the mold cavity.

4-1.1 MATERIALS HANDLING

The affinity of nylons for moisture and the effects of moisture and contaminants on the characteristics of the material require careful handling of materials. For consistent product quality the feed system must supply a uniform stream of raw material. A well-engineered materials handling system must do the following:

1. Expose the materials to a low, uniform level of moisture.
2. Avoid contamination.
3. Maintain a controlled, adequately high temperature.
4. Minimize waste and spillage.
5. Supply the molding system with a stream of ground material that has a uniform virgin-to-regrind ratio, particle size, and level of material in the hopper.

4-1.1.1 Control of Moisture

Different nylon polymers absorb water at different rates and have different levels of moisture saturation. The absorption rates and saturation levels are shown in Table 4-1. These values are based on testing conducted in accordance with American Society for Testing and Materials (ASTM) D 570, "Standard Test Method for Water Absorption by Plastics".

Inadequate moisture control can lead to such moisture-related problems as splay*, blisters, and drooling** in the final product, which result in decreased product quality and downtime while problems are resolved. Minimizing moisture contamination requires sealed material storage, mini-

*Splay is a surface defect usually consisting of small, "V"-shaped marks on the surface in mild cases to a frothy surface appearance in more severe cases.

**Drooling is the unwanted running or dripping of the nylon melt from the injection system between injection cycles.

TABLE 4-1. ABSORPTION OF WATER BY NYLONS (WT% ON DRY BASIS)* (Ref. 1)

NYLON TYPE	24-h EXPOSURE** ASTM D 570	AT EQUILIBRIUM WITH 50% RH	AT SATURATION
6	1.6	2.7	9.5
6/6	1.5	2.5	8.0
6/10	0.4	1.5	3.5
6/12	0.4	1.3	3.0
11	0.25	0.8	1.9-2.9†
12	0.25	0.7	1.4-2.5 est†

* Data from trade literature

** Water immersion

† Varies with temperature

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mum material exposure to the ambient environment, and control of that environment. The plant environment should be controlled by air-conditioning and dehumidifying equipment to keep the relative humidity (RH) below 35% and the temperature below 24°C (75°F) at all times.

Local environment control for exclusion of moisture in the vicinity of the machine can be used. Partial exclusion of moisture can be achieved with dehumidified hopper dryers that reduce the humidity of the air in contact with the raw material while it is within an automatic, closed material handling system. Total elimination of exposure to moisture can be achieved by purging the material handling system with inert gases. To be economically feasible, however, such systems must be leakproof to avoid losses of the relatively expensive gas. This requirement increases the cost and complexity of the system. The use of a blanket of inert gas reduces the oxidation of nylons in dryers having high temperatures (above 66°C (150°F)) and requiring long residence times.

Nylons should be stored in a dry environment at a temperature near that of the machine to prevent condensation of the water on the material as it enters the machine environment. When storage at temperatures below those of the machine environment cannot be avoided, the storage container must be allowed to equilibrate to the molding area

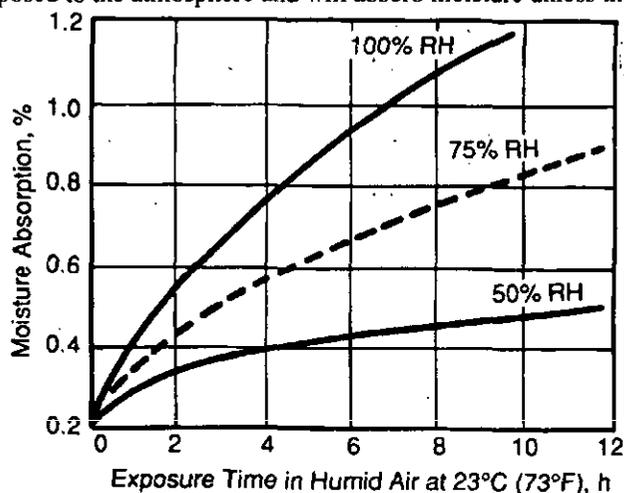
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temperature before it is opened. Storage should incorporate a "first in, first out" inventory policy.

Bulk nylon material is customarily supplied in containers ranging from 11.3-kg (25-lb) cans or 22.7-kg (50-lb) bags to 544-kg (1200-lb) cartons. The package size used should be compatible with the scale of the molding operation. Alternatively, smaller containers can be used to provide some flexibility if jobs of different sizes must be accommodated. Individual containers can be used for small-scale jobs, and multiple containers can be used for larger jobs. This method allows one size of container to be stocked and reduces the number of partially full containers that contain leftover material. The moisture pickup for nylon loaded into a hopper of a molding machine and drawn into the machine at a constant rate is proportional to one-half the time required to empty the container, i.e., 0.5 times the size of the container divided by the rate of resin consumption. The moisture absorption can be estimated by the absorption curves shown in Fig. 4-1 (Ref. 2). For material being reground the time of absorption prior to the grinding should also be considered in the estimate of absorption because the absorption by reworked resin before and after grinding is the most likely source of excessive moisture.

Under normal conditions the raw nylon material should be dried if it contains over 0.3% water unless it is used in processes that use high temperatures or long cycles. Under the latter conditions drying is necessary if the moisture content is above 0.2%.

In general, times of atmospheric exposure for nylon polymer at the loading station, through tubes, and in conveyors cannot be controlled unless there is uniform flow and accurate metering. Material passing through these systems is exposed to the atmosphere and will absorb moisture unless the



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Figure 4-1. Moisture Absorption of Nylon 6/6 Pellets (Ref. 2)

*A runner is a passageway in the mold that conveys the melted plastic from the point at which the mold joins the injector system (the sprue) to the mold cavity or cavities. Runner system, or "runner", also refers to the material that solidifies in these passageways.

environment is dehumidified. The optimal solution consists of total and prompt feedback to the control systems in order to maintain direct and constant flow of material, and it consists of selection of a container size whose contents will be consumed in a moderately brief time.

4-1.1.2 Control of Contamination

Contamination is the introduction of unwanted materials into the nylon being molded, and it arises from actions such as improper packaging and storage of raw materials, insufficient cleaning of equipment between production runs, improper lubrication, and poor machine maintenance.

Between production runs and especially after a change of molding material, the hoppers, conveyor, and grinding equipment and the screw, nozzle, nozzle valve, and barrel of the injector should be carefully examined and, if necessary, cleaned. The equipment should be configured so that rust, lubricants, and paint from the molding or auxiliary machines cannot enter the raw material stream. Defective valves, manifold surfaces, fittings, and failed O-rings can contribute to oil contamination problems and thus should be kept in good repair. Grease contamination is usually caused by overlubrication. Chilled molds may cause condensation, which can lead to rust or moisture contamination of the melt.

The purity necessary for plastics used in biomedical applications, aerospace, computers, and communication equipment drives the requirements for stringent control of contaminants during plastic manufacturing. "Clean room" technology developed by the semiconductor industry is being applied to production of plastics for applications for which purity specifications are high. Such facilities are described in Refs. 3 and 4.

Contamination of nylon can occur by use of dirty storage containers that contain dust, dirt, or residue from other materials previously stored in them. The containers should be kept sealed when not in use to prevent contamination with dust or dirt. Reusable containers should be cleaned thoroughly to remove any residue of previously stored materials since moisture or static charges may cause the "fines" and "shavings" of previous contents to adhere to the walls and bottoms. Paper bags should be opened by clean cutting rather than tearing to prevent paper fibers from falling in the nylon.

The raw materials, products, and scrap for regrinding should be examined frequently. Particular attention should be given to the material being reground since it has had longer exposure to the environment than virgin material.

The automatic material handling systems that handle molded parts and scrap, e.g., runners*, should protect the parts from contamination while accommodating a wide variety of shapes of parts and runners. Temporary fixes such as cardboard shields or covers are seldom satisfactory be-

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cause they provide little protection from contamination from the environment. Covered conveyors offer better protection from dust and contaminants. Dry lubrication bearings, however, should be used in conveyors along with belts that are resistant to abrasion, oil, grease, and temperatures up to 93°C (200°F) (Ref. 5). The best approach to the transport of material is to use pneumatic and vibratory systems that keep the parts totally separated from the ambient environment.

The seams and gaskets of automatic loading equipment, dehumidified hopper dryers, and hopper feed ports offer a possible route from which fines can spill or contaminate the material stream. This route of contamination may be reduced by fitting relief openings with filters, better structural rigidity, gasketing, and separate screening of fines.

Grinders can contaminate the environment with powdered material that can contaminate other processes. The grinder feed chute should accept the various size runners and prevent unintended ejection of chips (flyback) from the grinder. An oversize feed throat is better than undersize. Auger grinders can be used to reduce the amount of flyback. Good fits and gasketing of the collection bins and rotor axle reduce spillage from grinders.

Ferrous metals can cause machine damage by plugging gates, interfering with check ring operation, or damaging the machine itself. These metals can be removed with large magnets. Nonferrous metal particles are harder to separate, so measures should be taken to prevent their introduction into the mix. Brass rods should not be used to remove material that has solidified and become lodged in the sprue, the inlet passageway through which the molten nylon is injected into the mold. Plastic rods are a better alternative because any residue could become part of the molding. Compressed air is not recommended for sprue removal for safety reasons.

Overheating nylon in the material handling system can lead to oxidation of the material and excessive absorption of moisture over a period of time. The effects can be reduced by either reducing temperatures or minimizing the time the nylon spends at elevated temperatures in uncontrolled environments. Usually it is not beneficial to cool heated material between steps in the process since the material would have to be reheated. Instead it is more productive to minimize the residence time of the product between steps in the processing. At completion, however, it is desirable to cool the product before packaging to stabilize its dimensions and prevent discoloration. Dehumidified hopper driers should be temperature controlled. Temperatures need not exceed 80°C (175°F) to achieve effective drying. Residence time at these temperatures should be kept below four hours to prevent discoloration. Overloaded or improperly maintained grinders can heat the material being ground and cause localized high temperatures that can damage the grinder and/or the nylon.

4-1.1.3 Control of Feed

Control of feed refers to the characteristics of the raw material fed to the molding machine. Parameters to be controlled include the ratio of virgin-to-regrind resin, the particle size, and the feed rate, which is dependent on the level of material in the hopper. Variation in these parameters can lead to changes in processing characteristics, such as melt viscosity due to a change in molecular weight, melting rate because of variation in particle size, and freezing point via nucleation by chance contamination. These variations cause the product quality to fluctuate. In general, a constant 50% or lower regrind level will allow production of satisfactory nylon engineering parts. Only in very specific situations, such as the molding of glass-reinforced nylons, critical appearance applications, or tight dimensional control molding, does it become necessary for the regrind ratio to be held below 50%.

Grinding equipment should produce clean regrind with an average particle size close to that of the virgin nylon. Fines and shavings produced by the grinding process should be removed since they impair the function of automatic loaders by plugging filters. Because they absorb moisture and melt faster than the granular virgin regrind resin mix, they lead to an inhomogeneous melting and can cause product discoloration and degradation of properties. Fines and shavings can be removed with separators that use vibrating screens or cyclone.

For continuous stream processes the level of material in a feed hopper should remain constant to provide uniform exposure and feed rate. Level-sensing devices can be used in conjunction with a feedback control system to maintain a constant level in the hopper with limit switches to warn of a malfunction in the control system or supply.

Hoppers used with batch operation machines should be designed to provide a steady flow of material into the machine barrel with a minimum of turns or restrictions. The hopper should have sufficient capacity for at least one hour of machine operation.

4-1.1.4 Automatic Handling Systems

The considerations of subpars. 4-1.1.1 through 4-1.1.3 apply equally to manual and automatic material handling systems. Automatic systems do provide advantages in terms of the rate and precision at which the material is supplied, and they lead to reduced exposure to the environment, less contamination, and lower moisture content. However, for achievement of these improvements, the automatic system must be a well-engineered and well-maintained system (Ref. 6).

Automatic handling systems that transport the molded product away from the machine must reliably capture the molded parts and runners, separate the parts from the runners, and transport the desired parts to a station for packaging. Effective capture of the parts and runners requires consideration of the part ejection provisions of the mold design

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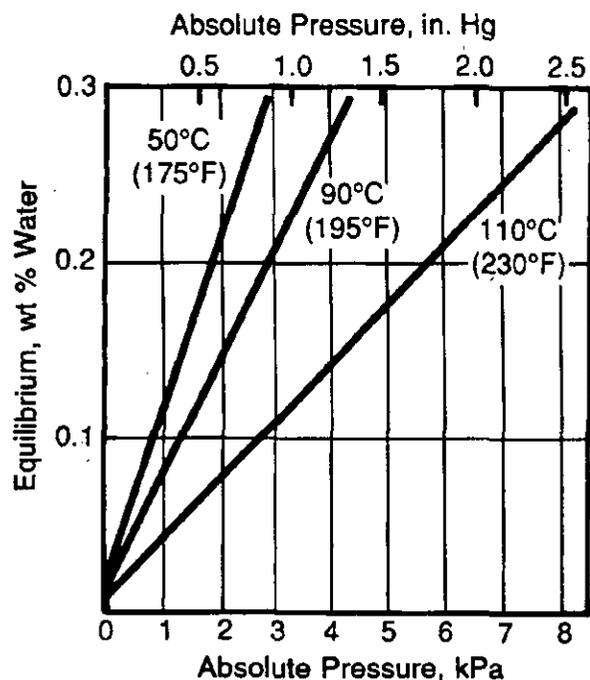
and baffles, doors, chutes, and other guiding assemblies that are a part of the material handling system designed to capture the ejected parts. Part-runner separation may be performed at the mold by designing the mold so that the desired parts are broken from the runners as they are removed from the mold. Robotic units can be used to sort the parts from the scrap runners as they are removed from the mold.

4-1.2 DRYING

The time required to dry ground nylon depends on the initial and target moisture contents, the dimensions of the polymer particles, the volume of the material to be dried, the flow rate of dry air through the material, and the temperature and humidity of the drying air. The granular resin should be dried in beds less than 25 mm (1 in.) deep for faster drying. The drying rate will vary slightly between different types of nylons, but the prior processing and conditioning will have a large influence on the drying time.

For maximum effectiveness of dryers the drying unit and the air ducts leading to it should be sealed to prevent the entry of ambient air. A vacuum may be used to improve the drying rate. The improvement depends on the temperature and is shown for nylon 6/6 in Fig. 4-2 (Ref. 7).

Hopper dryers offer a number of advantages. They minimize contamination by not mixing the air in the hopper with ambient air. They can be used in the feed stream of automated systems, either at the molding machine or farther



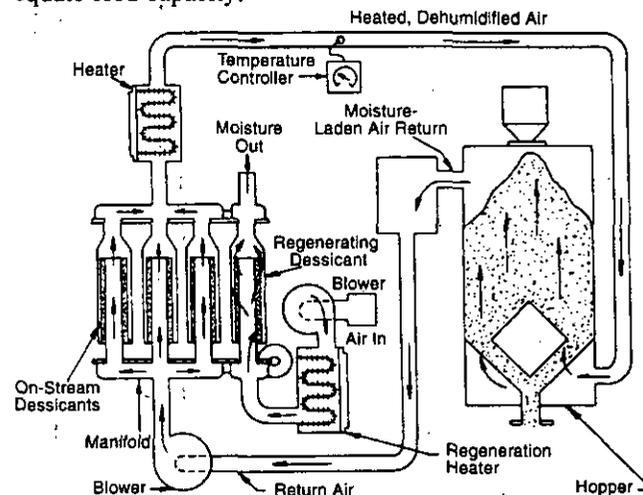
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Figure 4-2. Effect of Drying Temperature and Vacuum on Equilibrium Moisture Content of Nylon 6/6 (Ref. 7)

upstream. Although the material being dried in a hopper is bulk, which leads to longer drying times when compared to the thinner bed configuration, the hopper dryer permits countercurrent flow so that dry polymer is fed into the molding machine from the bottom, whereas moist resin is added at the top. Air passed through the dryer is dried by desiccant dryers employing several desiccant cartridges. One or more of the cartridges is used to remove moisture from the air while the remainder are being regenerated by a warm airstream. The cartridges are continually switched between drying and regenerating functions by a valve or a carousel arrangement. Fig. 4-3 shows a four-cartridge, carousel-type desiccant system using recycled air. Molecular sieves are commonly used as the desiccant because they are efficient and can be regenerated by purging with air heated above 205°C (499°F). No refrigeration system is required. Silica gel desiccant and mechanical dehumidifiers have also been used.

Sensing the humidity in the dryer allows detection and correction of malfunctions before defective products result from dryer failure (Ref. 9). Most commercial nylon resins are dried at about 82°C (180°F). Higher temperatures may cause oxidation of the resin surface, which yellows the resin. Drying times depend upon the initial moisture content of the resin and the relative humidity, temperature, and velocity of the drying air.

The manufacturer's recommended drying times for the drying system described in the preceding subparagraph are given in Table 4-2 for different air velocities at 71°C (160°F) for several types of nylons and hopper dryer sizes and drying system outputs (Ref. 8). The rate of heat energy in a drying system for an injection molding machine should be sufficient to dry at the required processing rates. Adequate drying capacity for the resin is as important as adequate feed capacity.



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Figure 4-3. Carousel-Type Hopper Dryer (Refs. 7 and 8)

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**TABLE 4-2. DRYING TIMES AND AIR VELOCITIES FOR CAROUSEL-TYPE
DRYERS AT 71°C (160°F) (Ref. 7)**

NYLON	WATER, %	TIME, h	AIR VELOCITY			
			0.057 m ³ /s (120 ft ³ /min)		0.113 m ³ /s (240 ft ³ /min)	
			HOPPER CAPACITY	OUTPUT	HOPPER CAPACITY	OUTPUT
11 or 12	1	2	118 kg (260 lb)	59 kg/h (130 lb/h)	238 kg (525 lb)	118 kg/h (260 lb/h)
6, 6/6, or 6/10	1	3	238 kg (525 lb)	86 kg/h (190 lb/h)	492 kg (1085 lb)	172 kg/h (380 lb/h)
6, 6/6, or 6/10	2	4	168 kg (370 lb)	45 kg/h (95 lb/h)	363 kg (800 lb)	86 kg/h (190 lb/h)

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The flow rate and pressure of the dry air from the dryer air supply must be sufficient to overcome the frictional losses in the interconnecting lines and the bed of material being dried. If the blower is undersized, not enough air is available, and insufficient energy is transferred to the material being dried to exsiccate it. Increasing the air temperature to overcome the reduced airflow causes two problems. First, the heat losses will increase and negate the expected gain from increasing the temperature. Second, if the drying air temperature is too high, the resin pellets may partially melt and stick in the lower portion of the hopper or in the throat of the molding machine.

An important design parameter of the hopper dryer is capacity because it determines the residence time, i.e., the length of time a batch of material is exposed to drying air. The residence time required for nylons is usually between 2 and 4 h. Therefore, the hopper should hold enough material to supply the machine at a typical feed rate for that length of time. Thus the capacity of the hopper should exceed the feed rate multiplied by the residence time. For example, 136 kg/h (300 lb/h) of a nylon with a residence time of three hours would need a hopper with a capacity of 408 kg (900 lb).

For even drying of the nylon resin pellets in the hopper, the drying air must flow evenly over each cross section of the hopper, and the vertical flow of the pellets must also be uniform over each horizontal cross section. A spreader cone in the bottom of the hopper helps to accomplish this uniform material flow and also helps to spread the air evenly around the pellets.

The shape of the hopper is a compromise. A tall, cylindrical hopper would provide the ideal, uniform airflow and material flow characteristics within each cross section. However, it will not usually fit in the available space, and it has a greater heat loss than a shorter, funnel-shaped hopper. The most common hopper shape is one with a height equal to twice its diameter. Because the material in the hopper is hotter than ambient, a better heat distribution and energy savings can be achieved by insulating the sides.

Additives used to color the nylon product should also be

dried. The drying temperature for most additives, however, is cooler than that of the resin since the melting temperature is lower. Therefore, a separate hopper for additives is necessary so they are not subjected to the resin-drying air.

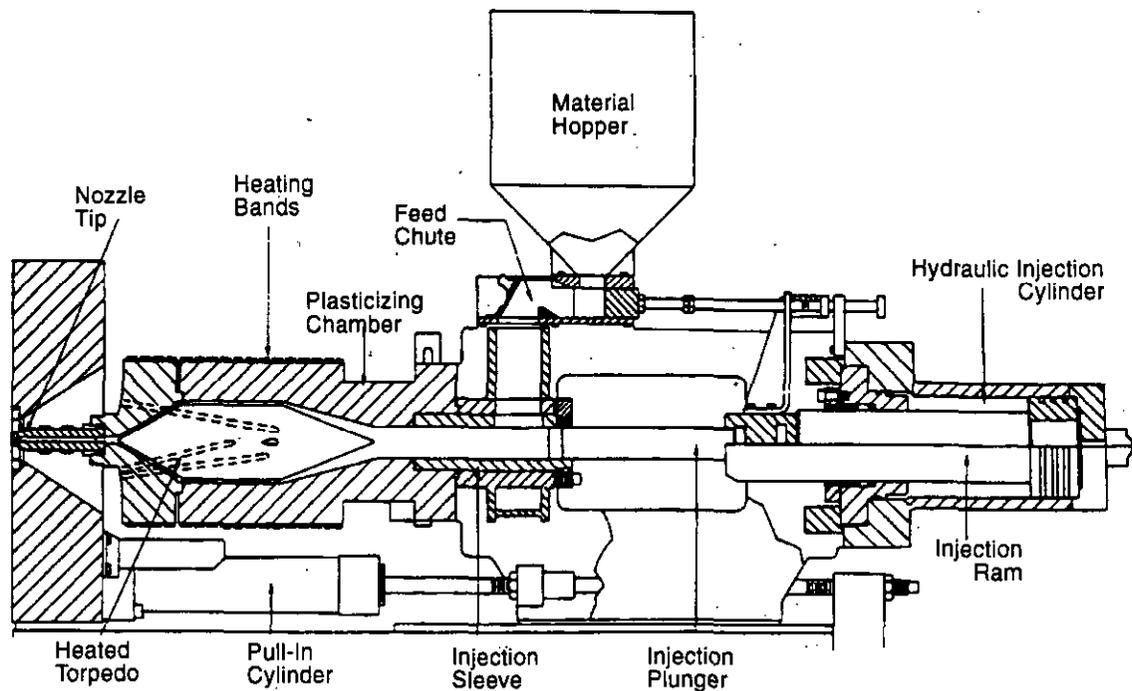
4-1.3 INJECTION MOLDING EQUIPMENT

4-1.3.1 Injection Molding Machine Types and Operation

There are basically two types of injection molding machines: a plunger-, ram-, type machine and a reciprocating screw. The straight plunger machine, the first type used for injection molding and now used only for a few applications, consists of a piston-type plunger in a heated chamber that forces resin, which was melted in the chamber, through a nozzle into a mold. This system, shown in Fig. 4-4, uses a "torpedo" to spread the stream of nylon resin as it flows past the heated walls to improve heat transfer to the resin and to homogenize the stream. The current plunger-type machine used is the two-stage screw-plunger, or screw-preplasticator. This injection unit uses an extruder screw to plasticize the nylon (first stage) and to feed it into an injection chamber. As the injection chamber fills, the injection plunger is forced back into the injection cylinder until it reaches a predetermined point. The screw stops and the injection plunger moves forward injecting the melt into the mold (second stage).

The reciprocating plunger screw machine uses a screw in a long, narrow, heated cylinder that pumps the resin material from the feed hopper to the nozzle end. The resin is melted by a combination of the energy transferred to the resin from heater strips surrounding the cylinder and from the mechanical work done on the resin by the screw. In operation the screw forces the resin along the cylinder until the pressure of the accumulating and melting resin at the nozzle end forces the screw away from the nozzle a predetermined distance. The screw is then forced forward by a hydraulic cylinder acting as a ram to force the melted resin through the nozzle into the mold. The resin in the mold is allowed to solidify, and the cycle is repeated.

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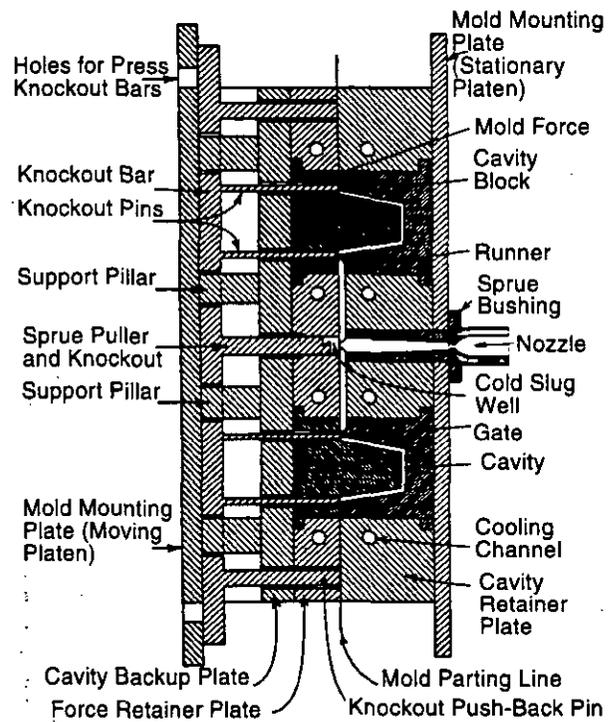
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Figure 4-4. Schematic Drawing of Injection End of a Single-Stage Plunger Machine (Ref. 10)

The mold is a two-part, hollow assembly with cavities shaped to produce the objects to be molded. Molten resin from the nozzle of the injection unit enters the mold through a common manifold, referred to as the sprue, and branches out through one or more channels, referred to as runners, to the cavities in which the finished products are to be formed. The typical mold, illustrated in Fig. 4-5, consists of two plates that may be separated to expose the mold cavities and the runners that feed them and thus allow for the removal of the molded products and the scrap material that solidifies in the runners. Knockout bars and a sprue puller, shown in Fig. 4-5, are included in one of the plates to eject the solidified resin from the parted mold.

In the injection molding process the resin (in either powder or pellet form) is dropped from a hopper into a heated chamber to be melted or softened. When the plastic has reached the molding temperature, it is pushed into a cold mold by a hydraulic ram through a small nozzle in the heated barrel of the machine. The injection mold is made of at least two pieces held together during injection of the melt with an opposing hydraulic ram or a mechanical toggle clamp. The melt squirts through the nozzle and into the cavity machined in the two halves of the mold; here it is quickly cooled to a temperature at which the part can be removed without distortion. The hydraulic ram is withdrawn to allow more plastic to drop into the heated chamber, and the clamp holding the mold halves closed is released to allow the part to be removed. Sometimes a rotating screw, shown in Fig. 4-6, is used to heat and pump the plastic resin into a reservoir immediately behind the nozzle.

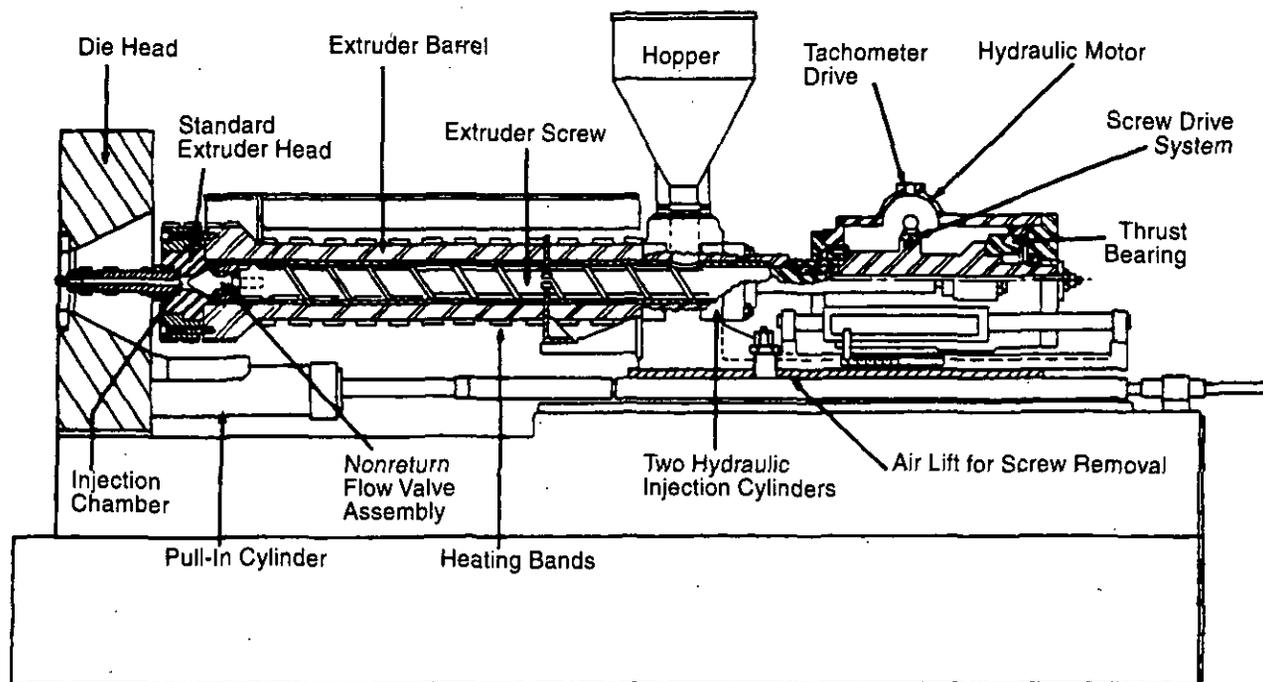
When injection occurs, the screw stops rotating and acts as a ram to push the melt into the mold cavity.



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Figure 4-5. Two-Plate, Two-Cavity, Edge-Gated Mold (Ref. 11)

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Figure 4-6. Injection End of a Reciprocating Screw Machine (Ref. 10)

Molten resin from the injection cylinder is injected into a multipart mold containing hollow cavities shaped to produce the desired products. A series of runners conveys the resin from the sprue to the cavities. After the material has solidified in the cavities and runners, the mold is opened and the solidified material is removed. The parts are passed on for further processing and/or packaging. The scrap material from the runners and sprue is reground and mixed with the virgin resin material for remolding.

4-1.3.2 Machine Design or Selection Considerations

4-1.3.2.1 Injection System

4-1.3.2.1.1 Mechanical Considerations

The injection cylinder must deliver the molten nylon to molds at sufficient pressure and rate to fill the mold and support the desired rate of part production. For molds having long, thin runners or molding cavities, injection pressures as high as 138 MPa (20,000 lb/in.²) may be required. The typical injection rates for nylons are around 49 cm³/s (3 in.³/s), but the requirement seldom exceeds 82 cm³/s (5 in.³/s). Almost all modern molding machines will inject at these rates.

Control of the amount of material injected into the mold (shot size) is important for good product yield. Factors that may negatively affect the metering include variability in the piston or screw travel during the injection stroke and leakage from the injection cylinder. The latter factor, leakage, includes both leakage of the material intended for injection

through cracks to the outside of the mold and leakage around seals or check valves that allow the melt to be forced back down the injection screw during the injection stroke.

For screw-type injection molding machines, the travel limits of the screw must be tightly controlled. Devices that stop the movement of the screw after recovery are often desirable to improve shot uniformity when electric drives are used. Unmelted material lodged in the check valve at the front end of the screw can allow some material to be forced back down the screw during the injection stroke and cause shot-to-shot variations. Devices to prevent overrotation of the screw contribute to better control of screw retraction.

Sensing of displacement is best accomplished by following movement of the screw—during both injection and retraction—with potentiometers or other position transducers. The sensed position may be used to indicate displacement or as an input to the control system. A fast-response control system is required to provide the repeatable screw movement needed for accurate shot control (Ref. 12).

Certain portions of the injection molding cycle are controlled by timers. Variations in timed intervals can affect shot size control. Solid-state timers allow control of time intervals to fractions of a second and offer improved performance over the mechanical timers they replace.

The nozzle tip used with a low-viscosity material such as molten nylon should be the reverse taper type to facilitate sprue extraction (removal of the solidified material from the mold sprue and the nozzle tip) and minimize drooling (the

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leaking of melted nylon from the end of the nozzle between injection segments of the molding cycle). The physical parameters of the nozzle design, i.e., bore length and diameter, are chosen based on resin mass flow and heat transfer considerations. Drooling is avoided by allowing the melt to solidify in the end of the nozzle. The solid part is then pulled out of the nozzle when the contents of the mold sprue are extracted from the mold. In fast-cycle operation longer nozzles are necessary so the heat from the injection machine does not prevent solidification of the melt in the nozzle. (Ref. 13)

Valves at the nozzle are also used with low-viscosity materials such as nylon to prevent drooling from the nozzle. A secondary benefit from use of these valves is separation of the molten nylon remaining in the injection cylinder from the nylon solidifying in the mold, which allows rotation of the screw while the contents of the mold are removed. These valves should be streamlined for flow and preheated to ensure proper operation.

4-1.3.2.1.2 Temperature Control

The injection end of a molding machine for nylons must have adequate heat energy from the combination of electrical power from band heaters and of mechanical power from the screw drive to melt and inject the nylon. Band heaters normally deliver a power density of 3.9 to 5.4 W/cm² (25 to 35 W/in.²) over the heated surface, and the screw drive should have 746 W (1 hp) for every 3.2 to 3.6 kg/h (7 to 8 lb/h) of melt output based on continuous rotation of the screw and on the assumption that an efficient screw is used to transfer the energy to the material.

The melt temperature in the nozzle depends on heater band regulation, back pressure, and screw design. To achieve heater band control, it is necessary to

1. Divide the heater bands into zones, preferably four.
2. Locate the temperature-sensing elements properly with respect to these zones.
3. Select the proper depth for the sensing elements in the wall of the barrel, and ensure contact.
4. Calibrate regularly the sensing elements and controllers.

Uniformity of screw retention depends on screw design, material factors, and operating factors. Material and operating factors are discussed in subpar. 4-1.4.

Fast-response, rugged thermocouples or platinum wire resistance temperature devices (RTD) with fast-response controllers or recorders should be used to measure and control cylinder and nozzle temperature. The RTDs eliminate the problem of cold junction compensation that is necessary for thermocouples. It is desirable to have continuous readouts of temperature rather than to depend on periodic inspections.

4-1.3.2.2 Mold Clamp

The portions of the mold must be held together with sufficient force that the melt does not force the mold halves apart and allow material to flow into the mold parting line and solidify. Such action causes a thin rib, flash, to be molded onto parts that has to be trimmed before the part can be used. The mold is supported between platens that provide the force to keep the halves together and the support to prevent deformation of the mold.

The platens must be parallel and rigid so the mold is evenly supported and does not deflect under high injection pressures. The front is inherently weaker because of openings for injection of the molten resin. Platen parallelism should be checked periodically. Care should be taken with small molds to see that the platens are not deformed by the localized stresses in them that are due to the compression of the smaller mold between them.

The clamp mechanism should apply pressure that is evenly distributed over the outer mold plates to keep the mold closed while the resin is being injected at high pressure. To minimize flash with the rather fluid nylon melt, clamping pressure should be 30 to 70 MPa (2 to 5 tons/in.²) for each unit area of the molding cavity and runners depending on the pressure required to fill the mold, which is usually between 48 to 62 MPa (3.5 and 4.5 tons/in.²). The molding cycle, including the opening and closing of the mold, should be accurately programmed and precisely timed. The opening and closing strokes should be cushioned (or decelerated) to minimize the shock to the mold assembly. Knockout pins used for ejection of the molded piece should be adjustable for position, speed, and sequence (multiple knockouts).

4-1.3.2.3 Molding Head Design

The mold must be designed to cast parts with the desired shape and dimensional tolerances, to minimize resistance to the flow of the melted resin, to remove heat quickly, and to facilitate extraction of the finished part and solidified scrap material.

The mold consists of two or more plates housing a molding cavity or cavities. Fig. 4-5 is a cross-sectional view of a two-plate mold showing the components used to distribute the molten resin, the cavity in which the part is formed, and the components used to eject the completed product and waste. The resin enters the mold through a sprue, the main channel into the mold, and divides among runners or channels, which carry the resin to the molding cavities. Knockout pins are used to free the molded part from the mold. A sprue puller, such as that shown in Fig. 4-5, has an undercut surface in order to pull the solidified material from the sprue and runners when the plates of the mold are separated, and it releases the material when the undercut surface of the puller is pushed above the surface of the mold plate in which it is retained.

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The design of the sprue-runner system involves a compromise between large diameter runners, which provide better flow to the mold and easier extraction, and smaller diameter runners, which require less cooling and result in less scrap to be reground. The junction between the sprue and the runners is the thickest part of the layout and thus may be difficult to eject, so separate cooling of this area should be considered.

Nylon can be molded with sprueless molding. Sprueless molds would eliminate the scrap from material solidifying in the sprue and make the provisions for its ejection unnecessary (Ref. 14).

In many molds nylons flash easily at the viscosities typical of injection-grade resins. For this reason the contact areas around cavity edges should withstand clamp pressures, be ground flat and parallel, and be hardened to 50 to 62 Rockwell C. Cutting the channels for the runners into their own hardened plate reduces the damage from the accumulation of flash along the edges of the runner channels, which could otherwise lead to poor fits and dimensions or breakage of pins or other destruction in the mold.

Venting of the cavity is necessary to allow the air to escape as the cavity is filled with resin. If venting were not provided, the air could prevent the complete filling of the cavity, or the plastic-air mixture could ignite. Vents are provided along the parting plane at the side of the cavity opposite the gate through which the resin enters the cavity. The vents should be broad and shallow with depths less than 0.025 mm (0.001 in.).

Unequal distribution of material among the molding cavities can be corrected by adjusting the cross-sectional

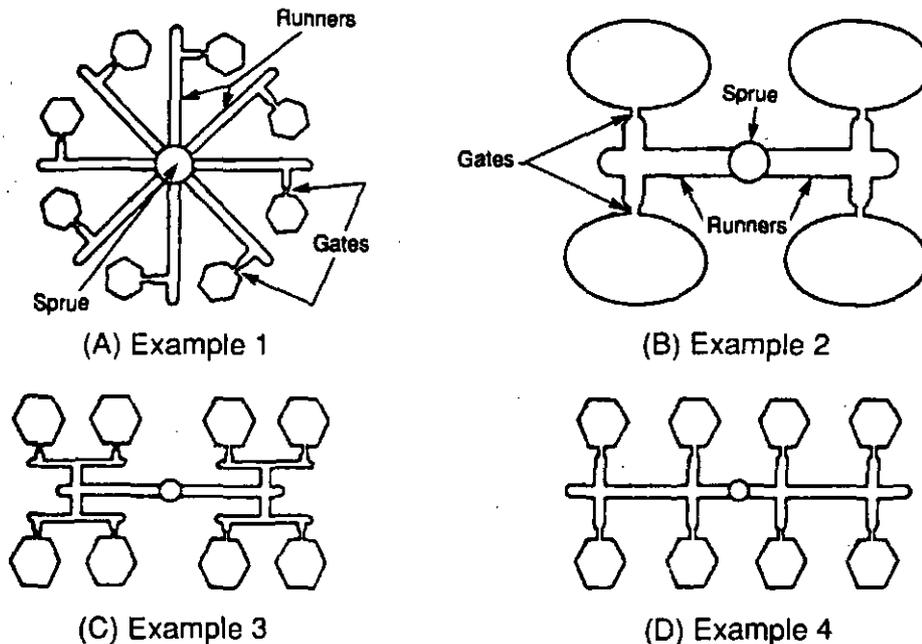
area of secondary runners. Control of the flow into molding cavities with gate geometry is undesirable since it affects gate-sealing times.

Gates (small, restricted entrances to cavities) perform several functions:

1. They throttle the flow of resin into the molding cavity.
2. They isolate the cavity from the high pressure of the injection cylinder when the material solidifies in the gate and thus seal it.
3. They allow parts to be easily broken off with only a small mark left on the part.

The pressure vs time profile in the molding cavity affects the properties and reproducibility of molded nylon parts. Gates are not normally responsible for a major portion of the pressure drop in a mold layout except after the material in the gate solidifies and isolates the cavity from the runner system. However, gate sizing is critical to the molding of nylons to prevent freezing in the cavity before it is completely filled. Small gates can present problems in generation of high temperature through high shear rates and jetting. (If jetting occurs, the molten material may squirt across the mold cavity and solidify as it impacts the wall. The additional material would then fold on top of it. This action creates stress lines in the material and poor surface quality.) Large gates allow the material to flow back from the cavity into the runner after the pressure is released.

The layout of runners and molding cavities should be evenly distributed across the face of the mold so that the pressure of the injected resin is evenly distributed and does not tend to warp the mold. Fig. 4-7 illustrates various lay-



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Figure 4-7. Relationships Among the Sprue, Runners, and Gates (Ref. 11)

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outs used for the sprue, runners, and molding cavities as viewed on the open face of the mold.

For automated systems and high throughput, small gates are used to seal the cavity off from the runner rapidly and make separation of the molded piece from the runner easy. Tunnel or submarine gates are used to aid separation of the molded product from the runner. The tunnel gate differs from the conventional gate in that the restriction is not exposed when the mold is separated; it is buried in the metal of the mold. The plastic in the gate breaks when the part and/or the runner is ejected. The design and construction of such gates require care. The metal around the tunnel must be substantial enough to break the molded material in the gate area as the part is ejected without deforming it. Also the gate must be configured so that the material solidified in it is removed reliably along with the runner.

Nylon is an excellent material for injection molding. Its resiliency allows removal of the product from complex cavity designs. It can deform and recover; thus it can be removed from undercuts without permanent deformation. Nylon products with thin ribs and deep, thin walls and deep-draw cores can be extracted from molds easier than products made of other materials.

Design of the molding cavity for nylons is as much an art as a science because of complexities such as wide variation in cavity design, differences among nylons in the rate of crystallization, moisture-induced growth, deformation problems during ejection, and anisotropy in the molded part. Gates and vents must be located so that the cavity fills completely and evenly to preclude surface marks or voids. The cavity must match the design of the piece to be produced with allowance for shrinkage. Part design is discussed in Chapter 5.

All surfaces of the molded object adhere to the mold and require some force for their removal. The force required depends on many factors including the total drag area of walls, ribs, and bosses; the coefficient of friction between the metal of the cavity and the nylon; the presence of undercutting in the cavity design; and the presence of any forces caused by the mold shrinking to compress the molded object. Use of lubricants can significantly reduce the ejection forces required for nylon objects.

The ejection forces must be distributed over the objects being ejected to reduce deformation of the molded object and prevent binding between the object and the mold. Appropriate distribution of the forces is aided by the use of guide pins and bushings that keep the ejector plate parallel with the mold plates during activation. In automatic operation it is advisable to return the ejector assembly prior to closing, and normally hydraulic ejection is used rather than mechanical ejection.

Because of the high specific heat content of nylon, good heat transfer must be provided away from parts having thick walls. This is done by the selection of materials with good thermal design properties including good thermal con-

ductivity and by the appropriate layout of cooling channels in the mold. The mold must also be designed to withstand the cyclic, selective thermal expansion-contraction cycles of the portions of the mold exposed to the nylon. Mating faces of the mold must have a good fit so that wear from differential movement is minimized.

As the cycle time of nylon molding is reduced, cooling capacity and efficiency become more important. Localized area heating of molds is used less, and cooling becomes more important. Poor coolant water control and quality are responsible for many of the problems that occur with nylon molding. Scale buildup from minerals in the water can cause a poor distribution of cooling capacity across cavities within a mold. Coolant supply to the molding machines should be able to deliver adequate coolant at a constant pressure. Cooling capacity within the mold can be increased by using coolant at a lower temperature; however, the mold should not be cooled to the extent that "mold sweating", condensation of moisture in the mold cavities, occurs.

Extensive use of refrigeration systems for cooling results in a more complicated system that is dependent on additional machinery for reliable operation. Chiller failures must be noted promptly before product quality decreases. Controllers are available that mix chilled water with plant water based on the sensed temperature to produce an accurate temperature control system for individual molds.

4-1.4 THE INJECTION MOLDING PROCESS

Injection molding makes discrete objects through a molding cycle whereby a mold is filled with molten resin and cooled and the finished parts are removed. In contrast, extrusion (discussed in par. 4-2) is a process for making continuous objects, such as profiles, film, sheet, or pipe.

The operation of an injection molding system can be considered in three categories: the key process parameters, the properties of the polymer being molded, and the mold. The process parameters are melt temperature, melt pressure, melt displacement, and time. Polymer characteristics include viscosity (and the change in viscosity with temperature, polymerization, depolymerization, degradation, and shear), rate of crystallization, melting and freezing points, and thermal properties. The process parameters must be chosen based on the characteristics of the material and of the mold to be filled. Use of a different material can require a different set of operating parameters and perhaps some changes in the mold.

The optimal combination of operating procedures is best determined by a methodical trial and error process using all available information to establish an initial set of operating parameters. A good source of information is the resin suppliers who supply information on the dependence of melt viscosity on shear and temperature, gate seal-off times, recommended gate fill rates, and mold design factors. Table 4-3 gives broad limits of melt temperature, cavity pressure, and shear rate for various nylon resins.

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TABLE 4-3. NORMAL OPERATING LIMITS FOR INJECTION MOLDING OF NYLONS (Ref. 7)

NYLON	MELT TEMPERATURE RANGE		CAVITY PRESSURE RANGE		MAXIMUM* SHEAR RATE
	°C	°F	MPa	psi	s ⁻¹
6/6**	275-305	525-580	17.2 CLP†	2500 CLP†	10,000
6/6††	280-320	540-610	17.2 CLP	2500 CLP	2,000
6/10	230-290	450-550	13.9 CLP	2000 CLP	10,000
6/12	230-290	450-550	13.9 CLP	2000 CLP	10,000
6**	250-320	480-610	13.9 CLP	2000 CLP	10,000
6††	250-320	480-610	13.9 CLP	2000 CLP	2,000
11	200-290	390-550	13.9 CLP	2000 CLP	10,000
12	190-290	370-550	13.9 CLP	2000 CLP	10,000

*These are approximate values that depend on melt viscosity

**Normal molding grade

†Clamp-limiting pressure (CLP) is that cavity pressure which, when multiplied by the total mold projected area, does not exceed the available clamping force.

††Extrusion grade

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Control of temperature, pressure, displacement, and time is limited to the precision of the instrumentation employed. The effectiveness can be further reduced by the inaccuracy or slow response time of the instrumentation.

1. Temperature:

The temperature of the melt is an important parameter to be measured and controlled, but since it is difficult or impossible to measure while the process is running, temperatures of the cylinder wall and mold cavities are measured and controlled instead. It is still worthwhile, however, to measure melt temperature by collecting air shots (samples of the melt collected with the mold temporarily moved out of position) while maintaining the injection cycle and inserting a needle probe attached to a pyrometer into the ejected melt. Thus the melt temperature can be related to temperatures that can be measured while the process is running. The average melt temperature should be determined under different conditions of screw rotation, back pressure, and cycle timing. Adjustment of the melt temperature is possible by adjusting the power to the front and adapter sections of the injection cylinder. On a properly designed system melt temperature control to ± 1 deg C (± 2 deg F) is feasible. Normal fluctuations in melt temperature due to a change in either the resin, i.e., moisture content, regrind ratio, switching to a different lot, etc., or the inherent variability in machine performance, i.e., mold temperature change because of radical change in room temperature or controller response lag, injection pressure change because of change in oil temperature, etc., should be clearly distinguishable from shifts in melt temperature produced by machine failure.

Other temperatures that have an indirect effect on the process temperature, e.g., temperature of the coolant, or the mechanical system, e.g., the temperature of the hydraulic fluid, should also be measured.

The properties of the molded part are greatly influenced by the temperature of the part during molding and immediately after release. Mold temperature must be closely controlled, but it is also recommended that a direct measurement of the temperature of the part be made after the mold is opened instead of relying only on indirect measurements, such as mold or coolant temperatures.

Mold temperature can be regulated by monitoring inlet and outlet coolant temperatures while maintaining stable coolant flow rate and pressure. Again, ± 1 deg C (± 2 deg F) of control is both feasible and desirable. Mold temperature must be accurately controlled for proper mold cavity filling and solidification, gate sealing time, and part ejection. The injection molding machine should be operated at the lowest melt temperature that yields the intended properties and dimensions of the part in order to minimize undesired hydrolyzation or polymerization. Temperatures in different regions of the barrel can be adjusted to provide the proper melt temperature and machine operating performance. For example, increasing the rear-zone temperature and adding lubricants may eliminate variability in screw retraction. The specific effects of temperature in the different zones depend on the construction of the machine.

2. Pressure:

The hydraulic pressure directly affects the mold clamping force and the speed of operations such as ejection. It should be measured and controlled.

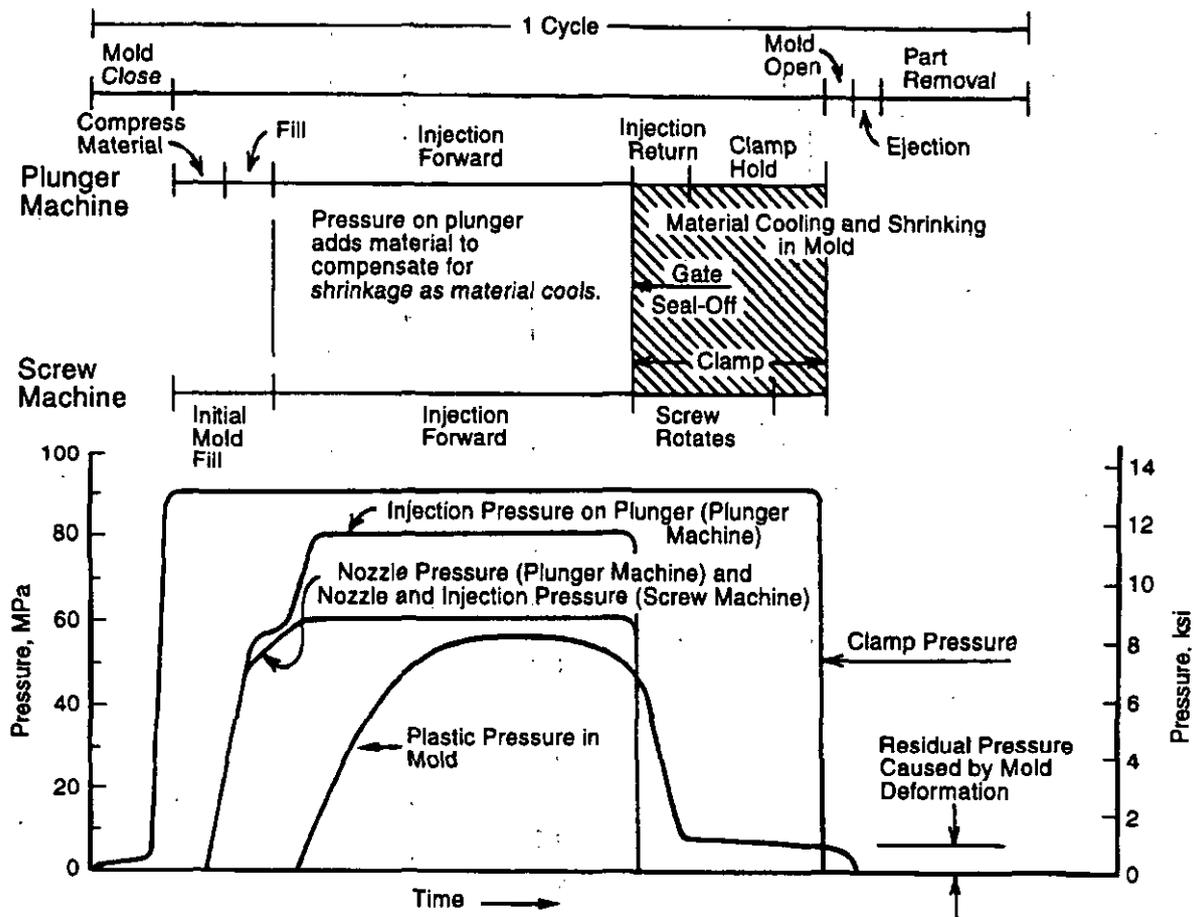
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The melt pressure vs time profile can be adjusted in various machines by timers, position switches, or pressure level controllers. The pressure in the nozzle and mold cavities should be monitored and controlled. For ideal product uniformity the cavity pressure should not vary more than 5% between injections. Adhering to this maximum variation may require sophisticated feedback control of several parameters.

Generally, a melt pressure of 13.8 MPa (2000 lb/in.²) in the cavity is required for satisfactory molding operations. In order to take into account the pressure losses between the injection system and the cavity, the first- and second-stage hydraulic pressures in the injection cylinder should be higher than 13.8 MPa (2000 lb/in.²) so that the desired pressure is achieved in the cavity. The time profile of the pressure in the cavity is also important. The pressure is determined in the early part of the injection cycle by the injection system until the material in the gate freezes and then isolates the mold cavity from the injection system. The injection system should maintain the injection pressure until after the gate is sealed. The weight of the molded part may

be lower if the level and duration of the injection pressure are lower than optimal. Specifically, the weight of the part will be lower if the pressure is not maintained for a specific time interval after injection. The length of this interval increases as the pressure decreases and is affected by melt and mold temperatures, which affect the time required to seal the gate. The internal pressures across an injection cycle of a plunger and reciprocating screw injection molding machine are shown in Fig. 4-8.

As mentioned earlier in this paragraph, the variety of available compositions and the ranges of molding operations in which these compositions are used require that specific molding limits be established by experimentation for any specific job. If the mold design, mold temperature, overall cycle, and approximate melt temperature required to achieve a full shot are known, a series of molding operations can be conducted at various injection pressures and melt temperatures to define the combinations that result in satisfactory molding operations. Products from each run are analyzed for surface defects, sink marks, and dimensional accuracy. The results are then plotted on a two-dimensional



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Figure 4-8. Cycle Time of Plunger and Reciprocating Screw Injection Molding Machines (Ref. 10)

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plot of pressure vs temperature showing the pressure-temperature combinations that resulted in successful molding operations. This plot reveals the injection pressure-temperature combination that yields the greatest margin for error. Tests can then be run for small changes in temperature, fill rate, etc., to identify the complete set of operating parameters.

3. Time:

Timing is critical to the operation of an injection molding machine, especially when automation is used to obtain greater productivity. Selection of the time intervals to be implemented involves understanding of all of the events that occur. An example of the timing sequence is shown in Table 4-4.

Once the operating parameters are determined, productivity issues must be resolved. Automated systems allow the close control necessary to shorten cycle times to increase throughput as well as improve uniformity in product quality. Addition of processing modifiers such as mold-release agents may be used to reduce cycle time further.

If the operating parameters have been established for a standard nylon resin in a reciprocating screw machine, the cycle time can be reduced by switching to a fast-molding resin composition and making the following adjustments to molding operations:

1. Reduce the period of time between the completion of injection and the time the mold is opened by about two seconds.
2. Increase mold cooling so the exit temperature that existed for the standard resin is obtained with the new resin and the shorter mold opening time.
3. Increase the screw rotation rate if there is insufficient time for the screw to retract fully.

4. Make the necessary adjustments in the operating parameters to return the melt temperature to the original value and to maintain molded product quality; change equipment if necessary.

5. Repeat Steps 1-4 until the screw retraction phase of the molding operation does not have time to complete.

6. Add a nozzle shutoff valve to permit screw rotation while the mold is open to allow additional time for screw retraction.

4-1.5 MOLDING DEFECTS—PROBLEM SOLVING

Injection molding faults may appear anytime a change is made in the processing, intentionally or not. Faults may occur when a new mold is used, when the material is changed, or when operating parameters are changed either by the operator or by a component failure:

The following are examples of molding failures (Ref. 7):

1. Short shots
2. Excessive flash on parts
3. Sink marks
4. Poor welds
5. Brittleness
6. Material discoloration
7. Splay, mica, and flow marks
8. Surface blemishes at the gate
9. Warpage and shrinkage
10. Dimensional control
11. Sticking in the mold
12. Nozzle drooling
13. Excessive cycles.

TABLE 4-4. INJECTION MOLDING EVENTS IN SEQUENCE (REF. 7)

EVENT	EXPLANATION
1. Ram in motion	Time from start of injection until the screw stops moving forward
2. Ram forward hold*	Time from end of screw forward motion until the screw starts to move back
(First-stage pressure)**	Time under first, usually higher pressure
(Second-stage pressure)**	Time from end of first-stage pressure until end of ram forward
3. Forward-screw decompression or "screw delay"	Time from end of ram forward until start of screw rotation
4. Screw rotation	Time from start to end of screw rotation
5. Rear-screw decompression	Time from end of screw rotation until end of all rearward motion of the screw
6. Screw deadback	Time from end of screw movement to mold opening
7. Mold opening	Time from start to end of mold opening movement
8. Mold open delay	Time from end of mold opening to start of mold closing
ejection†	Time from start to end of ejector action
9. Mold closing	Time from start to end of mold closing motion

*Just "ram forward" is commonly interpreted to include ram in motion and ram forward hold because one timer controls both events and special effort is necessary to determine only ram in motion.

**First- and second-stage pressures apply during ram in motion and ram forward hold and add to the same total time. Event does not add to total cycle.

†Ejection can occur during mold opening or mold open delay or both. Event does not add to total cycle.

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In most cases identification of the fault provides an indication of the cause. With knowledge of the cause the cure is usually obvious. Additional information on injection molding fault diagnosis is provided by manufacturers, both in printed materials and by technical service personnel. Also additional information on fault diagnosis is given in Chapter 5 of Ref. 10 and Chapter 10 of Ref. 11.

4-2 EXTRUSION

In the context of nylon and other thermoplastic materials, extrusion is the process of melting a granular resin and pumping it through an orifice shaped to produce an extruded product, i.e., a long stream of the solidified material having the same cross section at any location along its length. Examples of extruded products are rod, bar, tube, and ribbon as well as specially shaped materials used as moldings or edgings. Extrusion machines typically consist of a screw in a heated cylinder used to melt and plasticize the material and then force it out through an orifice called the die. A variation of this machine is the twin screw machine in which a second screw operates along the first to enhance the shearing and/or pumping action. The extrusion machine may be used with cooling and quenching machines to produce extruded products directly or with blow molding equipment to produce hollow containers or similarly shaped objects.

For effective extrusion the melted resin must have a high viscosity to maintain its shape after extrusion until it solidifies. Early nylons, 6/6 and 6/10, had low viscosities. Furthermore, they typically contained as much as 0.3% water by weight, a factor that reduced the viscosity even further. The low viscosity and the lack of adequately heated extrusion equipment at that time limited the use of nylon for extrusion. Since then, however, nylon compounds with higher molecular weights have been developed that are suitable for extrusion. Extrusion equipment now incorporates heaters capable of delivering the heat required to melt the high-melting-temperature resins and thus allow extrusion of more demanding applications such as blown and cast film, blow molding, tubing, pipe, profiles, and coatings. Extrusion of nylon over other materials, such as wire insulation, and coextrusion with other polymers are now commonly accomplished.

The specification of properties that define the feasibility of extrusion is not simple. The melt viscosity, melting point, and rate of crystallization are determining factors. A high or low melt viscosity is required depending on the application: 5000 Pa·s (50,000 poises) for blown films or free extrusion of rod or bar stock or 2000 Pa·s (20,000 poises) for coatings and monofilament line. By varying the temperature of a resin, the viscosity of the material may be changed to make it suitable for other types of extrusions.

The melting point of a nylon resin is an indicator of its performance as an extrusion material. Low-melting resins require less energy to liquefy, but they do not solidify or

crystallize as quickly, particularly if copolymerization is responsible for the low melting point. Slow crystallization may be an advantage for applications requiring minimum distortion and shrinkage and requiring that the extruded material crystallize slowly and uniformly. It can, however, lead to material sticking to relatively cold metal surfaces, as in blow molding or making cast film. Also slow crystallization can complicate the formation of dimensionally critical components, i.e., any handling immediately after extrusion that induces uneven stresses in the extruded material will cause permanent deformation.

Resins formulated for extrusion that have been properly packaged can be processed without further drying. However, resins that are intended for injection molding, reground resins, or extrusion resins that have been exposed to water need to be dried before they can be used in extrusion machines. Hopper dryers, described in subpar. 4-1.2, minimize contamination by recirculating the air through the resin material and desiccant columns and thus avoiding contact with the ambient air. They do, however, require considerable downtime when the type of resin being processed is changed.

The handling of nylon scrap to be reworked depends on many factors including the resin used, the process, and the processing requirements of the regrind. For example, extrusions that are quenched with air or chilled rollers can be reground and extruded again since the moisture level should be low. Thin extrusions, less than 0.7 mm (30 mil), should be repelletized before being recycled in an extrusion machine. The regrind can be blended with virgin resin and reextruded. Extrusions that have been quenched with water can be reground and extruded if the quench was hot enough to evaporate the surface water immediately. Once reground, the resin should be kept in an inert gas environment to prevent absorption of moisture.

Scrap nylons can be ground to a granular mixture suitable for reprocessing by using a granulator used for most plastic materials. These machines have rotating knives that continuously cut the material until the particles are fine enough to pass through a screen. The size of the grains is determined by the opening size of the screen; 9.5 mm (0.375 in.) is a typical size used for nylon. Smaller openings result in too many too small particles, and larger openings allow longer particles to pass through that can cause problems in extruding machines.

In applications that generate a considerable amount of scrap material, consideration should be given to use of a resin that can be extruded after being reground, i.e., one that retains a high melt viscosity and requires a minimum amount of drying.

Care must always be used to minimize contamination of the reground material (Ref. 15). For the best protection against contamination, nylon scrap should be reground immediately and stored in airtight, polyethylene-lined containers. Many extrusion processes can extrude resin com-

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prised of 100% regrind or a mixture of regrind and virgin material as long as the ratio of regrind to virgin material remains constant while the process is running. The fraction of regrind material that can be accommodated by an extrusion process is determined by the material being reground, and the color, toughness, and other quality requirements.

4-2.1 EXTRUSION EQUIPMENT

Many nylon resins can be extruded with conventional extrusion machines, such as those designed for use with polyethylene, as long as the screw design and temperature are appropriate for the nylon resin. A schematic cross section of an extruder is shown in Fig. 4-9. The die in the schematic is turned at a 90-deg angle from its normal position so that an end view can be shown.

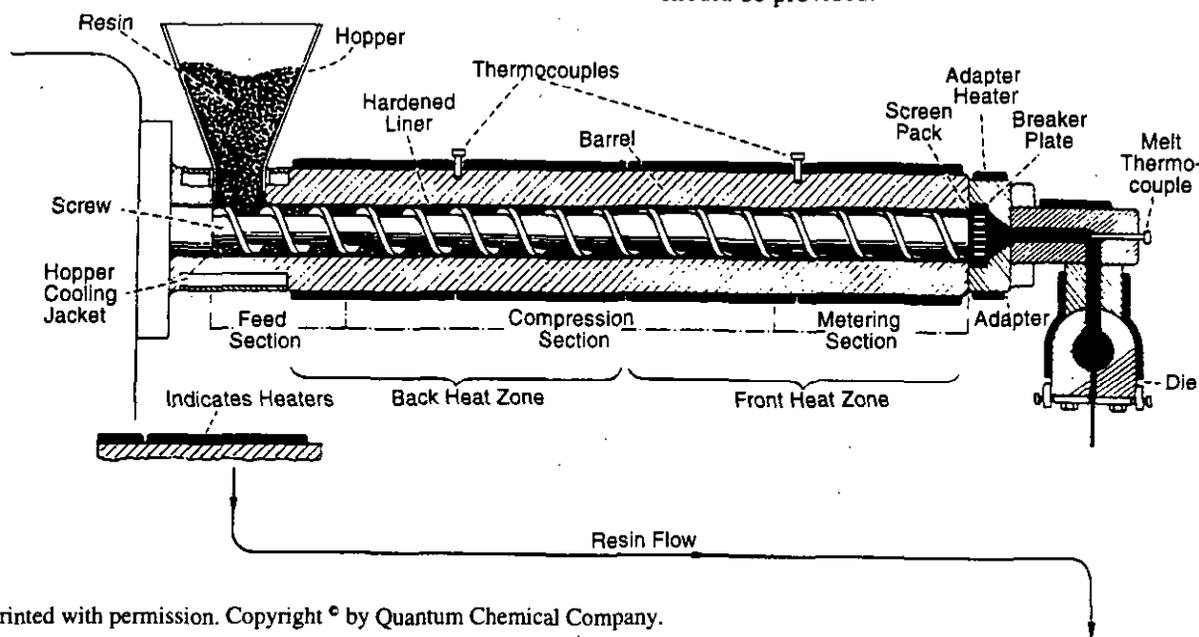
A major selection criterion, and published specification for nylon extrusion machines, is the output in mass per unit time necessary for profitable operation when the machine is operating at 50 to 75% capacity.

Typically, nonvented, single-screw extruders are used for nylon. Vented extruders, i.e., those with a vent on the screw barrel to allow the escape of moisture released from the resin during compression, can be used with resins that are likely to contain moisture, such as regrind. The quality of the product made from regrind in vented extruders, however, is more difficult to control satisfactorily, and resin caught in the vent zone may carbonize and thus contaminate the resin melt with black particles. Also the vented process can lead to excessive loss of volatile additives, such as plasticizers. For these reasons, the vented extrusion process is not as desirable as the separate-drying extrusion process, although it is more direct.

Twin-screw extruders are used to mix additives with the nylon resin. Additives include colorants, plasticizers, and fillers. The twin-screw machines provide an additional shearing action that aids the mixing of the materials. They can also raise the temperature of the resin to excessive temperatures, which lead to insufficient viscosity for extrusion. Although twin-screw extruding machines could be designed to produce resin melt at moderate temperatures, the additional complexity of the machine is not justified in commercial use for nylon.

Extruders are usually described by the length-to-diameter ratio of the barrel. Although barrels having a length-to-diameter ratio as small as 10 or 12 have been used, greater output and smoother extrusion performance can be obtained with length-to-diameter ratios of 24. For vented extrusion machines a ratio of 24 is a minimum requirement.

Extruders, like the reciprocating screw injection molding machine, melt the resin by a combination of the mechanical energy imparted to the resin by the shearing action of the screw and the thermal energy from heaters located on the barrel and nozzle. Insufficient heating within the extruder results in poor quality extrusion and a potential safety hazard. Adequate heat must be provided to the breaker plate and screens located between the outlet of the extrusion machine and the die to prevent freezing of the melt and clogging of the machine output. This clogging would cause the melt pressure to reach dangerously high levels leading to "blowing off", a rupture of the system with explosive force. For adequate heating, approximately 46 kW/m^2 (30 W/in.^2) of heating capacity should be provided for the outside surface area of each unit of barrel and die. For example, if the outer surface area of the barrel adapter and die is 0.26 m^2 (400 in.^2), 12 kW of heating capacity should be provided.



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Figure 4-9. Cross Section of an Extruder (Ref. 11)

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Temperature should be accurately controlled by suitable controllers and properly located sensors to prevent overheating or freeze-offs and to control the viscosity of the melt accurately. Extrusion quality is dependent on the viscosity of the material as it is being extruded, so accurate control of temperature at the die is essential. More sophisticated controllers are used in the die and associated adapters to maintain the degree of control necessary. For some extruders precise control of the rear-barrel zone is also necessary because the feeding characteristics of nylon resin are affected by the temperature of this zone. Variations in the temperature of the rear-barrel zone can cause erratic feeding of the extrusion granules, which in turn will cause variation or surging of the extrusion. Control of the center- or front-barrel zones is not as critical since much of the heat in these regions comes from the shearing of the material by the screw, and the controller keeps the heaters in these regions turned off much of the time.

Thermocouple placement is also very important for accurate control of temperatures. The most precise temperature control is usually obtained by using shallow-well thermocouples close to the heat source. Control systems using thermocouples embedded 9.5 mm (0.375 in.) deep in the barrel usually provide stable temperature control. The thermocouples should be held in intimate contact with the barrel to minimize the effect of ambient temperature on the measurement. Spring loading of the thermocouple should be used to hold it against the metal at the bottom of the "well". Also thermally conductive compounds should be placed in the thermocouple/metal interface. Independent heat and temperature control of the various extruder zones should be provided. The barrel usually is divided into at least four separate zones, and each extruder attachment, e.g., adapter and neck, is individually temperature controlled. Barrel cooling is not used on extruders used for nylon.

Direct measurement of the melt temperature is required for adequate control of the extrusion temperature. This measurement is usually made directly in the melt within the adapter between the extruder and the die by using unshielded thermocouples for rapid response. The melt temperature can be recorded or read out on a numeric display. A better technique, however, is to sense the temperature of the nylon remotely by using an infrared thermometer to detect radiation from the molten material (Ref. 16). The sensitive end of the instrument is aimed at the nylon extrusion, and the temperature is read from an associated display. This method offers the following advantages over sensing the temperature of the melt by direct contact techniques:

1. Visual access is the only constraint for measurement location. Therefore, the temperature of the extrusion near the die can be measured.

2. The temperature of the melt is measured remotely. No contact with the melt is made, so the extrusion is neither contaminated nor disturbed.

3. Imaging techniques can be used to determine the temperature distribution over the entire area of the extrusion. These techniques can also be used to ensure uniformity across films.

4. The temperature along the extrusion can be measured to determine the cooling rate of the extruded material.

Routine displaying and recording of temperatures are invaluable to evaluating the performance of the temperature control system and troubleshooting defects caused by improper temperature control. Preferably, each temperature from each zone should be displayed and recorded. Sensed temperatures can be obtained by tapping into temperature signals available within the control system or by installing a second set of sensors for independent acquisition of temperature data. Dual sensors are available to avoid the necessity of drilling and tapping additional holes in the extruder for sensor installation. One-half of the dual sensor is used with the control system, whereas the other half is used for temperature monitoring. Display of the monitored data allows the operator to verify proper operation of the extruder and correlate observations of the extruded product with the internal operation of the extruder. Most importantly, it allows the operator to detect operational adjustments that are necessary to prevent the wasteful generation of unsatisfactory product.

Like other thermoplastics, nylon can be extruded when the screw pumps the extrudate against an optimum head pressure. The actual pressure encountered typically ranges from 3.4 to 20.7 MPa (500 to 3000 lb/in.²) and depends primarily on screw design and rotation rate, melt viscosity, extrusion rate, and die design. The pressure can be controlled by adding or removing a restriction to flow at the extruding die. This adjustment is usually effected by inserting screens upstream of the die to constrict the flow of the melt while also filtering it. The amount of restriction is adjusted to provide the desired head pressure by the number of screens used and the size of the openings in each. A combination of two 80- and two 120-mesh screens is commonly used for nylon. Because of their fragility, the 120-mesh screens are generally supported between more substantial, coarser screens. Control of head pressure by insertion of screens is simple but not without limitation. The amount of restriction is set at the beginning of the process and cannot be intentionally adjusted without disassembling the machine. Foreign material can clog the screens and raise the pressure for the duration of the run. Excess pressure caused by the pumping action of the extruder before operating temperatures are reached can drive chunks of material through the screens and thus reduce their effectiveness. Provision for adjustment of the restriction can be made by several mechanisms (Ref. 11):

1. Use of a screen changer allows a new, clean screen pack to be slid in in place of the existing pack by pushing it out the side in a manner similar to a photographic slide in a slide projector.

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2. Use of valves adds additional, controllable restriction to that provided by the screen pack. These valves may be formed by an obstruction screwed into the path of the extrusion flow, like a needle valve, or by adjusting the longitudinal position of the extruder screw, changing the clearance between the end of the screw and the shoulders of the opening through which the extrusion must pass.

These mechanisms allow adjustment of the head pressure without interrupting the extrusion process, but their cost is not justified for most nylon processes.

Once extruded, the nylon material must be cooled so the product can be stored, packaged, or handled. The cooling system must be selected based on the following considerations:

1. The maximum rate of extrusion
2. The initial temperature of the extruded material
3. The rate of crystallization of the nylon resin
4. The required dimensional tolerance of the finished product
5. The melt viscosity and tendency of the material to stick.

Various quenching techniques are used to cool the nylon to a temperature at which it can be handled and any final forming operations necessary to achieve the required dimensional tolerances can be performed. These techniques include water quenching, air quenching, and cooling by contact with chilled rollers.

For applications having critical dimensional requirements, uniform cooling is necessary, and it becomes more important with materials having high crystallinity and a high melting point. For example, a nylon 6/6 extrusion warps and distorts more readily than one made from a resin with a lower melting point. For solid extrusions such as rods and slabs, slow cooling is necessary to prevent formation of shrinkage voids inside the part. These voids result from uneven cooling, i.e., the outside cools and solidifies first and is followed by cooling, solidification, and shrinkage of the interior. Because the outside dimensions are fixed by the solid material, shrinkage of the interior leaves voids in the material. Reducing the rate of cooling allows the inside to cool at a rate nearer to that of the outside and keeps the outside pliable as the inside approaches the solidification temperature.

The most convenient and economical quenching mechanism is the extrusion of material downward into water because the cooling rate can be controlled by adjusting the distance between the die and the surface of the water. Also gravity keeps the water away from the heated die. The vertical orientation eliminates the need to support the extruded material with guide rollers before it solidifies, but guide rollers are necessary to redirect the cooled extrusion back out the top of the cooling tank. This method is well suited for monofilament, film, and narrow sheet (strip) extrusions.

When the extrusion cannot be bent sufficiently to enter and exit a quenching tank along the same path, a horizon-

tal quenching tank can be used. Water is sprayed to cool all sides of the extrusion before it enters the tank to prevent uneven cooling of the extrusion and to reduce dimensional distortion of the product.

The temperature of the water bath should be controlled to achieve a constant crystallization rate and dimensional stability during quenching. Often tap water at 10 to 21°C (50 to 70°F) is used, but higher water temperatures may be necessary to obtain better physical properties (Ref. 17).

Water cooling can cause surface stickiness on some extruded nylons, which causes problems during winding or stacking of the extrusion. Coating the surface with lubricants or talc prevents the material from sticking to itself and allows winding. Alternatively, air quenching can be used to avoid the problem.

Air quenching is useful if moisture absorption by the extrusion is to be minimized. It eliminates the problem of water marking caused by fluctuations in the water flow. It also affords more control over the cooling process by allowing placement of air jets around the extrusion so they cool selected areas more rapidly than others to minimize warpage. Air quenching is usually performed by multiple, adjustable air jets. The airflow to each air jet should be individually controlled and monitored by a flowmeter to detect any variation in quenching conditions.

Chill roll cooling is used primarily for thin extrusions such as film, sheet, and extruded coatings applied directly to other sheet materials. The extruded material is pulled in a serpentine path over several large rollers cooled by liquid coolant circulating within the rollers. The inlet temperature of the coolant is normally as high as possible commensurate with optical properties and easy release of the film or sheet from the roll. For nylon, temperatures of $93 \pm 28^\circ\text{C}$ ($200 \pm 50^\circ\text{F}$) are common. The quench roll temperatures are purposely kept high to minimize the condensation of vapors, such as oligomers or monomers, and the subsequent buildup of residue on the cooling surfaces. This residue can be a clear liquid or a waxy solid and, if excessive, can cause splotches on the extrusion.

Quench rollers are often used to impart a desired finish on the extruded material, e.g., either a smooth, polished appearance or a texture, such as that of leather. A negative relief of the desired texture is formed in the quench roll and is then embossed onto the extruded material as it passes over the roll.

If tight dimensional control of the extrusion is required, it may be passed through a cooled forming box that functions as a second die. The surfaces of the die that contact the extrusion may be coated with a thin layer, 0.03 to 0.05 mm (1 to 2 mil) thick, of a tetrafluoroethylene (TFE) resin to prevent sticking (Ref. 18). Because it is thin, this layer does not appreciably affect the cooling performance. It does, however, reduce friction and the tendency of the material to stick. Uniform cooling of the forming box is essential to prevent distortion of the extrudant.

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Solid nylon shapes, such as rods and slabs, are generally produced by forcing the extruded nylon under pressure through such a forming box, which is usually water cooled. Hollow shapes, e.g., tubing and pipe, also use a forming box to mold the outer surface to the desired cylindrical shape by using inert gas pressure applied to the inside of the extrudant to hold it against the forming block.

Since it is the differential pressure that holds the pipe against the forming block, the same effect can be achieved by applying a vacuum to the outer surface in the vicinity of the forming block. This technique has the advantage of maintaining the inner surface at ambient pressure, which allows the pipe to be cut and thus exposes the inside of the pipe to room atmosphere. There is no effect on the operation of the forming block that could alter the dimensions of the pipe.

4-2.2 EXTRUSION OPERATION

To prevent the hazardous "blowing off" mentioned in subpar. 4-2.1, the area around the die should be heated above the melting point of the resin being processed. This preheating ensures that the resin flow path will not be clogged with solidified resin, which can lead to a buildup of pressure and possible rupture of the system. Before start-up the temperature of all zones should be checked with a sensor-readout system that is independent of the temperature control system to confirm that the heating system is operational and that the extruder has reached operating temperature.

Prior to beginning extruder operation the operator must ensure that the front portion of the barrel and the die are heated above the melting point of the resin and that the temperature of the feed zone is below the melting point. If the feed zone is heated excessively, the resin being fed into the machine will partially melt, stick together, and form a "bridge", i.e., a solid conglomeration of resin granules that blocks the feed throat, that prevents additional material from entering the extruder. The blockage may be detected by the absence of load on the drive motor of the extruder screw. When this condition occurs, the extruder should be cleaned and restarted. Sometimes the bridge can be removed by increasing the temperature of the barrel in the feed area and feeding in chunks of nylon. However, this method is time-consuming and usually does not completely remove the nylon that is clinging to the screw in the feed zone. Thus recurrence of the bridging occurs within a few hours.

To satisfy the requirement for temperatures above the melting temperature of the resin near the die and below the melting temperature in the feed area, a temperature profile is required in which the temperature increases along the barrel from the feed area toward the die. The feed zone temperature is usually 6 to 15 deg C (10 to 25 deg F) below the melting point of the resin, and the die-end temperature is 17 to 28 deg C (30 to 50 deg F) above that. To ensure that the

massive extruder components, i.e., the front barrel, die, adapter, and clamp, reach operating temperature, the heaters for these sections should be energized and allowed to reach operating temperature before the remaining barrel heaters are turned on. When all temperatures reach the desired control range, the extruder should be allowed to equilibrate for 30 min before it is started. After start-up the temperatures can be trimmed to values found to be effective based on previous experience. At first, the screw should be turned at slow speed, about 10 rpm, while the melt-pressure gauge is observed. Hand feeding the resin until it emerges from the die allows early detection of bridges or other resin feed anomalies.

The appropriate procedure used to shut down the extruder depends on whether it is to be off-line for an extended period of time or not. If the extruder is operating at temperatures below 288°C (550°F) and is to be shut down for short periods, e.g., 10 min or less, it may be shut down by removing the drive power to the screw without disturbing any temperature controller settings. For long-term shutdown all temperatures should be set to the melting point of the resin being processed, and the extruder should be run until the current drawn by the screw drive motor begins to increase due to the increased viscosity of the lower temperature resin. The extruder is run until it is empty; then all heaters can be deenergized. If a resin with a high melting temperature is being processed, it can be purged with a resin having a lower melting temperature to allow shutdown at a lower temperature. This method minimizes the chance of oxidation or degradation of the nylon in the extruder during the shutdown process. Also the purging resin melts more readily and minimizes the likelihood of "blowing off" the machine. The resin with the low melting temperature need not be nylon. Polyethylene can be used as the purging material if the machine is designed to be easily and completely purged. Polyethylene containing a blowing agent is used to purge nylon from large extruders having massive or complicated dies, such as machines used to extrude coatings onto other materials (Ref. 19).

When the configuration of the extruder is changed, it is necessary to clean the solidified nylon from its components. The plastic residue can be cleaned by burning from parts that are not chrome plated. Small parts can be cleaned with a propane torch or by heating in an oven specially designed with an inert or reducing atmosphere to minimize oxidation of the metal components. Immersing the parts in a potassium nitrate or sodium nitrate salt bath prior to burning allows more rapid residue removal, but the materials may react explosively. A more modern technique involves cleaning parts in a heated, fluidized aluminum oxide bed. Residue remaining after burning, typically carbon, can be removed by liquid sandblasting.

The cleaning needed may be minimized by removing as much of the resin from the extruder as possible during the shutdown procedure. One method is to purge the extruder

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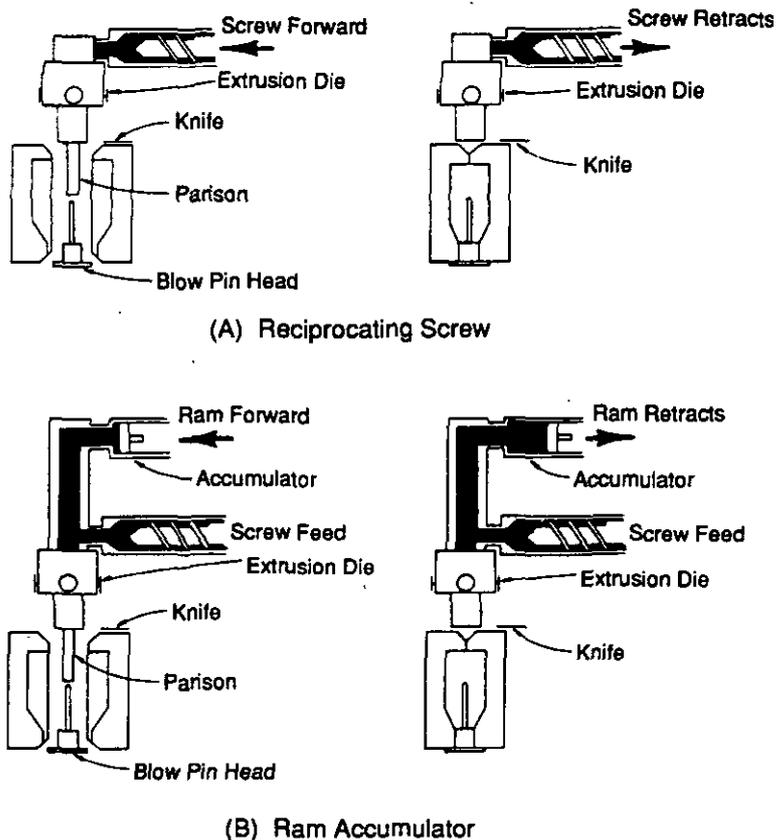
with a polyethylene material having a 1.0 melt index and then lower the temperature to 177°C (350°F) after the nylon is removed. Next the polyethylene is purged with polyvinyl chloride (PVC) and the extruder is allowed to run dry. Finally the system is shut down, and the PVC is physically removed from the parts.

A second technique uses a ground acrylic material to clean the screw and barrel of the extruder. First, the extruder is purged with polyethylene as described previously. Then the die, adapter, and other accessories are removed from the extruder and cleaned by scraping and burning the nylon material from the components of the extruder. The extruder screw and barrel are cleaned before they cool by running granular cast acrylic compound through the extruder. This compound is made by grinding scrap cast acrylic monomer, which has a high molecular weight and does not melt in extrusion machines at temperatures used to process nylon. The extruder is run without the die and adapter in place at a fast speed while small amounts of the acrylic purging compound are dumped into the feed hopper. Additional compound is added to the hopper and run through the machine until the powdered acrylic discharged from the end of the barrel is a nylon-free powder. The extruder is run until it is empty and then is disassembled and cleaned of any powder residue.

4-3 BLOW MOLDING (Refs. 20 and 21)

"Blow molding" describes a family of processes that have the inflation of a molten slug, called a parison, against a cold mold as a common element. Typically, hollow objects, such as liquid containers, are produced by the blow molding process, although other objects, such as signs, have been made by blow molding. The three primary variations of blow molding discussed in this paragraph are extrusion, injection, and cold parison.

In extrusion, or conventional parison, blow molding, which is by far the most commonly used type of blow molding, a uniform cylinder of molten plastic is extruded through an annular die downward, as shown in Fig. 4-10. The two sides of a two-part mold encase the extruded cylinder, or parison, by pinching the top closed and sealing the bottom around an air nozzle. The cavity created by the two-part mold is the shape of the object to be molded with the opening around the air jet shaped as the neck or top of the bottle. The cavity is larger than and completely encompasses the smaller parison. A blast of air inflates the parison against the cooled mold. Vent holes allow the air between the parison and the mold to escape so the molten plastic can conform to the mold with no voids. The plastic solidifies quickly upon contact with the cold mold so that the mold



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Figure 4-10. Two Types of Intermittent Blow Molding Concepts (Ref. 20)

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can be opened, the part ejected, and the process repeated. In simple extrusion blow molding machines, the uninflated parison is a cylinder with a constant wall thickness. Consequently, if the parison is expanded against a form having an irregular shape, the wall thickness of the finished product will vary; it will be thinner where the parison had to stretch more before reaching the form. This restriction can be overcome by using extrusion dies having opening sizes that can be changed dynamically. In one example the die consists of a round opening with a tapered plug centered in it, i.e., a ring-shaped opening whose thickness can be changed by moving the tapered plug in and out. By dynamically controlling the position of the plug during the extrusion, the thickness of the parison can be changed along its length to produce a profile appropriate for the mold being used. Other techniques used to achieve the same result include dynamic control of extrusion pressure or rate. For objects that are not symmetrical about the central axis, an ovalized or notched die can be used to allow extrusion of more material on one side of the die than the other. (Ref. 22)

An alternative blow molding process, injection blow molding, allows generation of a parison of arbitrary shape. Injection blow molding is a two-step process beginning with the formation of a parison in one mold and followed by the blowing of the parison to the final shape in a second mold. In this process a molten resin is injected into a split mold centered around a "blowing mandrel". This mold determines the shape of the parison. The mandrel and parison are removed from the first mold and inserted in a second mold having a cavity the size and shape of the final object and in which the parison is inflated with a blast of air through the mandrel. The mold is opened, and the part removed from the mold and mandrel. The injection blow molding process is usually used only for small containers of less than one liter in volume.

In cold parison blow molding, parisons are made by extruding lengths of tubular material, cooling them, and cutting them to length to produce "preforms". Later these "preforms" are reheated either in a furnace or with a hot mandrel, clamped into a split blowing mold, inflated, and cooled as the final product.

Hollow shapes can be blow molded from various types of nylon resins. Nylon is also used as a barrier material either on the inside or outside of the blown container. This construction is formed by a unique technique known as coextrusion blow molding. In this method a second, smaller extruder is used in combination with the main extruder to produce a parison that is a laminate consisting of a thick layer of a body material and a thin layer of a barrier resin. A bonding agent ensures adhesion between the two layers. To extrude the parison, the two melts are sent through a special coextrusion head, which simultaneously applies the bonding agent between the two melts as they are extruded. Final blowing is done in a conventional manner.

Body materials used include polypropylene, high-density

polyethylene, or low-density polyethylene mixed with a bonding agent. The barrier material used is nylon. The following are some of the advantages claimed for the coextrusion process:

1. With the nylon layer on the outside,
 - a. There is an excellent aroma barrier.
 - b. There is a brilliant surface gloss.
 - c. The surface is ready for printing. (No flame treatment is needed.)
 - d. There is good scratch resistance.
2. With the nylon layer on the inside,
 - a. There is excellent resistance to a number of chemicals with corrosive properties.
 - b. There is an excellent barrier to hydrocarbons.

For blow molding, the nylon resin and operating temperatures must be chosen to produce a melt with a melt viscosity sufficiently high to enable the parison to retain its shape. General-purpose extrusion resins having a melt viscosity of 2500 to 5000 Pa·s (25,000 to 50,000 poises) can be used for small objects, i.e., ≤ 200 mm (8 in.) in length. Resins of higher melt strength and a melt viscosity of over 10,000 Pa·s (100,000 poises) are used for larger objects. Blow molding machines designed to use polyethylene can be used for nylon processing as long as sufficient heating capacity is available for the resin being blown. (Nylon requires more heat per unit volume for melting than polyethylene.)

Since most nylon resins do not have sufficient melt strength to enable the parison to hold its shape, they should be processed in machines having the capability to extrude the parison at a high rate so the parison can be formed and quickly moved to the blow molding mold before it has time to sag. Extrusion times of one or two seconds are required to minimize parison sagging. Because continuous extrusion is not required to generate parisons, an accumulator is usually added to the screw-type resin extruder. This accumulator consists of a cylinder filled with extrudant pumped into it by the action of the screw. When an appropriate amount of material has been pumped into the cylinder for one parison, a piston forces the extrudant out through a die. Accumulator-equipped extruders allow extrusion of parisons two or three times faster than nonaccumulator-equipped extruders.

Resins with high melting temperatures, such as nylon 6/6, freeze quickly after extrusion and shrink away from the mold due to their high degree of crystallization. When used with this material, molding machines can be operated at fast rates. Resins with low melting temperatures solidify slowly and shrink little while freezing, so they are more difficult to remove from the mold. Also crystallization is not complete until the product is quenched in coolant. Therefore, care must be taken not to deform the product when it is being removed from the mold. A comprehensive troubleshooting guide for blow molding is given in Ref. 11.

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4-4 MONOMERIC CASTING

Certain products that cannot be fabricated by extrusion or injection molding can be cast using the monomer nylon 6. Casting is usually economical for large parts, up to 680 kg (1500 lbs), but is generally not practical for production of small parts, under 454 g (1 lb). Pure nylon 6 is used in applications such as heavy-duty bearings, gears, and propellers. Complex shapes requiring undercuts can be molded with multipart molds that can be disassembled for removal of the product. The ease of mixing the catalyzed resin makes nylon 6 convenient to use for cast-in-place components or low-volume production of components outside the customary production facility. The moderate temperatures involved allow fabrication of small- and moderate-size items that use ordinary materials for molds and melting vessels.

4-4.1 RESIN SYSTEM

Nylon 6 (caprolactam) is cast as a catalyzed liquid made by melting caprolactam flakes and adding a catalyst and activator. Polymerization takes place at moderate temperatures, 160 to 200°C (320 to 392°F). Shrinkage during the polymerization step is moderate but predictable within 1%; this predictability allows fabrication of parts that require minimal finish machining. Mineral-filled resin can be used to produce a stiffer, less resilient material. Filled systems also result in less shrinkage. The monomer is hygroscopic; reactions are adversely affected by the presence of moisture. Therefore, keeping the ingredients dry is essential. Additives, such as pigments and various insoluble fillers, may not mix well with the nylon and can settle to the lower portions of the casting. Many commercial dyes or colorants cannot be used because they affect the properties of the finished product, e.g., they are susceptible to chemical attack, they decompose at processing temperatures, or they impact the polymerization reactions. All additives must be dry before being added to the nylon.

4-4.2 MANUFACTURING PROCESS

Preparation of the nylon for casting involves four steps: melting the caprolactam, adding catalyst and activator to separate portions of the melted caprolactam, combining the portions to form a uniform caprolactam-catalyst-activator mixture, and pouring the catalyzed mixture into the mold.

Flake caprolactam must be melted under very controlled conditions of temperature and humidity. Flake caprolactam stored under dry conditions has a moisture content of 0.015%, but this percentage rapidly increases if the flakes are exposed to moderate or high humidity. Excess moisture interferes with the polymerization and must be avoided. Constant temperature control must be maintained during the polymerization step to achieve satisfactory polymerization.

To form a homogeneous mixture of the melted nylon, the catalyst, and the activator, the melted nylon is divided equally into two separate portions. The catalyst is mixed

with one, and the activator is mixed with the other. The two solutions are then mixed together and poured into the mold. This process should be carried out in sealed containers purged of air with inert gas. However, satisfactory results can be obtained by using stainless steel, covered containers to keep moisture from the mixture, a controllable heating unit, and thermometers. The temperature of the resin should be maintained in the mold long enough to allow complete polymerization. An example temperature vs time profile is shown in Fig. 4-11.

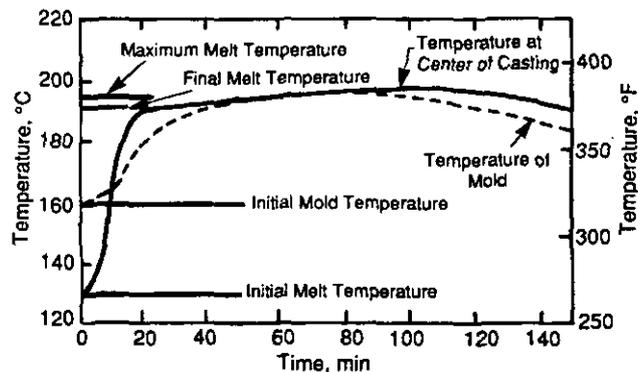
After casting, it may be necessary to relieve internal stresses by annealing, i.e., either by allowing the part to retain the heat of polymerization for a period of time by keeping the part in a warm oven or by insulating the part from the cooler environment for about 24 h. The temperature should be maintained at 140 to 180°C (280 to 360°F). For massive parts, however, submersion in a temperature-controlled oil bath yields better results in less time (0.5 to 4 h depending on part size and thickness).

4-4.3 PROPERTIES

When compared to molded nylon 6, cast monomeric nylon 6 has improved physical characteristics that result from its higher molecular weight and crystallinity. It also has higher tensile and compressive strengths, higher moduli of tension and compression, greater high-temperature tolerance, improved solvent resistance, improved dimensional stability, and lower moisture absorption.

4-5 FLUIDIZED-BED AND ELECTROSTATIC COATING

Powdered nylon resins are applied to substrates, usually metals, by either a fluidized-bed or electrostatic technique or by combinations or modifications of these two basic methods. By the use of such techniques, coatings can be applied quickly and in relatively thick gauges without the use of solvents. Coatings applied by these techniques are frequently referred to as fusion coatings. Such coatings are



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Figure 4-11. Temperature vs Time in a Typical Cast Polymerization of Nylon 6 (Ref. 7)

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used primarily to provide resistance to corrosion and weathering and to decrease friction of moving parts. Although a variety of substrate materials, including metals, glass, and even other plastics, can be coated using the fluidized-bed process, metals are the vast majority of articles coated. Normally any substrate to be coated is heated to 50 to 150 deg C (90 to 270 deg F) higher than the melting point of the coating materials, e.g., the melting points of nylons 11 and 12 are 186°C (367°F) and 176°C (349°F), respectively. Pre-heat temperatures are generally in the range of 230 to 360°C (446 to 680°F). The substrate to be coated should be free from grease, dirt, corrosion, and mill scale in order to provide maximum adhesion of the coating to the substrate. For nylon coatings the metal should be primed prior to coating.

4-5.1 CONVENTIONAL FLUIDIZED-BED COATING

In the conventional fluidized-bed technique the metal part or object to be coated is heated in a preheat oven after thorough preparation of its surface. It is then transferred to the fluidized bed shown in Fig. 4-12. Agitation of some sort is usually required for optimum coating.

The bed, or chamber, shown in Fig. 4-12 is swept with a current of gas, usually air, at room temperature. The gas levitates the resin powder in a manner resembling a boiling liquid, hence the name "fluidized bed". Heating in the pre-heat oven brings the object to be coated to a temperature high enough above the melting or sintering point of the resin to enable the object to retain enough surface heat after it is removed from the heat source to melt or sinter the resin powder particles onto the substrate and thus form an

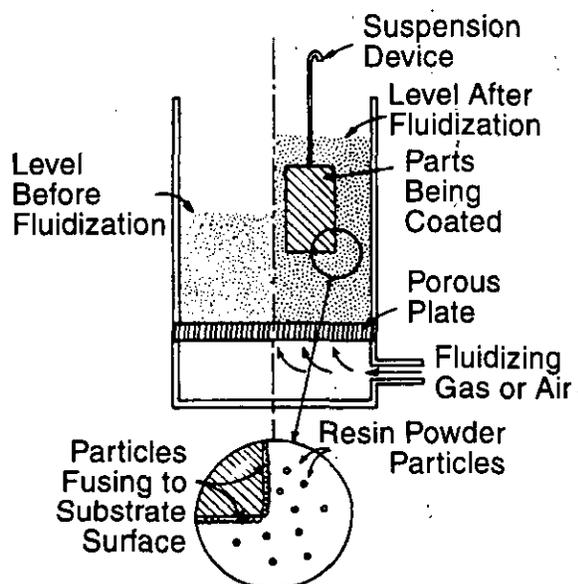


Figure 4-12. Diagram of a Typical Fluidized Bed Used in Powder Coatings (Ref. 23)

adherent coating. Postheating, heating after removal from the fluidized bed, may or may not be used, depending on a number of factors. Postheating smooths the thermoplastic powder coating.

The thickness of the coating depends on the initial temperature of the part, the length of time it is maintained in the powder bed, and to a slight extent on how much the part is moved while in the bed.

Fluidized-bed coating is not confined to batch processing. The technique is well-adapted for continuous coating of wire products or parts on a conveyor belt.

4-5.1.1 Nylon Coating Materials

The characteristics of a nylon material pertinent to its application in a fluidized bed can be considered in two categories: those characteristics that affect the application process and those that determine the properties of the finished coating.

Application considerations include the particle size and the melting characteristics of the nylon material. For coating purposes the fluidized bed can accommodate a range of particle sizes above a minimum. If the particle size is too small, e.g., less than 30 μm , the particles are lifted from the bed in a dust cloud. A size distribution for a typical powder of nylon 11 to be used in a fluidized bed is shown in Table 4-5.

The powders used in fluidized beds are available in two grades (named for the processes used to create them), namely, the precipitated grade and the melt mix grade. The precipitated grade is produced by a solution precipitation technique resulting in limited availability of colors, i.e., black, gray, and white. The melt mix is produced by extruding a ribbon of material and grinding it into a powder using cryogenic techniques. Additives can be mixed with the nylon before extrusion to modify the color or physical characteristics of the extruded material and consequently the final coating.

Nylon powders used for coating should have a low enough melting temperature to enable the pieces to be coated to melt the powder and cause it to adhere to the pieces. When a smooth finish is needed, the part can be

TABLE 4-5. TYPICAL PARTICLE SIZE RANGE FOR FLUIDIZED-BED COATING POWDERS (NYLON) (Ref. 7)

MESH	SIZE, μm	% RETAINED ON INDICATED SCREEN
70	210	0-5
100	149	15-30
140	105	45-60
200	74	65-80
325	44	80-95
Through 325 mesh	<44	5-15

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reheated to allow the material to flow and smooth out. Nylon 6/6 cannot be used because the material degrades when heated to a temperature sufficiently high to allow the material to flow and form a continuous film.

Nylons 11 and 12 provide the desired properties in films applied by the fluidized-bed technique: low coefficient of friction; high resistance to abrasion, chipping, and scratching; safe for use with foods; and sterilizable. Powders of nylons 11 and 12 of similar molecular weight can be mixed without negative effects. Nylon 6/10, also used in fluidized-bed coatings, has many of the same properties but is generally more expensive.

4-5.1.2 Advantages and Disadvantages of the Fluidized-Bed Process

4-5.1.2.1 Advantages

Fluidized beds are applied without the use of solvents; therefore, coatings may be applied by this technique without polluting the environment. Heavier coatings, generally 0.25 to 0.38 mm (10 to 15 mil) (i.e., 10 to 20 times thicker), with complete coverage of corners and sharp edges may be applied by fluidized beds than by other techniques.

The nylon coating applied by fluidized beds provides lower friction and better resistance to scratching, abrasion, and mechanical abrasion than uncoated parts have. Because of the complete coverage provided by the coating, coated parts have a much longer service life in corrosive or outdoor environments.

4-5.1.2.2 Disadvantages

Fluidized beds cannot be used to apply thin films, i.e., less than 0.12 mm (5 mil) thick. If fluidized beds are used for applications requiring only a thin coat, more material is applied than is necessary or desired. Material is wasted, and an unsatisfactory coating may be produced. Because the coating machines require a sizable quantity of material for operation, they are most often used to coat a number of parts with the same material. The process is not economical to use to coat small quantities of parts (especially small quantities of large parts) or parts that must be painted different colors. Also, because of the expense of setting the machine up with a quantity of powder, it is more expensive to use this process to test new coatings on samples or prototype parts or to evaluate new coating compounds and application parameters.

4-5.2 ELECTROSTATIC DEPOSITION

Electrostatic deposition is the most common technique used to apply powdered nylon to a surface for fusing into a uniform coating. Powder is sprayed from a gun charged with high voltage so the powder leaving the nozzle is charged (Ref. 24). The object to receive the coating is grounded and placed in the spray pattern where it attracts the charged particles from the sprayed cloud and causes them to collect on all surfaces of the object.

The coated part is then heated to a temperature high enough to fuse the coating into a smooth homogeneous coating in the same manner as is done to improve the surface quality of the parts coated by the fluidized-bed technique.

The electrostatic deposition process is slower than the fluidized-bed process, but it has the advantage of being able to apply thinner coatings, 25 to 75 μm (1 to 3 mil). A limitation of this process is that the distribution of powder on the surface of the part being coated is a function of the electric field in the proximity of the part produced by the difference in potential between the part and the charged cloud of powder. The fields are distributed such that inside corners do not receive as much powder as smooth or radially convex surfaces. Thus complete and uniform coverage of irregularly shaped parts is more difficult to obtain.

4-5.2.1 Nylon Spray Powders

The same nylon powders used for fluidized-bed application, nylons 11 and 12, are used for the electrostatic spray technique.

The moisture content of the nylon powder has a significant impact on the effectiveness of the electrostatic spray process. The moisture greatly affects how the powder accepts a charge as it is sprayed, and this acceptance affects the effectiveness of the collection of the powder on the article being coated. It also affects the physical flow characteristics of the powder. Nylons with water contents between 0.5% and 2% by weight may be sprayed, but powders having higher moisture contents can be dried either overnight in a fluidized bed operated with dried air or for several hours in shallow trays placed in a convection oven heated to 120°C (248°F).

4-5.2.2 Advantages and Disadvantages of Electrostatic Spray Coating

Like fluidized coating, the electrostatic spray technique is environmentally friendly. No volatile solvents are used in the process that could evaporate and pollute the environment. Efficiency of material usage approaches 100% when recovery systems are used. Electrostatic spray coating can be incorporated in automated production lines that run continuously for long periods. The electrostatic spray process is as economical as conventional solvent-based spray coating processes because of the thin film that can be applied (25 to 75 μm (1 to 3 mil)), the low melting temperatures required (150 to 220°C (300 to 430°F)), and the efficient use of material.

4-5.3 ELECTROSTATIC FLUIDIZED-BED COATING

The electrostatic fluidized bed, a combination of the fluidized-bed process and the electrostatic deposition process, uses a high voltage applied between a fluidized bed and the objects to be coated, which are suspended over it. The charge that the particles accumulate causes them to repel

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each other mutually and form a cloud over the bed through which the objects to be coated are passed. Similarly to electrostatic deposition, the fields cause the powder to be attracted to the object to be coated. This method is suitable for small or long, thin parts because the attraction forces are not strong enough to carry the particles long distances from the bed to the top of an object with a large vertical extent. Attempts to coat such objects with this method would result in a significantly thicker coating on lower portions of the object. Electrostatic fluidized-bed coating offers faster processing than a regular fluidized-bed coating and good control of coating thickness. The process is also suitable for automation and can be used to coat long objects that feed continuously.

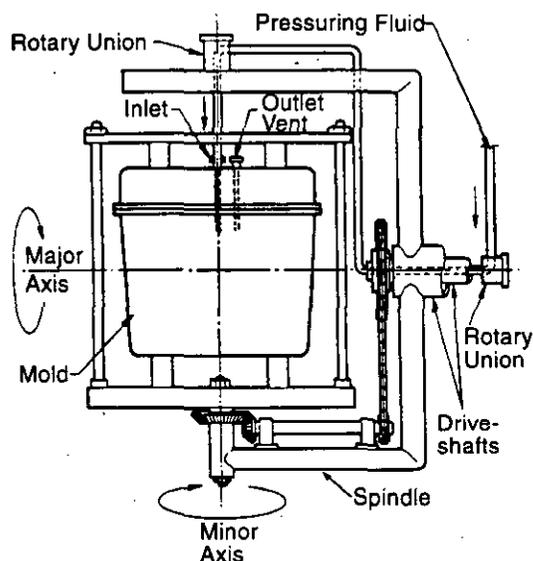
Although nylon powders are good insulators, they readily accept a charge and are, therefore, ideal for electrostatic coating techniques. Because of the effectiveness of the charging, uncoated metal parts should be exposed to the beds at a uniform, continuous rate to prevent excess accumulation of particles on them. There should not be extraneous grounded objects in the vicinity of the bed because they will quickly become heavily coated. Electrostatic beds are often totally enclosed, so they have ports for entry and exit of the processed objects. The exposure time for a coating thickness of 130 to 180 μm (5 to 7 mil) is approximately 5 to 8 s with the electrostatic spray process, whereas similar coatings may be applied by the electrostatic fluidized-bed process in only 2 to 4 s.

4-6 ROTATIONAL MOLDING

Rotational molding is the process used to fill a large mold with a small amount of nylon resin, place it in an oven, and continuously rotate it about two axes until the entire inner surface is coated with the molten resin. The mold is removed and cooled, and the part removed. This technique is used for large, hollow products requiring a uniform wall thickness and good surface finish, possibly with a complicated shape. The process has been used for fuel tanks, furniture, tilt trucks, industrial containers, storage tanks, and appliance housings (Ref. 22).

4-6.1 PROCESS

For rotational molding of nylon a mold is filled with a nylon 11 or nylon 12 powder. The mold is closed and placed in an oven. The mold is rotated simultaneously about two axes through a gimbal-like rotating mechanism (shown in Fig. 4-13) so that the powder coats the inside of the mold and fuses into a nylon coating on the inside surface of the mold as the mold is heated. When the lining is completely fused, the mold is chilled until the nylon solidifies, and the part is removed. Additional information about this technique is in Refs. 11, 22, 25, and 26. A troubleshooting guide for rotation molding is given in Ref. 11.



Courtesy Ferry Industries, Inc.

Figure 4-13. Mold in Rotational Apparatus—Spindle Turns on Primary Axis; Mold Rotates on Secondary Axis (Ref. 22)

4-6.2 PROPERTIES AND APPLICATIONS

Nylons are used for rotomolding because of their superior strength, toughness; ability to withstand low temperatures and solvents, and their low permeability to hydrocarbons. This last characteristic makes them suitable for fuel tanks for aircraft and military vehicles. For economy, fuel tanks are molded with an inner layer of nylon and an outer layer of polyethylene. Because of their ability to withstand high temperatures without distortion, nylons are also used for heating ducts for aircraft.

Nylons are prone to thermal degradation. Therefore, the resin must be well stabilized for these applications, and special grades are required. Similar to coating powders, the relatively expensive nylons are used only in applications requiring their chemical resistance and temperature tolerance.

4-6.3 ADVANTAGES AND DISADVANTAGES

4-6.3.1 Advantages (Ref. 22)

Advantages of rotational molding follow:

1. Products can have layered walls of different materials to combine the advantages of each, e.g., a chemical storage tank with a wall comprised of an outer layer for strength and rigidity and an inner layer for chemical resistance.
2. Corners and edges can be thicker than the surrounding material.
3. Parts are free of strain.
4. Wall thickness is uniform.
5. Surface finishes are clear of marks resulting from ejection pins, gates, etc.

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6. A wide range of product sizes can be accommodated.
7. Metal inserts can be incorporated into the molded object during the molding process.
8. Equipment cost is low.
9. There is little or no scrap material.
10. The molded object is complete. No further processing is necessary in most cases.
11. Wall thickness can be changed without any modification to equipment.
12. Parts of different colors or different shapes can be molded simultaneously in the same production line.
13. Switching molds is easy.
14. Little operator training is required.

4-6.3.2 Disadvantages

Disadvantages of rotational molding follow:

1. Material cost is high because fine powder is required.
2. Production is limited to parts with wall thicknesses over 0.76 mm (0.030 in.).
3. Cost is high for large production runs of small parts compared to other molding processes.

4-7 PRESSED AND SINTERED PARTS

Products can be formed of a combination of nylon and other fillers by using sintering techniques to incorporate desirable characteristics that differ from those of nylon alone. Nylon powders are blended with fillers or other modifying ingredients, pressed into a rigid mold, and heated until the materials fuse together to form the final part. Up to 80% (by volume) of fillers and modifiers can be added to the nylon as required to obtain the desired characteristics.

4-7.1 PROCESS AND MATERIALS

The base ingredient for nylon-based sintered parts is nylon 6/6 and nylon 6/10 powder prepared by solution and precipitation (Ref. 27). The resultant powder is compacted and ground to a particle size of 4 to 10 μm (0.16 to 0.4 mil) in order to allow better compaction and mold filling. Inorganic fillers are then added. For example, mica and molybdenum disulfide are used to reduce creep or modify frictional characteristics. Powdered metals are added to improve thermal conductivity (Ref. 28).

The nylon-filler mixture is compressed at room temperature in closed dies to a pressure of about 276 MPa (40,000 lb/in.²). The parts are then removed from the die. The compressed parts are strong enough to withstand handling at this stage of the process. The parts are then sintered, i.e., heated to a temperature that will fuse the particles together but not hot enough to melt the nylon. The heating must be done in a nonoxidizing atmosphere; if it is not, the material will oxidize and deteriorate. This is achieved by sintering the parts in a hydrocarbon-based oil, typically for 30 min at 257°C (495°F) with a two-hour heating up and cooling down period (Ref. 29).

Low moisture content of the powder is critical for successful sintering. If the moisture content exceeds 1%, cracking of parts may occur during sintering.

4-7.2 PROPERTIES AND APPLICATIONS

The physical properties, e.g., tensile strength, of pressed and sintered nylon parts are generally inferior to those of standard injection molded specimens. The creep and frictional characteristics, however, are generally improved over standard nylon parts, so the parts are suitable for use in bushings, bearings, and cams. Parts fabricated with lower compression pressures have a porosity that provides them with the ability to be saturated with lubricants, i.e., they can hold up to 50% by volume. This ability further improves their suitability for these applications.

4-8 MOISTURE CONDITIONING AND ANNEALING OF MOLDED PARTS

Moisture conditioning is the addition of moisture to a dry-molded part for one of the following purposes:

1. To reduce the dimensional changes to the part that would occur when it is placed in the application environment
2. To produce a test part with a specified moisture content
3. To increase the impact resistance of recently molded objects.

Two methods are typically used for moisture conditioning. The first method is the immersion of the object in water, which is usually heated to accelerate the process. The second method, which uses a potassium acetate solution, permits uniform distribution (equivalent to equilibrium with 50% RH) of water at less than the saturation level. This procedure is more complex than boiling in water, but it is useful for preparing test samples.

In water-immersion conditioning, the parts to be conditioned are immersed in water, which is usually boiling to expedite absorption of the water into the nylon. The amount of water absorbed can be determined by weighing the object before and after immersion and is controlled by the time of immersion, i.e., longer times are required for thicker objects. The water content will be higher on the surface of parts subjected to this process unless they are allowed to remain in the water until they are completely saturated. This technique does not allow equilibration of the part to a moisture level below saturation level, but it could serve as an accelerated process to force water into the object that is then allowed to equilibrate at some intermediate level of humidity for a long period of time. The initial immersion would shorten the period of time necessary for the moisture levels to reach equilibrium levels throughout the part. Fortunately, improvements in impact strength and dimensional stability are obtained before the moisture is evenly distributed throughout the material, so long periods of immersion are usually unnecessary. Conditioning of material sections

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3.2 mm (0.125 in.) thick requires approximately 3 h, whereas 6.4-mm (0.25-in.) thick sections require 18 h. For material more than 6.4 mm (0.25 in.) thick, saturation with moisture takes a very long time but is rarely necessary because the absorption of moisture will be very slow during use and saturation typically occurs only for parts that are used underwater.

Conditioning to 2.5% moisture is easy to perform with the immersion technique. The objects are immersed until the weight increase indicates a 3% moisture gain. The part is removed from the water bath and allowed to equilibrate. Initially the moisture is concentrated near the surface. Some of the moisture will be lost from the part through evaporation as the remainder spreads uniformly through the part. The resultant moisture content is approximately 2.5%. If moisture content is critical, before and after weights should be used to confirm that the desired amount of moisture was absorbed in the time allowed.

The technique using potassium acetate solution provides a conditioning medium for nylon parts that have an equivalent relative humidity at values below 100%. A nylon part immersed in a solution of 125 parts potassium acetate to 100 parts water will equilibrate to 2.5% moisture content, the same moisture content that would result from equilibration of nylon in 50% relative humidity for an extended period. For fastest conditioning, parts are immersed in the solution near its boiling point of 121°C (250°F).

This procedure is not without problems, however. It does allow equilibration to intermediate levels of moisture content below saturation, but it will take longer to achieve those levels. For example, equilibration of nylon objects with thicknesses of 3.2 and 6.4 mm (0.125 and 0.25 in.) require about 20 and 65 h, respectively, in potassium acetate solution compared with 3 and 18 h for the boiling water procedure described previously in this subparagraph. Also the potassium acetate solution must be maintained at a constant concentration requiring special apparatus to prevent evaporation of the components, so the procedure is more expensive to implement. Finally, nylon conditioned in potassium acetate absorbs trace amounts of potassium acetate that can affect the electrical properties of the material and make it unsuitable for electrical uses.

Annealing of nylon parts is done to remove the stresses that remain after certain molding processes. Annealing should not be done in air; it should be done by immersion in a suitable liquid. The annealing temperature should be at least 28 deg C (50 deg F) above the temperature to which the material will be exposed during use. A temperature of 150°C (300°F) is commonly used to ensure against dimensional change caused by uncontrolled stress relief, which

occurs below this temperature. The annealing time required is normally 15 min per 3.2 mm (0.125 in.) of cross section. Upon removal from the heat-treating bath, the part should be allowed to cool slowly in the absence of drafts. Otherwise, surface stresses may set up. Placing the heated article in a cardboard container is a simple way to ensure slow, even cooling.

The choice of the liquid to be used as the heat transfer medium should be based on the following considerations:

1. The heat range of the liquid and its stability over that range
2. The chemical compatibility of the liquid with nylon
3. The toxic fumes or vapors given off by the liquid
4. The fire hazard introduced by use of the liquid.

High-boiling hydrocarbons, such as oils or waxes, can be used as heat transfer media if the deposit left on the surface of the molded items is not objectionable, e.g., parts that will be lubricated in use. Work has been done that shows a nitrogen atmosphere is suitable for annealing but requires the use of special equipment and ovens.

The heat-treating bath should be electrically heated and thermostatically controlled to maintain the desired temperature. For best thermal control, heat should be supplied through the sidewalls as well as through the bottom of the vessel. A large number of small items are best handled by loading into a wire basket equipped with a lid to prevent their floating and then immersing the basket in the bath for the required period of time.

If the maximum application temperature will be 71°C (160°F) or less, acceptable stress relief can be obtained by immersion in boiling water. This method has the advantage that some moisture is absorbed by the nylon and thus partially conditions the piece. For stress relief 15 min per 3.2 mm (0.125 in.) of cross section is sufficient. Longer times are required if the piece is to be moisture conditioned to or near equilibrium.

4-9 EXAMPLES OF MILITARY HARDWARE USING NYLONS FABRICATED OR APPLIED BY VARIOUS PROCESSING TECHNIQUES

Par. 8-3 of this handbook discusses the military applications of nylons. Table 4-6 lists the processing or fabrication methods used to manufacture military items of nylon. The obturator applications are for antitank gun rounds. The M16A2 5.56-mm assault rifle is in use as the United States (US) infantry rifle. The AR-15 and AR-16 rifles are civilian designations for rifles used by the US Army infantry prior to the M16A2. The Galil assault rifle is an Israeli weapon.

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**TABLE 4-6. EXAMPLES OF NYLON PARTS FOR MILITARY HARDWARE:
THEIR COMPOSITION AND METHOD OF FABRICATION**

PART	HARDWARE	NYLON TYPE	MOLDING AND/OR FABRICATION METHOD
Centering band	105-mm APDS-T* M392 A2	Nylon 6/6	Injection molding
Nylon-coated machine-gun ammunition belt links (Experimental to increase rate of fire)	30-cal machine gun	Nylon 11	Fluidized-bed coating of metal
Obturator	120-mm APFSDS-T** M829 and 829A1	Nylon 6/12	Extruded stock machined to dimensions
Obturator	105-mm M735 APFSDS-T	Nylon 6/6	Centrifugal cast tube machined to dimensions
Handguard; pistol grip; butt plate	M16A2 5.5-mm assault rifle	Glass-fiber-reinforced, lubricated nylon 6/6	Injection molding
Magazines	AR-15, AR-16, and Galil assault rifles	Glass-reinforced nylon [†]	Injection molding
Butt stock; handguard; pistol grip	M249 5.56-mm light machine gun	Glass-reinforced nylon 6	Injection molding
Washers; locknut; cap	Stuffing tubes for shipboard electrical cables per MIL-S-19622E	Nylon 6/6 per ASTM D 4066, Group 1, Class 8, Grade 1	Injection molding
Cartridge case	MC/AAAC 75 mm	Glass-filled nylon 12	Injection molding

* APDS-T = armor-piercing, discarding-sabot tracer

**APFSDAS-T = armor-piercing, fin-stabilized, discarding-sabot tracer

†Nylon type not identified

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CHAPTER 5

DESIGNING WITH NYLONS

Information is given on the general design principles to be used with nylons. Part design considerations, design methods, and typical design examples are discussed. Methods of permanent and temporary joining are also discussed. Such topics as self-threading screws, press-fitting, snap-fitting, cold or hot heading, spin welding, ultrasonic welding, ultrasonic heading and stud welding, ultrasonic inserting, vibration welding, hot-plate welding, and cementing are reviewed. Quality control of finished parts covers sampling, visual defects, part weight control, and voids.

5-0 LIST OF SYMBOLS

- D_A = pitch diameter of gear, in.
 D_m = pitch diameter of gear, mm
 E_y = Young's modulus for material, Pa (psi)
 m = metric module, mm
 N = random sample size, dimensionless
 N_t = number of teeth in gear, dimensionless
 p = internal cylinder pressure, MPa (psi)
 P_d = diametral pitch, in.⁻¹
 R = inside radius of cylinder, mm (in.)
 s_1 = longitudinal stress, MPa (psi)
 s_2 = design hoop stress, MPa (psi)
 t = thickness of cylinder walls, mm (in.)
 ϵ_x = strain (elongation), m/m or dimensionless
 σ_x = applied stress, Pa (psi)

5-1 INTRODUCTION (Ref. 1)

The effective design of nylon parts for manufacture requires an understanding of the properties of the nylon material, the behavior of the material during the manufacturing processes, the constraints imposed on the part design by its use, and the requirement imposed upon the part design in order to allow additional processes or assembly techniques. This understanding is necessary if a part design that will satisfy the application requirements and a fabrication process that will efficiently produce the desired part are to result. The part design and the manufacturing process are not independent. For example, molding is an appropriate process for the production of solid parts, such as small gears. The shape of the gear, however, must be carefully designed so the uneven shrinkage that occurs upon solidification of molded nylon does not distort the part.

Designers must be aware of the differences between working with plastics such as nylon and with other engineering materials. The same equations that describe the physical characteristics of metals, e.g., deformation of the material with temperature or applied stress, apply to plastics as well, but the parameters are different. Plastics usually have a lower modulus of elasticity, higher creep rates, and lower failure stress. The most significant consideration that applies to plastics is their sensitivity to the environment. Careful consideration must be given to operating temperature, moisture levels, and

level and duration of loading. Plastic parts must be designed with a higher safety factor than metal components, so careful consideration of design parameters as well as the configuration of the component is required. Careful consideration of the material characteristics necessary for this process will emphasize the differences among different types of nylons and will lead to an understanding of the advantages and disadvantages of each (Ref. 1). A major difference that gives plastics an advantage over other engineering materials is the flexibility of design allowed by the manufacturing process. For example, a complex part containing multiple gears, bearings, and cams, each of which has a different surface finish, resilience, and strength, can be produced by a single molding operation. A functionally equivalent component fabricated from metal would require either the assembly of multiple components or multiple machining operations.

To take advantage of the flexibility afforded by nylon manufacturing operations, attention must be given to the design. If a single plastic part can be designed that will replace the functions of several conventional metal parts, the number of manufacturing operations can be reduced. Additional economy can be gained by incorporating assembly features that are not available or are difficult to implement in metal components, such as snap-together components or mechanically welded components. Although more economical to produce or assemble, nylon parts still offer improved performance in comparison to equivalent metal components because of the physical properties of the material, i.e., strength, resilience, wear resistance, and low coefficient of friction.

5-2 DESIGN—GENERAL

5-2.1 DESIGN PROCESS (Ref. 2)

5-2.1.1 Identification of Requirements

The first step in the design of a part is to determine the requirements, i.e., the performance requirements determined by the function the part is to perform and the environmental requirements determined by the environment in which the part will function while in service. Investing the time to develop a complete specification of requirements before beginning the design may prevent redesign later in the development process and the loss of more time than that needed to complete the requirements. Items that should be considered prior to the development of a part are given in Table 5-1.

MIL-HDBK-797 (AR)**TABLE 5-1. DESIGN CHECKLIST (Ref. 2)**

GENERAL INFORMATION	APPEARANCE
What is the function of the part?	What style should it be?
How does the assembly operate?	What shape should it be?
Can the assembly be simplified by using nylon?	What color should it be?
Can it be made and assembled more economically?	What surface finish should it have?
What tolerances are necessary?	Should it have any decoration? If so, what?
Can a number of functions be combined in a single molding to eliminate future assembly operations and simplify design?	ECONOMIC FACTORS
What space limitations exist?	What is the cost of the present part?
What service life is required?	What is the cost estimate of the part in nylon?
Is wear resistance required?	Are faster assemblies and elimination of finishing operations possible?
Is light weight desirable?	Will redesign of the part simplify the assembled product and thus yield a saving in installed cost?
Do analogous applications exist?	MANUFACTURING OPTIONS
STRUCTURAL CONSIDERATIONS	Should the proposed design be machined, injection molded, or extruded, considering the number of parts to be made, the design geometry, and tolerances?
How is it stressed in service?	If injection molding is chosen, how can mold design contribute to part design?
What is the magnitude of the stress?	In subsequent assembly operations, can the properties of the chosen nylon be used further, i.e., by spin welding, snap fits, etc.?
What is the stress versus time relationship?	After preliminary study, several steps remain to convert design ideas into production.
How much deflection can be tolerated in service?	
ENVIRONMENT	
What will its operating temperature be?	
To what chemicals and solvents will it be exposed?	
To what humidity level will it be exposed?	
How long will its useful life in the environment be?	

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5-2.1.2 Drafting the Preliminary Design

Based on the identified requirements, the part design is defined by drafting. This process is usually accomplished in several stages that begin with preliminary sketches showing the general configuration followed by successively more detailed drawings showing detailed features, such as radii, thicknesses, and features designed for manufacturability.

5-2.1.3 Prototyping the Design

A prototype is a full-scale, functional unit prepared in order to be evaluated before manufacturing operations are begun. The prototype is not necessarily prepared by the same manufacturing technique as the mass-produced product; therefore, some differences in the characteristics of the material between the prototype and the final product may be introduced, e.g., a different grain orientation or machining marks. Prototype nylon parts are usually made by machining the part from rod or slab stock. Care should be taken to ensure that the material is void free, especially where complex machining operations are required. The material may be examined by X ray to detect voids. Standard medical-type X-ray units can be used to detect 1.6-mm (1/16-in.) diameter voids.

As mentioned previously, the method of fabrication may affect the final characteristics of the part. In some situations it may be necessary for the prototype to be constructed using the same technique as the final part in order to evaluate the suitability of the part, to determine more precisely the characteristics of the manufactured part, and to determine the parameters associated with the manufacturing process. When the final part is to be molded, machining of the prototype may introduce differences for the reasons that follow:

1. Parts machined from rod stock usually have greater crystallinity and higher molecular weights than parts molded from nylon 6/6. Some properties of rod stock, e.g., abrasion resistance, may be higher than those of molded material.
2. Marks left by machining operations may concentrate stresses and thus reduce the strength of the prototype below that obtained with a molded part.

For parts to be produced by injection molding, prototypes may be made using prototype molds to evaluate the effects of gate placement because the location of gates can affect the grain orientation of the final product and therefore its toughness. This check of grain orientation is especially needed for glass-reinforced nylon parts for which the fiber orientation

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will significantly affect the product. Similarly, the use of molded prototypes allows determination of the shrinkage of the molded product. The prototype molds are similar to production molds except they can be machined from softer metals, such as aluminum, brass, or beryllium copper.

5-2.1.4 Testing the Design

Samples of all parts, both the prototype and the final product, should be tested to ensure that the application requirements are satisfied. Testing may be in one of three forms:

1. Actual end-use testing during which the part is placed in service. The advantage of this type of testing is that the part is exposed to the service environment. The disadvantage is that any service life tests are not accelerated and therefore require long periods to evaluate the service life of the part. Also the part may not be subjected to occurrences of severe environmental factors that occur infrequently in the application environment.

2. Simulated service tests involve placing the component in a controlled environment, simulating the end-use operating environment, and testing the part for its required attributes, e.g., strength, flex-life, and hardness. For example, parts used in the vehicular environment might be exposed to high temperatures, hydrocarbon-based fluids, and vibration for an extended period and then tested for tensile and impact strengths, flex-life, and hardness. Military items require testing similar to that for commercial items except the environmental parameters are more severe and may include exposure to nuclear, chemical, or biological agents.

3. Standard tests, such as those developed by the American Society for Testing and Materials (ASTM), do not provide data that are directly applicable to evaluating the performance of parts in a specified application. They do, however, provide data under uniform conditions, which allow the comparison of new components or materials with older units operating under identical conditions.

Tests of the types described in Nos. 2 and 3 can be accelerated by creating an exposure environment more harsh than the one that will be encountered in normal service life. The service life can then be estimated by extrapolating from the accelerated life determined during the tests using assumed acceleration factors. The uncertainty of this approach is that the assumed acceleration factors are estimates based on experience with accelerated testing, but they can vary due to peculiarities of the application.

5-2.2 GENERAL DESIGN CONSIDERATIONS (Ref. 3)

5-2.2.1 Tolerance Specification

The designer must determine the requirements for dimensional accuracy of the component and the temperature range over which that accuracy is to be maintained. Overspecification of dimensional tolerance is costly because of the increased cost to manufacture precision components. If toler-

ances are specified too stringently, fabrication of parts meeting the specification can be impossible because of dimensional changes due to temperature alone. Often it is possible to utilize the resiliency of the nylon or other design features to relieve the requirements for tight dimensional tolerances.

The specification of tolerances for plastic parts should be recorded according to accepted practice for mechanical drawings. There are, however, some practices made necessary by the dimensional characteristics of the plastic material:

1. Dimensions and tolerances should be specified for a specific point in the manufacturing process, such as after molding, after annealing, or after moisture conditioning.

2. Tolerances should be given in terms of a change in length per unit length, e.g., "all decimal tolerances $\pm 0.00x$ mm/mm or $\pm 0.00x$ in./in.", instead of the conventional practice of specifying an overall tolerance in absolute terms, e.g., $\pm 0.00x$ mm or $\pm 0.00x$ in.

3. Tight tolerances should be specified only for dimensions for which they are specifically required. The remaining tolerances should be governed by an overall tolerance requirement specified for the entire piece.

Very loose tolerances during molding should be specified for the surfaces of parts to be machined because the machining operation will yield their final dimension.

Allowance must be made for cavity-to-cavity variation in a multicavity mold. Single-cavity molds can produce parts with a tolerance of ± 0.002 mm/mm (± 0.002 in./in.). For multicavity molds, this tolerance must be increased by 1 to 5% per cavity.

5-2.2.2 Dimensional Stability

Compared with other engineering materials, nylon is more susceptible to dimensional changes caused by temperature, moisture absorption, crystallization, and stress relief. Frequently, the dimensional instability of nylon can be offset or compensated for by the resiliency of the material or by incorporating dimensional tolerance in the design. If the absolute end-use dimensions of a molded object are required, the measurements must be specified very carefully because the dimensions are subject to change with the environmental conditions.

Verification of critical dimensions should be performed as the parts are fabricated to allow early detection and correction of manufacturing defects; however, the dimensions of the parts may change over time after fabrication due to temperature, moisture absorption, crystallization, and stress relief. For critical applications one of the following three approaches can be used to assure dimensional accuracy of delivered parts:

1. Manufactured parts are annealed, measured to ensure that they comply with the dimensional requirements, and packaged in sealed containers. The dimensions are based on dry, stress-free components. The end user must allow for any dimensional changes that occur if the part is exposed to moisture in the final application.

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2. Dry manufactured parts that satisfy the dimensional requirements are packaged in sealed containers and shipped to the distributor or end user. Parts remain in sealed containers for at least three to four weeks, during which the parts become stress relieved. Again, the end user is responsible for compensating for any dimensional changes that occur due to moisture in the environment of his application.

3. Parts are manufactured and then conditioned in boiling water until the moisture content reaches the value typical of pieces in use in the actual application. Dimensions are verified and the parts are packaged in sealed containers to prevent changes in moisture content.

5-2.2.3 Appearance and Structure

Nylon can be molded in a wide variety of colors and finishes. When the material was originally introduced, its unique bone color distinguished it from other plastics. This recognizable color identified products made of a quality material having greater strength and toughness than other plastics available at the time. Later, techniques were developed by which to add coloring materials to the nylon to produce a material resistant to sunlight and suitable for cosmetic applications, for which material of specified colors was required. No longer, however, is it possible to identify nylon materials by color alone. For military hardware coloring of the part may be necessary for deception or camouflage, and the surface texture is extremely important, especially for the grips on hand-controlled weapons.

Nylon parts can be accurately fabricated in almost any shape. The major constraint on part shape arises from the need to be able to remove the part from the mold. Undercuts in the fabricated part require expensive, multipart molds or multi-step processing, e.g., molding the part in more than one piece and cementing the two parts together, and should be avoided unless absolutely required for the application. For molded parts surface texture is generally controlled by the mold; however, improper design of the part can lead to dimensional distortion and surface flaws caused by uneven shrinkage of the part after molding. Design considerations to minimize these effects are discussed in the next paragraph.

5-3 PART DESIGN CONSIDERATIONS

5-3.1 PART GEOMETRY AND WALL THICKNESS (Ref. 2)

To facilitate the molding operations, metal parts made by casting techniques usually have thicker wall sections than required. With nylons, however, the designer has more control. Because the material is typically injected into the mold under pressure, the part can be designed to use a minimum amount of material with no adverse effect on manufacturability. As long as the part is designed to meet specified strength requirements, reduction in material reduces only the material costs and equipment requirements.

One of the most important considerations in the design of

parts for injection molding is the necessity for uniform wall thickness throughout the part. In pieces with varying wall thicknesses, the material in the thicker sections cools more slowly than in thinner sections because heat transfer to the cooled mold is slower. Since the material contracts as it cools and solidifies, the material in the thinner sections draws molten material out of the thicker sections as they solidify. The thicker sections then collapse and the molding problems that follow occur:

1. *Sink Marks*. Small depressions in the surface produced by the material drawn out of thicker sections into adjacent thinner sections that cooled and solidified first
2. *Warpage*. Deformation of the overall part shape after cooling; it is caused by the uneven distribution of material.
3. *Stress Points or Cracks*. Areas under tension caused by uneven shrinkage of the molded part during cooling
4. *Voids*. Holes in the interior of thick sections produced by material drawn out of thicker sections into adjacent thinner sections that cooled and solidified first.

Uniform wall thickness may be enhanced by techniques such as these:

1. Rounding corners so that equal thickness is preserved at all points along the radius
2. "Coring" or introducing a void in the center of a thicker, built-up area, which replaces the raised solid area with a hollow area partially enclosed within walls of the same thickness as the rest of the piece.

When varying thicknesses cannot be avoided, gradual transition regions should be provided between areas of different thickness, and the ratio of thickness between thin and thick regions should be kept under 3:1. Also glass-filled nylon shrinks less than homogeneous nylon, so it can be used to reduce the problems with shrinkage, such as fill marks.

5-3.2 RIBS AND STRENGTHENING MEMBERS

Strength can be added to parts without an excessive increase in material by the use of ribs or other strengthening members. Using ribs allows fabrication of lighter, stronger structures with less material and thus produces economical parts. Using ribs also allows parts of constant thickness to be fabricated when the function of the part requires raised or thicker sections, e.g., bosses.

The design of ribs should enable the ribs to contribute adequate strength to the part. The thickness of the rib, however, should not be excessive, or sink marks may be introduced in the reinforced wall on the surface opposite the rib. The rib should be about 0.75 times as thick as the reinforced wall. Ribs taller than three times the wall thickness should be supported to prevent buckling. Where additional strength is needed, multiple ribs should be used instead of excessively tall or thick ones.

For ease of ejection from the mold, the ribs should be perpendicular to the mold parting line and tapered, i.e., thicker at the bottom than at the top. Taper angles of 0.5 to 3 deg also aid part ejection.

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5-3.3 FILLETS AND RADII

Sharp corners tend to concentrate stress in their vicinity and therefore lead to failure of the plastic in that region. Elimination of sharp corners by rounding the inside corners with fillets improves the ability of the piece to withstand greater applied loads without failure. For effective stress reduction, fillets should have a radius 0.6 times the thickness of the material. Smaller radii can be used if the resulting decrease in part toughness can be tolerated. The minimum radius that should be used is 0.51 mm (0.02 in.).

The use of fillets also increases the manufacturability of the part by allowing better streamlines for filling the mold and consequently reduces wear and stress on the mold. Depending on the location of the fillets, parts with fillets are easier to eject than those without.

5-3.4 DRAFT

Draft is the taper placed on a protruding feature of a part or on a recess within the part and is specified in degrees measured from a central axis of the part. For example, consider a rib protruding from a horizontal surface. If the rib is tapered so that each of its surfaces is inclined at an angle of 1 deg with the vertical (2 deg between the opposite surfaces), the rib is said to have a draft of 1 deg.

Some positive draft facilitates removal of the part from the mold. The specific angle of draft chosen for various part features depends on manufacturing considerations. A draft of 0 deg is sometimes used for small, shallow parts to cause the molded part to adhere reliably to a specified side of the mold when the halves are separated. Normally, a draft for nylon parts is at least 1/8 deg, although the appropriate amount of draft depends on wall thickness, the depth of the part, molding conditions, and the material being molded. For example, glass-reinforced nylon requires more draft, 0.25 to 1 deg, because of the reduced shrinkage of the material during molding.

5-3.5 PARTING LINES

The parting line is the intersection of the part and the plane corresponding to the interface between the halves of the closed mold. The parting line is evident on the finished part as fine, protruding material encircling the part. The location of parting lines is a mold design issue because the orientation of the molding cavity is chosen to produce a part that can be readily ejected. If possible, the mold should be designed so the parting line falls along marks on the part. Thus the resulting ridge on the part is less noticeable. If the part is to be used as a bushing or wear plate, the parting line should be located where it does not cross a bearing surface.

5-3.6 THREADS

External and internal threads can be molded into plastic parts and thereby eliminate the need for separate thread-cutting or -rolling operations; however, special techniques are necessary, particularly for internal threads, because of the

undercuts in the mold, which tend to make ejection difficult. Some of these techniques follow:

1. A threaded pin may be screwed into the mold before injection and unscrewed before the mold is opened. The part then ejects normally.

2. If shallow threads are used, the part may be forcefully stripped from the mold.

3. Use an insert with external threads, which is placed in the mold before filling, ejected with the molded part, removed from the part, and replaced in the mold.

4. Employ a collapsible core that allows the core threads to be retracted from the threads in the molded piece before ejection.

For external threads the techniques include these:

1. Arrange the threaded portion of the object so that the axis of the screw lies in the plane of the mold faces.

2. Mold the threads in a removable section of the mold, which can be removed from the molded part by unscrewing it before the mold is opened.

3. Use inserts with internal threads that are placed in the mold before the nylon is injected. These inserts are ejected with the part, removed from the part, and replaced in the mold.

5-3.6.1 Stripped Threads

If parts containing internal threads are to be forcibly stripped from the mold, the designer should specify rounded threads molded into thin walls to achieve the resiliency necessary for the threaded mold to be removed from the part without damage to the threads. The walls into which the threads are formed should have a diameter-to-wall thickness ratio greater than 2:1.

The technique of stripping the male threaded mold from the molded part should not be used with rigid materials, such as glass-reinforced nylon.

5-3.6.2 Formed Threads

Threads molded in nylon parts usually are American National (sometimes called Unified) threads. These threads have slightly rounded roots and crests to minimize the sharp edges and stress concentration at the roots. Molded threads are usually no finer than 32 threads per inch. Threads molded onto protrusions extending outward from a solid body should be terminated one thread's length away from each end of the protrusion, especially at the shoulder end. Threads cut lower would introduce a weak point at the base of the threaded protrusion and increase the likelihood of its breaking off. Internally threaded holes located close to a wall should be located so that a wall thickness remains that is greater than or equal to the root diameter of the thread to prevent enlargement of the threaded hole under load and subsequent fastener pullout.

5-3.7 UNDERCUTS

An undercut is a projection from the wall of a part that interferes with simple ejection from the mold. There are two classes of undercuts:

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1. *Internal.* A protrusion into the sides of a cavity of a molded part. During molding, the cavity of the part fits over the core of the mold, and these protrusions fit into depressions in the core of the mold. They tend to hold the part onto the core.

2. *External.* A protrusion from the exterior of a molded part. During molding, these protrusions fit into depressions in the sides of the molding cavity.

An undercut can be eliminated by placing the protrusion on the parting line, but if there are multiple undercuts or other *overriding considerations for parting line placement*, such elimination may not be possible. If undercuts are unavoidable, they can be molded by using split-cavity molds (for external undercuts) or collapsible cores (for internal undercuts) or by forced stripping of the part from the mold (for shallow undercuts). These mechanisms increase tooling costs and reduce the rate of production of a given machine.

The amount of undercut is specified in percent to relate the height of the protrusion to the overall dimension of the piece at the point of the protrusion. For protrusions that encircle the device, the height of the protrusion would be doubled before calculating the percentage since the height extends above the part profile on two opposite sides. For internal undercuts the calculation is based on the protrusion height and the overall dimension of the inner cavity of the piece. For external undercuts it is based on the protrusion height and the overall dimension of the outside not including the protrusion.

Because of the resiliency of nylon, parts with up to a 6 to 10% undercut can be stripped from a mold. The shape of the undercut should be rounded with fillets to aid release from the mold. In addition, the undercut part should be free to stretch and/or compress so it can deform sufficiently to allow the undercut portion to clear the mold recess during ejection. For the more rigid glass-reinforced nylon, undercuts are limited to 1% for a 38°C (100°F) mold and 2% for a 93°C (200°F) mold. For larger undercuts collapsible-core or split-cavity molds may be appropriate.

5-3.8 HOLES

Holes in the molded product can be produced by placing pins in the mold cavity at locations corresponding to where holes are desired in the molded part. The pins are subject to large forces by the resin injected during the molding operation, so they must be well anchored. Through holes use a pin that can be anchored at both ends and therefore can be more reliably produced than blind holes. Blind holes should be limited to a depth of twice their diameter so that the pins used to form them can be made strong enough to withstand the flow of the melt across them.

5-3.9 INSERTS (Ref. 4)

Metal, threaded inserts can be molded into nylon to provide a durable, reusable fastening mechanism. These inserts increase the cost of parts because placing the inserts in the mold

before injection increases the cost of manufacture. The additional expense, however, may be justified in some applications because of the following advantages gained through the use of threaded inserts:

1. Assembly and/or disassembly cycles do not weaken or deteriorate the threaded inserts.

2. Metal inserts provide higher pullout strengths for fasteners compared to self-tapping fasteners or molded machine screw threads.

Inserts can be used for purposes other than fastening, e.g., to reinforce parts by adding rigidity or strength in selected portions or providing a bearing surface that can withstand greater forces than nylon alone.

5-3.9.1 Insert Types

5-3.9.1.1 Molded-In Inserts

The properties of nylon make possible the secure embedding of inserts in molded products. It shrinks upon cooling and thereby grips the insert tightly; it adheres to the part as long as the surfaces are dry, clean, and free of grease. Nylon is tough and resilient, so shocks imparted to imbedded inserts will not fracture or deform the nylon material as long as it is sufficiently thick. Thin layers of nylon molded onto metal hubs, such as nylon gear teeth molded onto a metal hub, are susceptible to fracture if the section containing the gear teeth is very thin, e.g., ≤ 1.6 mm (1/16 in.) thick when molded around a 15-cm (6-in.) hub. Glass-filled nylon tolerates less elongation and therefore is somewhat susceptible to fracture when stressed by the inserts.

Guidelines necessary to ensure the reliability of molded-in inserts follow:

1. The inserts should be clean and dry prior to installation. For best results the insert should be preheated to a temperature in the range of 93 to 121°C (200 to 250°F).

2. Inserts should have rounded corners. Sharp corners can introduce stress points that will induce fracture of the nylon material, especially if glass-filled nylon is used.

5-3.9.1.2 Pressed-In or Self-Threading Inserts

Metal inserts that are pressed in or threaded in after molding can be used to avoid the necessity of molding in inserts. These inserts simplify the molding process but require an additional assembly step after the molding process is complete.

A self-threading insert is inserted into a smooth-sided hole in the molded part in the same manner as a self-threading screw. Pressed-in inserts may be knurled to increase their holding capacity and then pressed in with the aid of heat or ultrasonic vibration. Like the molded-in inserts, these inserts must be surrounded by adequate material to prevent cracking of the material caused by loads placed on the insert or by stresses induced by the differing rates of thermal expansion of the metal insert and the plastic surround.

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5-3.9.2 Hole Diameter for Inserts

For self-threading inserts the diameter of the hole for the insert should be less than that of the pitch and greater than that of the root of the threaded insert. This practice will provide maximum stripping torque and, since the threads cut into the material, will produce a minimum amount of radial stress on the plastic material.

For pressed-in inserts the hole diameter is related to the outside diameter of the insert and the amount by which the hole can be elastically expanded during installation of the insert. Holes for installation of inserts in bosses formed in nylon plastic can expand more than holes in bulk, rigid, glass-reinforced plastic. For inserts to be installed in a boss that is only approximately 25% larger than the insert, the hole should be made about 4.3% smaller than the insert. For inserts in larger bosses or in solid material, the interference can safely be higher; 5.2% is a recommended value. (Ref. 2)

5-3.9.3 Diameter of Bosses for Installation of Inserts

Bosses that are added to parts in order to retain inserts should be at least 2.5 to 3.0 times the outer diameter of the insert. Bosses having a diameter smaller than this criterion are subject to failure from stresses caused by loading applied to the insert by external sources or by the thermal contraction of the nylon material surrounding the insert. Bosses having a small diameter do not maintain adequate gripping force on the insert and, relative to bosses with larger diameters, have lower pullout strengths.

5-3.9.4 Effects of Time (Relaxation) on Insert Strength

The pullout strength of inserts is related to the degree of undercut of the insert after installation and the compressive force in the material, which tends to maintain that undercut. For pressed-in inserts the material is stretched during installation, and the elastic forces that attempt to return the material to its original shape are responsible for the compressive force that grips the insert. Over time these forces diminish as the material adjusts to its new shape. This relaxation results in a long-term decrease in pullout strength for pressed-in inserts. Therefore, the design of the part must allow for this weakening effect over the life of the part. Over long periods the outside diameter of the boss expands slightly as the boss adjusts to the expansion force produced by the slightly over-size insert placed in the core of the boss. Measurements indicate that the growth of the boss expressed in terms of the diameter is 50% of the amount of interference between the insert and the hole provided for it (where the interference is the difference between the diameter of the insert and the diameter of the hole).

When used in appropriately sized holes in nylon material, self-threading inserts do not expand the opening; they rely on the thread-cutting action of the insert to produce the undercut,

which grips the insert. Because the nylon does not expand, there is no relaxation effect; therefore, the pullout strength does not diminish over long periods of time, as is the case with pressed-in inserts.

5-3.9.5 Strip-to-Drive Ratios

The effort necessary to thread a machine screw into an insert is small compared to the effort necessary to drive a self-threading insert into an appropriately sized hole in the nylon material. (Inserts expanded by the insertion of the machine screw are exceptions. The force required to insert the machine screw is higher for these inserts.) If the hole is smaller than the recommended size, the force required to thread the insert into the material may be sufficient to shear the machine screw used to insert it.

Inserts are sufficiently captured by the surrounding material that a 6.14- × 12.7-mm (1/4- × 1/2-in.) brass machine screw will shear before it can cause a properly installed insert to rotate in the material. A torque of 2.5 to 4.0 N·m (22 to 35 lb·in.) is required to rotate an insert immediately after insertion and one year later (Ref. 2).

5-3.9.6 Stresses Caused by Thermal Expansion and Contraction

As mentioned previously, the thermal expansion coefficient of nylon is six to eight times higher than it is for metals used in inserts. Therefore, the nylon material surrounding a molded insert will shrink more than the insert as they cool and cause the nylon around the insert to be in tension. This can lead to the development of cracks in the nylon. Heating the inserts prior to placing them in the mold minimizes the difference in the amounts of contraction between the nylon and the metal.

The differences in expansion coefficients should be considered in the design of systems that use both metal and nylon components, especially if those systems are to be operated over a wide temperature range. These differences may result in changing clearances with changing temperature. The design must consider the dimensional changes so that clearances and contacts are maintained where required.

5-4 DESIGN METHODS

The analytical techniques for and manner of specification of the physical properties of other materials such as metals are also applicable to plastics. Therefore, engineers who lack specific experience with plastics can draw on their experience with other materials if they remember two basic differences between plastics and other engineering materials:

1. The stress-strain characteristic of plastics is nonlinear and environmentally sensitive.
2. Many of the properties of the material are affected by environmental conditions.

These two factors are discussed in the following subparagraphs.

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5-4.1 STRESS-STRAIN CURVE (Ref. 1)

The stress-strain curve provides a measure of the change in material dimensions in response to applied loading. For an ideal material the stress-strain relationship is linear and time invariant, i.e., the strain or elongation of a material is directly proportional to the tensile force applied to the material for both positive (normal tensile) and negative (compressive) loadings. The relationship can be written as

$$\sigma_x = \epsilon_x E_y \quad (5-1)$$

where

$$\begin{aligned} \sigma_x &= \text{applied stress, Pa (psi)} \\ \epsilon_x &= \text{strain (elongation) m/m or dimensionless} \\ E_y &= \text{Young's modulus for material, Pa (psi).} \end{aligned}$$

For most engineering materials, such as metals, this relationship is a good approximation for those values of σ_x that do not cause a permanent deformation of the material. For these materials the value of E_y is not dependent on the polarity of the applied force, i.e., tensile and compressive loadings of the same magnitude produce dimensional changes of the same magnitude, although opposite in sign. As the applied stress σ_x increases, the actual strain ϵ_x begins to differ from that predicted by Eq. 5-1 as the elastic limit of the material is approached. At some value small increases in stress lead to large values of elongation and subsequent failure of the material. The specific shape of the stress-strain curve depends on whether the material undergoes plastic or permanent deformation before failure. Ductile materials, such as aluminum, undergo permanent deformation when sufficient stress is applied. However, others, like cast iron, undergo recoverable deformation when stress is applied but fracture before any permanent deformation occurs.

The characteristics of the stress-strain curve for plastics differ from those of other engineering materials in several respects. First, the stress-strain curve for positive stress levels differs from that for negative stresses, particularly at higher stress levels. Second, the stress levels tend to be nonlinear. Last, the curve is strongly environment dependent; it is affected by both temperature and humidity. As a result, the engineering approximation represented by Eq. 5-1 is not sufficient for designs using nylon materials. Instead complete curves must be used to determine the expected strain for a value of stress since the linear relationship, an extrapolation of a single-point measurement, is not sufficiently accurate. Also the dependency of the stress-strain characteristic on environmental factors must be considered. From the families of stress-strain curves, the curve appropriate for the material, temperature, and humidity must be selected for the environmental factors, those at the time of either manufacture or end-use. For example, if a nylon part is to be used in an application requiring snap-fit assembly, the thickness of the spring members must be calculated based on the environmental conditions at the time of assembly. If the conditions during manufacture are well controlled, an accurate determination of the

stress-strain relationship can be determined from the curves, and the part dimensions can be calculated based on that data. However, if the conditions are not completely specified but are known to fall within a certain range, the modulus that would handle the worst-case situation must be determined. For example, at low temperatures the part must have sufficient flexibility to allow the snap-fit portions to be coupled with a moderate amount of effort. At high temperatures the *spring latches must retain enough elasticity to maintain the latched condition*. Calculations should be made under both conditions to ensure that both are satisfied.

5-4.2 ENVIRONMENT

As noted in subpar. 5-4.1, environmental conditions must be considered in the component design not only to determine the characteristics of the material in the anticipated environmental conditions but also to ensure that the designed part will meet the functional requirement throughout the range of environmental conditions. Nylon, like other plastics, is more sensitive to environmental conditions than other engineering materials, metals in particular. The environment affects not only the stress-strain characteristics of the material but dimensions as well, so the expected range of temperature and humidity conditions should be considered during the design process. For most cases the design should be based on the characteristics of the material at the highest expected humidity. Experience has shown, however, that the moisture content of most nylon parts equilibrates to the level corresponding to 50% atmospheric humidity. Thus many parts are designed based on the characteristics of nylon at that moisture level.

5-5 TYPICAL END PRODUCTS

The wide variety of nylon compositions and the number of applications for which these compositions are well-suited make it impossible to discuss design examples for each application. Therefore, the examples presented in the following paragraphs are representative of the design process and illustrate the considerations appropriate for design of nylon parts.

5-5.1 A PRESSURE VESSEL UNDER LONG-TERM LOADING (Ref. 2)

The first step in the design process is to define the requirements, including the performance requirements and the environment the part must withstand. This is especially true for a pressure vessel for which safety is critical and the performance requirements, particularly the pressure rating, have a direct impact on the geometry of the device. In this example, a cylindrical vessel is desired that will withstand pressures of 0.69 MPa (100 psi) for 10 years at 65°C (150°F). A relative humidity (RH) of 50% is assumed. The volume to contain the pressure is a cylinder with an inside diameter of 18.14 mm (0.714 in.) and a length of 50.8 mm (2.0 in.). The ends of the vessel are rigidly supported, so the only stress borne by the cylinder walls is the stress induced around the periphery that is caused by the pressure within, i.e., the hoop stress. A safety

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factor of three is desired for the cylinder construction.

Nylon 6/6 is chosen for this application because of its high impact and yield strengths when equilibrated to a 50% RH atmosphere. Because of the long-term aspect of this application, the designer should use creep data or data based on slow deformation under load instead of short-term stress-strain data. For this application the long-duration, hoop stress data shown in Fig. 5-1 are applicable (Ref. 2). For thin-walled cylinders the hoop stress is related to the cylinder geometry and the internal pressure by (Ref. 5)

$$t = \frac{pR}{s_2} \quad (5-2)$$

where

- s_2 = design hoop stress, MPa (psi)
- p = internal cylinder pressure, MPa (psi)
- R = inside radius of cylinder, mm (in.)
- t = thickness of cylinder walls, mm (in.).

From the curve in Fig. 5-1 the hoop stress level, 18.63 MPa (2700 psi) at 10 yr, can be used for the hoop stress of the design. From Eq. 5-2 the required thickness with no additional safety factor is

$$t = \frac{(0.690)(9.07)}{(18.63)} = 0.336 \text{ mm}$$

Because the thickness is directly proportional to the internal pressure, the safety factor is incorporated by multiplying the computed thickness by a factor of safety (FS) of three. Hence a cylinder with a minimum wall thickness of 1.01 mm is required to withstand the stated pressure with the required safety factor.

The cylinder is closed at the ends; therefore, a longitudinal stress s_1 of $pR/2t$ develops. If the cylinder were required to stand upright and the ends were flat, the cylinder would be

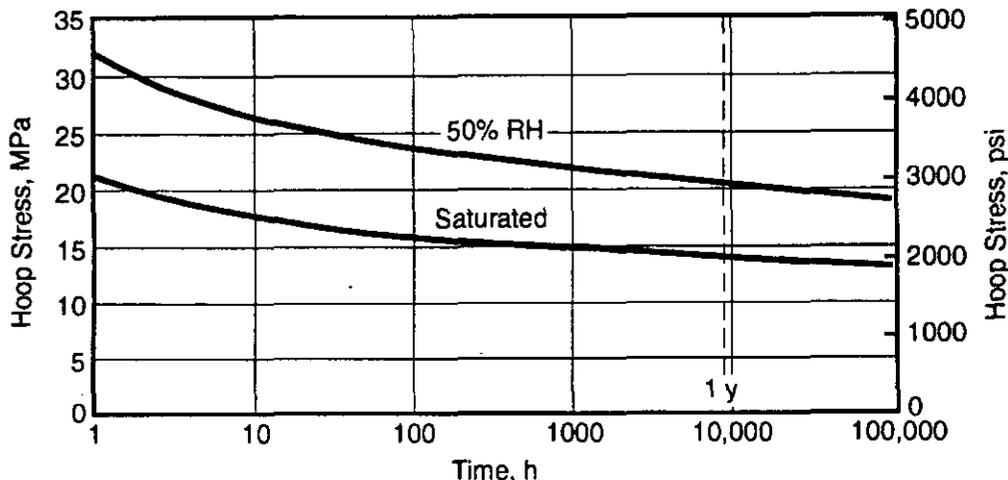
susceptible to buckling. Because s_1 is the same tensile stress developed in a spherical shell, the ends should be a hemisphere with an extension of the cylinder or skirt providing upright stability.

5-5.2 A PRESSURE VESSEL UNDER SHORT-TERM LOADING (Ref. 2)

Wall thickness is a critical design parameter for plastic parts. Reducing the wall thickness lowers the processing cost and reduces the probability of voids, which would weaken the wall, and molded-in stresses, which tend to warp the piece; however, since the strength of the piece is proportional to the thickness, limits exist on how thin the walls may be made without danger of component failure.

Following is an example of a pressure vessel design that illustrates a technique by which to minimize the thickness of the material with no sacrifice of the strength of the vessel. A cylindrical water tank with hemispherical ends is required that can withstand short-term exposure to 2.07 MPa (300 psi) pressures at temperatures from 0 to 50°C (32 to 122°F). The diameter of the tank is 220 mm (8.66 in.), and the length of the cylindrical section is 400 mm (15.75 in.). A safety factor of four is desired.

Because of its higher strength, reduced absorption of moisture, and improved retention of desirable mechanical properties in the presence of moisture, nylon 6/6 reinforced with glass fiber (33% by weight) was chosen for this cylinder. The pressure exposure is short-term, so the tensile strength data for glass-filled nylon saturated with moisture are appropriate for use in the design. From Fig. 3-2 the tensile stress for nylon saturated with moisture is 75 MPa (10,900 psi) or greater over the temperature range of 0 to 50°C (32 to 122°F). Solving Eq. 5-2 by using this tensile stress with the cylinder radius and pressure requirements yields a cylinder wall thickness of 3.04 mm (0.1197 in.) or greater that is required to contain the pressure. To achieve a safety factor of four, a wall thickness of



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Figure 5-1. Hoop Stress vs Time to Failure for Nylon 6/6 (Zytel® 101) at 50% RH and at Saturation at 65°C (150°F) (Ref. 2)

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12.2 mm (0.480 in.) is required.

This design can be modified to produce a design with improved manufacturability and reduced weight by reducing the wall thickness and adding ribs to maintain the same maximum hoop stress. In the original design the hoop, or circumferential, stress is twice the axial stress in the cylindrical portion of the tank (Ref. 5). Therefore, reducing the thickness of the cylindrical wall material by 50% and adding circumferential ribs of sufficient size and number to maintain the circumferential stress would result in equal axial and circumferential stresses. More importantly, it allows the design of a part having thinner walls, which increase the manufacturing rate and reduce problems with internal stresses and distortion that might occur upon cooling of the molded part. In order that circumferential stresses are not reduced, the cross-sectional area of the wall normal to the circumferential stress lines must be the same as that for the full thickness parts. The second constraint is that all ribs and walls should be the same thickness. This implies that the walls should have a thickness of 6.1 mm (0.240 in.)—half of the 12.2 mm (0.480 in.) determined in the original design—and should have ribs 6.1-mm thick and extending 12.2 mm (0.480 in.) above the wall. In addition to reducing the wall thickness, the end thickness can also be reduced because the thicker section is not necessary for mold filling (Ref. 2).

5-5.3 GEAR DESIGN

Nylon gears and metal-hubbed nylon gears have been used for a variety of automotive, appliance, instrumentation, and industrial machinery applications. The advantages of gears made from the resilient nylon material make them preferable over gears made from other materials including the traditional metals. These advantages follow:

1. Nylon gears operate more quietly and with lower friction than metal gears.

2. The resiliency of the nylon used in gears allows fabrication of gears to looser tolerances while it maintains lower backlash and shock resiliency than the more rigid metal gears.

3. The self-lubrication qualities of nylon make possible gears with lower lubrication requirements.

4. Nylon gears are not susceptible to rust or corrosion and thus may be used in corrosive environments.

5. Nylon gears are lightweight and have a lower moment of inertia, so they are useful in applications for which small forces are desired for gear acceleration.

6. Nylon gears are economical to manufacture. Assemblies of multiple gears, cams, and shafts can be molded as a single unit. Thus manufacturing costs are reduced further.

The nylon gears do have limitations. Compared to metal gears, nylon gears have a lower load-carrying ability, lower high temperature limits, and greater thermal expansion. If these limitations do not conflict with the requirements of the application, nylon gears are often the appropriate selection.

Design equations for conventional gearing may be used for the design of nylon gears as long as the appropriate material

properties for the nylon are used.

The reader should refer to source material such as Refs. 2 and 3 for design of nylon gears and use materials handbooks such as Ref. 2 for specific material properties. The designer must choose units and design equations carefully. Metric gearing is not only based upon different units of length measure but also involves its own unique design standard, i.e., metric gears and American-standard-inch diametral-pitch gears are not interchangeable. In the metric system the module m , millimeters of pitch diameter per tooth, is analogous to the diametral pitch P_d and

$$m = \frac{D_m}{N_t}, \text{ mm} \quad (5-3)$$

where

m = metric module, mm

D_m = pitch diameter of gear, mm

N_t = number of teeth in gear, dimensionless,

whereas

$$P_d = \frac{N_t}{D_A}, \text{ in.}^{-1} \quad (5-4)$$

where

P_d = diametral pitch, in.⁻¹

D_A = pitch diameter, in.

Therefore, design equations that are based on either P_d or m cannot be used interchangeably.

5-5.4 BEARING DESIGN

Nylon is an ideal material for lightly loaded bushings because of its low coefficient of friction (See Tables 2-12 and -13.), its resiliency, toughness, and ability to withstand abrasion without material loss (Table 2-11). It is easily molded to close tolerances. Its resiliency reduces the need for the careful alignment required by more rigid bushing materials and allows quieter operation. Nylon bearings are compatible with many fluids and lubricants (many of which are harmful to other plastic materials) and may be operated with or without lubrication.

Because of these characteristics, nylon bearings are commonly used in a variety of applications from small instruments and machines, toys, and appliances to large industrial machines and vehicles. The low coefficient of friction of nylon allows its use as a bearing material without the use of a contaminating lubricant. Its toughness prevents contamination of processed material with the particles of bearing material that sometimes result from wear with more brittle, metallic materials. Therefore, nylon is especially useful where the bearing must be operated within materials that must be kept pure, such as foods or high-purity chemicals.

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5-5.4.1 Limiting Speeds and Loads—PV Factor (Ref. 6)

The life of bearings is affected by the rate at which they dissipate the heat caused by friction between the bearing surface and the supported shaft. The heat generated within a bearing is proportional to the load on the bearing and the velocity of the shaft. A rating for plastic bearings that expresses their suitability in terms of these factors is the maximum PV factor that the bearing can withstand. PV is the product of P and V. P represents the load on the bearing over the projected area by which the bearing supports the shaft and is usually expressed in kPa (psi). V refers to the relative surface velocity between the bearing and shaft surfaces and is expressed in m/min (ft/min). As long as the bearing coefficient of friction does not change, the PV factor for the bearing is a measure of the frictional heating per unit area of the bearing surfaces. If the PV factor for the bearing application exceeds the rating for the bearing, heating of the bearing will usually occur and lead to one or more of the following:

1. Melting of the bearing material
2. Deformation of the bearing (cold flow)
3. Changing friction characteristics
4. Accelerated wear.

As with other heat dissipation rating criteria, the PV factor rating of bearings is limited by the temperature limits of the materials and decreases with increasing ambient temperature. Also the PV factor is dependent on the geometry of the device. The PV limits determined for each of a group of bearings with identical geometries but made from different materials can be used to evaluate the materials. It will be difficult, however, to extrapolate the results of one evaluation to a different bearing geometry.

Ordinary nylon bearings are generally unsuitable for use with heavy loads or at elevated temperature, but the design may be modified or fillers added to the nylon material to improve the performance of the bearing. To enhance the load-bearing capacity while retaining the low-friction characteristic of nylon, bearings can be fabricated with metal bodies and a thin nylon coating. A metal sleeve bearing set in a nylon block takes advantage of the resilient characteristic of nylon to allow small movement for shaft alignment or vibration isolation. The nylon material can be reinforced by adding graphite or molybdenum disulfide fillers to improve the resistance to cold flow and to improve wear characteristics. These and similar improvements allow bearings to be fabricated that can be used at higher temperatures. Conventional nylon bearings can be operated at 77°C (170°F), heat-stabilized compositions can be used to 121°C (250°F), and some filled nylons can be used to 149°C (300°F).

The PV limits determined experimentally depend on many factors including these:

1. Bearing geometry
2. Lubrication
3. Ambient temperature
4. Clearances

5. Materials in both the bearing and shaft
6. Bearing surface condition
7. Moisture.

Absorbed moisture, surface roughness, and elevated ambient temperature tend to increase the temperature of the bearing surface. Reduction of these factors leads to increased bearing reliability.

The effects of these seven factors on a specific application are not easily quantified, so information on bearing design in one application is not easily transferred with precision to a different application. Generous safety factors should be incorporated in bearing design to avoid unwanted failures.

Illustrations of the load-speed limits for plastic bearings and tables on limiting PV values for design purposes are given in Refs. 2 and 3.

5-5.4.2 Design Suggestions

The following suggestions should be incorporated wherever possible to reduce the buildup of heat in the bearing interface and thus prolong the life of the bearing:

1. Minimize the amount of material between the bearing surfaces and the metal body to improve heat conduction away from the bearing interface and to minimize the thermal expansion that would result from heat buildup.
2. Avoid bearings that have plastic sliding on plastic. Using metal for one of the bearing surfaces results in better heat conduction away from the bearing surface and yields a higher PV limit for the bearing.
3. Provide cooling of the bearing, either by air circulation or a good path by which heat transfers away from the bearing.
4. Use lubrication to reduce friction and heat buildup. Make sure the lubricant used is compatible with the nylon material and is stable at the expected operating temperature. Water generally is not a satisfactory lubricant for nylon and results in increased wear if used. Use of lubricant-impregnated, sintered nylon can significantly raise the bearing capability in comparison to unlubricated solid nylon.
5. Avoid having soft metals rub against nylon because a rapid rate of wear may result.
6. Provide means of keeping dirt and grit from the bearing surface. Possibilities include radial grooves to collect dirt before it can reach the bearing surface and seals or felt rings to prevent the entry of dust. Means that keep dirt and grit out may also be effectively used to keep lubricants in.

5-6 QUALITY CONTROL

Quality control is monitoring the quality of manufactured products and applying corrective action as required to correct deficiencies noted in the manufacturing process. The provisions for monitoring product quality depend on the complexity and performance requirements of the product. For example, ornamental products may require only visual inspection to ensure that product specifications have been met. Parts that have specific mechanical, thermal, or chemical require-

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ments, however, should be tested to verify that those requirements are maintained and that no changes have occurred in processing that affect the performance of the product. Because nylon is an engineering material used in applications that require its toughness, resistance to chemicals, and resilience, it is usually important that adequate quality control provisions be incorporated into the manufacture of nylon parts to ensure that these characteristics are preserved.

Use of nylon in engineering applications has led to more stringent specifications for the material and the products in which it is used; therefore, sophisticated and costly laboratory testing has become necessary to verify that the material and/or part characteristics satisfy the specifications. These tests are sometimes expensive, and some test results are not available as rapidly as is desirable to provide feedback for adjustment of process controls. Sophisticated process monitoring instrumentation and control systems have reduced the dependency on end-product testing by timely detection and subsequent correction of process faults that would otherwise result in inferior parts. However, end-product testing is still necessary to detect problems not detected by process monitoring, e.g., problems that arise from raw material quality and moisture content, especially those that occur from mishandling of scrap that is to be reground and remolded. (Ref. 7)

5-6.1 SAMPLING (Ref. 7)

In the context of quality control, sampling refers to the selection of products for inspection or testing and is used where it is either impractical or not cost-effective to evaluate all of the products. The sampling scheme appropriate for a specific manufacturing situation depends on several factors:

1. The costs associated with producing defective parts, which include the cost of replacement of defective parts after they have left the plant and of damage to the manufacturer's reputation by delivery of defective parts
2. The cost of production of parts
3. The number of parallel paths in the process, i.e., num-

ber of molding machines and number of cavities in a mold

4. Short- and long-term experience with the rate of defects

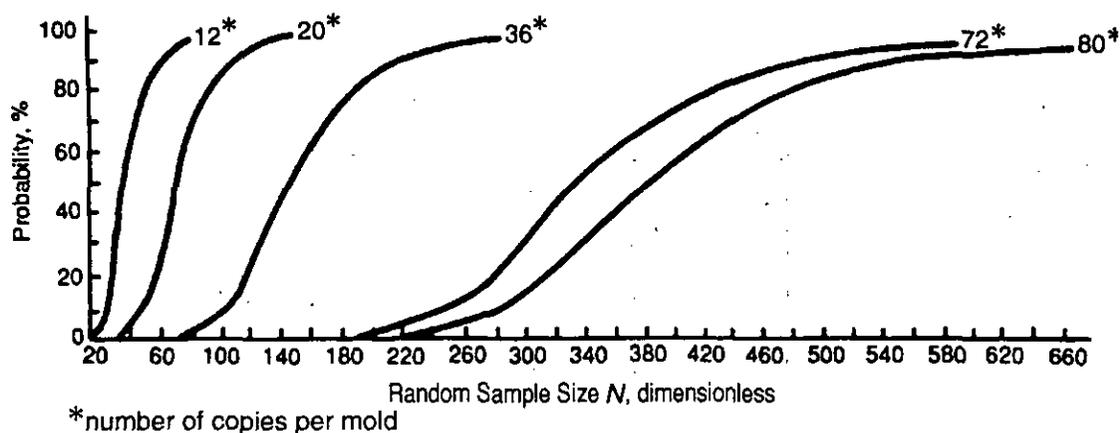
5. The production rate.

A typical sampling plan would be to collect and analyze a part from the manufacturing stream at regular intervals, e.g., every two hours. If manufacturing problems are not being detected in a timely manner, the sampling interval should be shortened. In some cases product specifications include specification of the sampling technique.

Simple sampling schemes can be successful, but statistically based schemes are usually preferred. Much information is available about statistical sampling techniques for quality control (Refs. 8 through 11). In general, an acceptable level of defective production must be determined by the manufacturer or customer. A sampling plan can then be designed to assure that plant production contains no more than the allowable number of defective parts. The sampling plan will include the number of pieces to be inspected or tested and the manner in which they are to be selected. Modifications to the plan (or deviations from it) may be made if the sampling plan is not found to be adequate.

Whether parts are produced in multicavity molds or in multiple machines, the sampling plan must include detection of defects related to a particular cavity in the mold or machine. In multiple cavity machines it is important to identify the cavity responsible for a defective piece, and this usually is done by molding a cavity number into the piece. This practice identifies the area of the mold responsible for defects that can be caused by problems with coolant flow in the mold or gate and vent locations in the cavity. Identification of the cavities responsible for the defects allows corrective action to be taken on the malfunctioning cavity or the blocking off of the cavity.

If labeling parts with cavity numbers is impractical, random sampling must be used with a sample rate that provides a reasonable probability of obtaining samples from all cavities. Fig. 5-2 shows the probability of obtaining a piece from each



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Figure 5-2. Random Sample Size N Versus at Least One Sample From Each Cavity of a Given Multicavity Mold (Ref. 7)

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cavity of molds with 12, 20, 36, 72, and 80 cavities for various sample sizes. Using sample sizes large enough to allow confidence that product from all cavities is sampled will provide assurance that all cavities are functioning if no defective parts are found. If defects are found, however, there will be no information regarding the cavities responsible for the defective parts.

It is important that testing of parts be conducted under specified environmental conditions because the characteristics of the nylon parts can change due to exposure to moisture or aging. For example, dry-as-molded samples are used for toughness tests because dry as molded is the worst-case condition for nylon toughness. Samples should be stored in sealed bags until testing can be performed. Even with this precaution, however, some variability may result depending on whether the samples are drawn at the point of manufacture or after delivery to the customer.

5-6.2 VISUAL INSPECTION (Ref. 7)

Visual inspection is often effective and sufficient to assess the quality of molded nylon parts. Aids for visual inspection include magnifiers, controlled lighting (including selection of color), and a bright light with an adjustable iris to examine thick sections. Samples of acceptable and nonacceptable parts are helpful for comparison with the parts being inspected.

Visual inspection is used primarily to detect incomplete filling of molds and surface defects including splay, burn marks, weld lines, and flash.

Splay usually consists of small "V"-shaped surface imperfections but may present a frothy appearance in severe cases. It is caused by excessive moisture during molding, which can also lead to lower molecular weight and decreased toughness. Parts that display this symptom should be tested for toughness.

Burn marks result from oxidation of the nylon material by air trapped in the mold cavity. The burn indicates not only a surface problem but also a structural problem since the existence of an air pocket indicates an incompletely filled mold. If burn marks are noted, cavity venting and/or the injection rate should be examined.

Weld lines are produced when an injection stream separates into two or more streams because of some partition in the flow stream and then does not completely recombine, or "weld" back, into a homogeneous mass. These lines are produced by too long an injection time or insufficient melt temperature.

Excess flash is produced by unsatisfactory mating of the mold halves or insufficient clamping pressure. Flash can be detrimental to the mold if allowed to accumulate on the face of the mold, and it can contribute to out-of-tolerance part dimensions and lowered impact resistance.

Other surface defects detectable by simple inspection are color contamination (detected by comparison with standards), sink marks, or unwanted indentations by ejector pins.

5-6.3 PART WEIGHT AND VOIDS (Ref. 7)

Measuring part weight is a means of detecting a dimensional change or void in the product introduced by a change in processing conditions. Monitoring part weight and plotting it on a control chart allow detection of a change in processing conditions that might otherwise go unnoticed. The allowable range of part weights is based on the accumulated history, i.e., the weights of parts and the variations therein, of parts that met all product specifications.

VOIDS in molded objects usually occur in thicker sections of the part and are often caused by gate freeze-off, which prevents maintenance of pressure on the melt during solidification of the material in the mold.

VOIDS in parts are easily detected because the parts weigh less than expected. A quick go/no-go test based on weight is the buoyancy test. Completed parts are placed in a solution that has a specific gravity which allows the part to sink slowly. Any voids in a part result in a reduced average density of that part and cause it to float. The fluid should be maintained at a nearly constant temperature and checked periodically to detect any change in composition that would produce a change in specific gravity.

For unpigmented parts voids can sometimes be detected by illuminating the rear side of the part with a small, bright light and observing the part from the front. Voids show up as visible bubbles in the material. Alternative techniques for void detection are X-ray, fluoroscopic, and ultrasonic examinations. Industrial X-ray machines are preferred over medical machines because their finer resolution allows detection of smaller voids. These instruments are useful for detecting voids in slabs or rod stock prior to machining operations. Ultrasonic tests are useful for detecting voids in parts with simple, regular geometry, such as extruded rods. Ultrasonic examination of more complex shapes generally requires the use of special purpose ultrasonic transducers, which is generally not economical.

5-7 ASSEMBLY TECHNIQUES

5-7.1 PERMANENT AND TEMPORARY ASSEMBLY

Assembly of several components manufactured or purchased separately may be required for several reasons:

1. To mold the complete product it would be impossible or more expensive to assemble several components fabricated separately
2. To incorporate standard components available from outside sources into the design
3. To allow disassembly for repair, maintenance, or reconfiguration
4. To fabricate composite assemblies that use multiple materials to satisfy the requirements of the application.

Early in the design process attention must be given to the provisions for assembly so that expensive redesign is not nec-

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essary. The designer must be familiar with the techniques used to assemble nylon components to other nylon components or to components of other materials and with the advantages and limitations of these techniques. Incorporating this knowledge into the initial design of the component may avoid redesign later, which can be very expensive if it is necessary after completion of prototyping, testing, and tooling. (Refs. 12 and 13)

For the discussion in this handbook, assembly methods are those methods used to fasten multiple components together and are divided into two categories:

1. *Permanent Assembly.* The separation of components with no provision for separation without damage to the components. These techniques include the welding and fusing methods by which the material along the interface between the components to be joined is melted and solidified, i.e., the two components are fused into one. It is necessary to cut or break the material to separate components joined in this manner.

2. *Temporary Assembly.* The attachment of components so they may be separated and reattached several times with negligible reduction in the effectiveness of the attachment.

The requirements of the application determine whether permanent or temporary assembly techniques should be used. Selection of the appropriate technique from within the selected category is determined by other considerations, including the fastening strength required, part geometry, economics, appearance, and production (Ref. 14).

5-7.2 PERMANENT ATTACHMENT TECHNIQUES

5-7.2.1 Heading (Ref. 2)

Heading is the deforming of a rivet, pin, stud, or similar part that protrudes through an opening in a mating part to fasten the two parts together. Heading is a low-cost assembly method that requires simple equipment for manual or automated assembly. The deformation may be accomplished by mechanical or thermal deformation of the pin or a combination of the two. Ultrasonic heading is sometimes used and is discussed in subpar. 5-7.2.3.

Heading is typically accomplished by applying a large force to the pin protruding through a hole in the mating piece(s) while the back side of the pin is supported. The protruding portion of the pin spreads because of the plastic flow caused by the load. An example of equipment used for heading is a simple arbor press with a vise to hold the pieces or a punch with multiple pins for staking several pins at one time. A spring-loaded sleeve surrounding the staking punch is used to press the pieces to be fastened together. After pressure is applied by this sleeve, the heading portion of the press is brought to bear on the end of the pin to load it until it permanently spreads into a head and clamps the pieces together in the same manner as a rivet.

For successful heading the applied force must be sufficient to introduce stress levels in the pin that exceed the compressive yield stress for the material. For nylon at 23°C (73°F) with a moisture content of 2.5%, this stress is 83 MPa (12,000 psi). Increasing the temperature to 95°C (200°F) reduces the required stress by 50%. Note that the applied force must increase as the head forms to maintain these stress levels because the cross-sectional area increases. Rate of application of force is not critical, although sharp impact loadings should be avoided. Typical application rates around 5000 mm/min (200 in./min) at room temperature have been successfully used to head parts (Ref. 2).

The tendency of nylon to recover its original shape after deformation tends to loosen headed connections. This effect is enhanced by exposure to elevated temperatures. For example, a stud headed at room temperature and then exposed to 95°C (200°F) for two hours will recover 15% of the length of the headed portion. This effect can be minimized by heading the nylon piece at a temperature equal to or above the temperature to which the part will be exposed during use. If the heading operation is conducted at a temperature above the ambient temperature for the device during use, negligible recovery will occur.

5-7.2.2 Spin Welding (Refs. 2, 7, and 15)

Spin welding is performed by rotating the surface of one plastic component against another until a film of molten nylon created by the frictional heating develops along the interface of the components. The relative motion is stopped and the pieces held together under pressure until the material solidifies; thus the pieces are welded together. This technique is appropriate to produce strong, leak-free welds on pieces with an interface that is circularly symmetric (so that one piece can be placed against the other and rotated until the melting action occurs). Parts may be welded in one to two seconds; therefore, production rates of up to 60 welds per minute are possible when automated equipment is used.

The components of spin welding equipment include the following:

1. A driving tool capable of gripping one of the parts to be joined
2. A chuck to hold the other part stationary
3. A means of rotating the driving tool
4. A means of applying a controlled compressive force to the joint.

Although spin welding is most conveniently performed on equipment designed exclusively for the purpose, it can be performed on equipment as basic as a drill press equipped with a driving tool and chuck. The compressive force would be controlled manually by the operator. For larger applications a machine lathe could be used. For high-volume applications an air cylinder is used to apply the compressive force under the control of a timer. Rotation of the part is performed under control of a motor sometimes equipped with a brake to bring the rotating part quickly to a halt.

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There are four manufacturing parameters that affect the quality of the welds produced by spin welding:

1. *Joint Speed.* The joint speed together with the joint pressure determine the rate at which energy is delivered to the nylon joint. Therefore, it controls the rate of heating and is directly related to the rate at which one piece is rotated relative to the other. A relative speed between the nylon surfaces of 6 m/s (20 ft/s) is typical for most nylon applications but may fall anywhere in the range 3 to 12 m/s (10 to 40 ft/s). Maintaining these relative speeds for small parts would involve excessive rotation rates. For those applications lower revolution rates may be used with longer spin times (Ref. 2).

2. *Joint Pressure.* The joint pressure determines the amount of friction between the pieces being joined during rotation and the rate at which molten nylon (and contaminants) is flushed from the interface area. For nylon parts a pressure of 4.8 MPa (700 psi) is typical. The actual value depends on the joint design.

3. *Spin Time.* Spin time determines the amount of energy accumulated in the joint, which determines the amount of material that is melted. Excessive spin time causes melted nylon to be squeezed out of the joint and form flash or nylon crumbs. Spin times for nylon parts generally range from 0.25 to 0.5 s. Rotation of the pieces must be stopped immediately at the end of the selected period to prevent tearing of the weld.

4. *Hold Time.* Hold time is the cooling period during which the pieces are held stationary relative to each other and the molten nylon in the interface is allowed to solidify. Insufficient hold time weakens the joint or produces a joint that leaks. Hold times of one second are typical but depend on the design of the pieces being welded.

During normal spin welding processes, some nylon material is squeezed from the joint. This excess material should be removed mechanically to enhance product appearance and to reduce the possibility of damage to critical mechanical assemblies by flash that separates from the welded product during use.

Joint design is important for positive alignment of the surfaces to be welded and consistent manufacturability. The design of the joint is based on the following considerations:

1. The joint should include grooves or a conical section to keep the two pieces being welded in alignment. Simple butt joints should be avoided; they do not produce strong welds.

2. At least one of the parts should be tubular so that it can conform to any out-of-roundness of the mating part.

3. The contact area between the parts should be maximized, and the amount of material should be minimized.

4. If visible flash is objectionable for visual appeal, traps should be designed within the seam to accept the flash and keep it hidden from the exterior of the product.

5-7.2.3 Ultrasonic Welding (Ref. 4)

Ultrasonic welding uses ultrasonic (20 kHz) vibrations to melt the material along the interface between the pieces to be joined. Pressure is applied to hold the pieces together during

the exposure period and afterward until the nylon resolidifies. The ultrasonic technique is very fast (usually requires less than two seconds), produces joints almost as strong as the intrinsic material, and is amenable to automation. Part design, process control, and moisture content of the nylon material are critical if ultrasonic welding is used.

Ultrasonic welding uses a high-power, high-frequency electrical power source, a transducer (which converts the electrical energy to mechanical energy), and a horn to direct and focus the energy on the part to be welded while pressure is applied to press the part together. Other important ancillary equipment includes the timing and control equipment and fixtures to locate and hold the parts under the horn.

The horn is an acoustically tuned assembly, optimized for the frequency of the welder (typically 20 kHz), made from high-strength alloys such as titanium or aluminum. The horn is shaped to contact the part as close to the interface to be welded as possible. The part should be designed to provide a convenient point of contact with the horn as well as direct transmission of the energy to the interface to be welded with the minimum amount of material in the path of the energy. A slightly raised portion of the surface over the area to be welded is desirable to improve contact with the horn (Ref. 16).

Ultrasonic welders are categorized by the distance through the material the acoustic energy must travel before reaching the interface to be welded. In "near-field" welding the energy must travel 6 mm (0.25 in.) or less, whereas "far-field" welding involves transmission through a greater thickness. For effective far-field welding the material must transmit the energy with minimal absorption, which limits this procedure to more rigid materials. Nylon is an excellent material to use with near-field welding and is rated "fair" for far-field welding. This rating indicates that special apparatus, such as slotted horns or multiple horns, may be necessary for effective welding of thicker material. (Refs. 4, 15, and 17)

Because of its high crystallinity and high melting point, nylon requires high-energy input to the interface that is to be welded in order to produce strong welds. Using proper joint design to ensure efficient use of energy reduces this requirement. High-energy transfer is accomplished by using a high-power horn, multiple horns, or a booster, a matching device which increases the amplitude of the ultrasonic vibrations. The use of boosters is generally required, except for small pieces, and generally reduces the time required to effect the weld.

Along with the ultrasonic vibration, pressure is needed to clamp the two parts together as the molten film forms between them. Excessive pressure will dampen the vibration and prevent transfer of the energy to the interface to be welded. Appropriate loading pressures must be determined experimentally for each application.

The moisture content of nylon at the time it is welded has a significant effect on the quality of the weld. Excess moisture in the nylon is released in the areas heated by the ultra-

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sonic energy and causes defects in the welds. A dry part exposed to 50% relative humidity at room temperature for 24 h will have welds that are only half as strong as welds made on parts that are dry as molded. Parts to be welded should be dry as molded or should be dried prior to welding (Ref. 17).

Joint design is critical to achieving good ultrasonic welds. The joints should be designed so the initial contact is over a relatively small area to ensure that the energy is concentrated and that that area is heated. As the material at the point of contact melts, the area of contact grows, but the heated material does not cool quickly because of the insulating qualities of the bulk nylon material. Additional energy keeps the melted material molten and melts more material to keep the parts separated by a thin layer of melted nylon.

There are two types of joints that can be easily ultrasonically welded, the butt joint and the shear joint. The butt joint consists of two flat, parallel surfaces with a ridge on one surface to minimize the actual contact surface area. The shear joint is an interfering, telescoping joint with a small annular recess to allow one part to fit loosely inside the other to a very limited depth.

The shear joint is preferred because it welds quickly, requires the lowest welding time and energy, and forms a strong, leak-free joint. When welded, the material where the two telescoping pieces overlap melts initially. As the two pieces are forced together with externally applied pressure, the heat in the joint is retained, and the molten material is isolated from the air by the bulk material to prevent cooling of the material and oxidation. As the parts slide together, the shearing action along the interface aids the bonding of the materials and creates a void- and leak-free weld.

The strength of the weld can be controlled by the length of time the ultrasonic energy is applied, which determines the depth of telescoping. Making joints with a telescoping depth of 1.25 to 1.5 times the wall thickness produces a weld with strength equal to or greater than the surrounding material.

Ultrasonics may be used to join nylons in other ways. Three such techniques are described in the following paragraphs:

1. *Ultrasonic Heading.* Ultrasonics may be used to heat and deform studs or rivets to fasten pieces together by heading. (Heading is discussed in subpar. 5-7.2.1.) A specially contoured horn is used to melt the top of a protruding stud and contour it to the desired shape of the rivet head. Since the head is formed by heat, there is no elastic recovery, which tends to loosen mechanically headed joints when they are exposed to elevated temperatures.

2. *Ultrasonic Stud Welding.* Nylon parts can be fastened by inserting headed pins or studs through a hole in one piece into a hole in a second piece. Making the second hole an interference fit and inserting the pin with ultrasonic energy applied allow the pin to be welded to the back piece with a shear-type weld. If the shear depth is equal to the radius of the pin, the strength of the weld will be equal to the tensile strength of the pin or stud. Several studs can be welded at one time with either one horn or a cluster of horns.

3. *Ultrasonic Inserting.* Metal inserts, similar to those pressed in or molded in, can be inserted ultrasonically. The insert is implanted into the nylon piece with pressure and ultrasonic vibration. The nylon surrounding the insert is melted by the ultrasonic vibration so the insert can be pressed in to the desired depth and the nylon can fill recesses in the exterior of the insert. The ultrasonic vibration is removed; the nylon solidifies and captures the part in place. Compared to molded-in or pressed-in inserts, ultrasonic inserts are easier and faster to manufacture, and the process is better suited to automation. Preheating or hand loading of inserts is eliminated and cycle times are shortened. The tolerances of molded holes for inserts are reduced with no decrease in the holding performance of the insert. Certain design considerations, however, do apply to this technique. If the insert will be subject to torsional loads, it should have flats, axial ribs, or knurled ribs to prevent rotation of the insert in the nylon. Also the interface between the insert and the bulk nylon material does not form a hermetic seal. If it is necessary to provide a hermetic seal around the exterior of the insert, an O-ring should be used under a flange on the insert.

5-7.2.4 Vibration Welding (Ref. 2)

Vibration welding, similar to ultrasonic welding, relies on the frictional heating of material produced by pressure and relative motion between the pieces along the interface. Ultrasonic welding relies on high-frequency vibration, e.g., 20 kHz, whereas vibration welding uses low frequencies, typically 90 to 300 Hz. Because the lower frequencies allow simultaneous vibration of larger areas, vibration welding of larger parts is technically or economically more feasible than other methods. Also energy directors are not required in the part design when vibration welding is to be used. (An energy director is a ridge or other structure designed to minimize the area of initial contact between the parts to be welded, so the ultrasonic energy used for heating is concentrated in a smaller area.) (Ref. 18)

In vibration welding one part is moved relative to another in an oscillatory manner; this relative motion is in the plane of the interface between the two parts. The parts to be welded are pressed together and vibrated for a short period (2 to 3 s); then the vibration is halted with the parts in alignment. The parts are held together until the molten nylon solidifies to weld the two parts together. Generally, the motion is linear and reciprocating. However, if one of the parts has a protrusion that fits into the other part or if a shaft passes through both parts, an angular motion may be used. The angular rotation would be about the center of the shaft or protrusion. The linear mode is preferred because several pieces may be welded simultaneously in the same machine and the heating is more evenly distributed since the relative motion is constant over the whole surface to be welded (Ref. 19).

Vibration welding can be used to weld larger nylon parts than can be accommodated by other welding techniques. Parts as large as 0.56 × 0.30 m (22 × 12 in.) with an interface area

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up to 6500 mm² (10 in.²) can be welded with standard equipment. Larger pieces can be welded by interconnection of multiple welding machines.

Vibration welding produces strong, pressure-tight welds. When tested to failure, pressure vessels, molded in two halves and welded together, have failed at points other than at the seam line. This mode of failure indicates that a properly formed weld can be as strong as the material.

Vibration welding allows the joining of complex, irregularly shaped parts as long as the parts can be properly supported to provide even pressure and relative motion at all points along the joining interface. Welding is not confined to a circular joint as it is with spin welding and is not limited to the periphery of the object. Hollow parts having dividers or internal supports can be welded around the periphery and at supports as long as the pressure and motion can be imparted to all surfaces to be welded, including those internal to the structure.

Surfaces to be welded using vibration welding should be flat to allow one part to be moved relative to the other. It is more convenient if all surfaces to be joined lie in a single plane; however, combinations of parts having interfaces on more than one plane can also be joined. Joint plane variation should be minimized for reliable welding.

The operating parameters associated with vibration welding follow (Ref. 20):

1. **Amplitude.** Amplitude is the range of relative motion between the two parts being welded and is expressed as a peak-to-peak linear distance. For vibration welding the amplitude is generally 3 to 4 mm (0.12 to 0.16 in.). It is controlled by adjusting the mechanical linkage between the power unit and the fixtures holding the parts rather than by reducing power to the mechanical transducer so that maximum power is always applied to the parts.

2. **Joint Pressure.** Sufficient pressure should be placed on the part to generate an even pressure of 1.38 to 1.72 MPa (200 to 250 psi) at the interface between the parts. The optimum pressure depends on the characteristics of the material and part geometry.

3. **Weld Time.** Weld time is the length of time the vibration and pressure are applied. Typically, weld time is a few seconds.

4. **Hold Time.** Hold time is the length of time pressure is maintained on the parts after vibration is stopped. It must be sufficiently long for the melted nylon to solidify. Because solidification occurs quickly, hold times of 0.5 to 1 s are usually sufficient.

Vibration welding is suited to larger parts and hollow parts with internal dividers. Thus it is possible to combine multiple parts into one assembly produced from two nylon parts joined by vibration welding. For example, in automotive applications containers for several fluids, e.g., brake fluid and windshield washer fluid, could be molded into other nylon panels or shrouds by molding one piece with separate compartments produced by dividers and then welding to it a second piece to

produce the sealed containers with removable lids. The resulting assembly would reduce labor installation costs.

The capability to weld two pieces together inexpensively offers an attractive alternative to the trend toward molding more complex devices in order to reduce the number of different pieces to be molded. Molding complex pieces, which challenges the capabilities of molding technology, in two parts and welding them will allow production of complicated pieces with numerous cavities, threaded openings, and other features from two comparatively simple molding operations and a welding operation. Also production of large pieces from multiple smaller ones would allow the use of small injection molding machines to produce the individual parts that are combined into the larger one.

5-7.2.5 Hot-Plate Welding (Refs. 2 and 4)

In the hot-plate welding procedure, the interface surfaces of the two objects to be joined are heated by contact with a heated surface until the plastic on the surface is melted; the pieces are removed from the surface and quickly pressed together. The heater used for this procedure is a temperature-controlled, heated aluminum plate, which maintains a uniform temperature over its entire surface. A thin fluorocarbon coating may be used to reduce the tendency of the melted nylon to stick to the aluminum surface.

The hot-plate welding method has limited applicability to nylon. Because the melted nylon is exposed briefly to the atmosphere, oxidation of the nylon material, which results in brittle, low-strength joints, may occur. Also the technique is slow and requires more manual attention than other techniques. These disadvantages limit its applicability to prototype and low-production assembly.

5-7.2.6 Cementing (Ref. 2)

Cementing is fastening pieces of an assembly together by means of adhesives. It may be used to fasten nylon to itself or to other materials. Since the process is not easily automated, it is suited to joining large pieces or complex shapes that do not have a flat interface and therefore are not compatible with the other welding techniques described in par. 5-7.

The following cements are suitable to bond nylon:

1. Aqueous phenol cement
2. Resorcinol ethanol solvent cement
3. Nylon-bodied calcium-chloride-ethanol solvent cement.

The following paragraphs provide guidance on the use of each of these cements. There are several guidelines on joint design, however, that apply to all three cements:

1. Joints that rely on the shear strength of the bonded surfaces are preferable to those for which the major stress is normal to those surfaces. For this reason lap and tongue-and-groove joints are preferred over butt joints.

2. Joints should have the maximum surface area practical because joint strength is proportional to the surface area.

3. If the part will be flexed in the vicinity of the joint,

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the plane of the joint should be perpendicular to the line of the applied force. For example, if a horizontal beam is loaded by a weight bearing on the center, the cemented joints should be horizontal lap or "finger" joints.

4. A fixture should be used to support and restrain the parts being cemented immediately after placing the cemented surfaces together. The part should remain in the fixture until the joint has developed sufficient strength to be self-supporting.

5-7.2.6.1 Aqueous Phenol Cement

The most commonly used cement for nylon is anhydrous aqueous phenol cement containing 10 to 15% water. This adhesive is available in a ready-to-use form and produces strong, water-resistant, and flexible bonds.

The following are general directions for the use of this cement:

1. Clean and dry all surfaces to be bonded.
2. Check the fit between the surfaces to be bonded. If they fit together well, apply the cement and assemble the parts immediately. If the surfaces to be bonded have small gaps or cracks when dry fitted, the cement should be applied and allowed to soften the surfaces for two or three minutes before assembly is attempted. It is important that the surfaces are wet with the cement when they are assembled. If the surfaces separate after assembly, more aqueous phenol can be applied, even if the surface is still tacky from the original application.
3. Clamp the assembled parts together so that a pressure of about 69 kPa (10 psi) is applied to the surfaces being bonded. Higher pressures are unnecessary and do not increase joint strength.
4. Immerse the assembled unit in boiling water with clamps in place. The length of time the unit should remain in the water depends on the size of the part, in particular, on the thickness of nylon through which the heat must pass to warm the joint. For parts with 3.2-mm (0.125-in.) wide glued surfaces, a 5-min curing time is sufficient. Longer times are necessary for thicker sections.

Air curing at room temperature is an alternative to boiling the piece in water; however, several days are required for the joint to achieve its full strength. This delay may be satisfactory for joints that are "self-clamping", i.e., held together by snaps or a tongue-and-groove joint. Air drying can be accelerated by using a circulating air oven heated to 66°C (150°F) for 30 min.

5-7.2.6.2 Resorcinol Ethanol Solvent Cement

The resorcinol ethanol solvent is an easy-to-use cement suitable for use with nylon. The cement is made by combining equal parts by weight of resorcinol and ethanol and stirring or shaking for 15 to 20 min. Since the prepared mixture is a solution of resorcinol in ethanol, proportions need not be exact.

Directions for the use of this cement follow:

1. Clean and dry all surfaces to be bonded.

2. Paint the cement solution on the surfaces to be bonded. The solution has a low viscosity, so it should be painted on two or three times with an ordinary paintbrush to ensure adequate coverage.

3. Allow the cement-coated surfaces to soften for 30 s. Allowing longer periods, up to 3 min, will produce even stronger joints.

4. Assemble the parts and clamp with light pressure for 10 to 15 min. The joint may then be handled, but 90 min should elapse before any load is placed on the joint. Full strength is not achieved for 24 h. The curing time may be accelerated by placing the cemented piece in a convection oven at 66°C (150°F) for 30 min.

5-7.2.6.3 Nylon-Bodied Calcium-Chloride-Ethanol Solvent Cement

The nylon-bodied calcium-chloride-ethanol solution is used to cement nylon pieces intended for service with food and drinking water. This cement is nontoxic, noncorrosive, and has no disagreeable odor. The cement is made from the following:

1. 10 parts of ground nylon 6/6
2. 22.5 parts calcium chloride
3. 67.5 parts ethanol.

The calcium chloride and ethanol are mixed and shaken until the calcium chloride is dissolved (approximately two hours). The solution is filtered and the nylon is added. This solution is stirred overnight to produce a clear, viscous cement that may be stored indefinitely. Directions for the use of the cement follow:

1. Clean all surfaces to be joined, and paint the cement on with a brush or cotton applicator.
2. Allow 30 s after coating and before assembly for the surfaces to soften.
3. Assemble the parts and hold under pressure. The parts may be handled after 30 min, and full joint strength is achieved in 24 h.

5-7.3 TEMPORARY ATTACHMENT TECHNIQUES

5-7.3.1 Machine Screws

Machine screws can be used with molded-in threads or inserts in nylon parts to assist fastening one part to another. Use of these threaded fasteners allows easy assembly by hand with ordinary tools and thus allows disassembly and assembly to be performed in the factory or by the consumer in the home or office.

Incorporation of molded-in threads, however, complicates the mold design. Threaded rods must be incorporated in the mold with an unscrewing mechanism to remove them from the part before it is ejected from the mold. The resulting threaded hole may be used repeatedly with metal or plastic screws.

If additional strength or wear resistance of the threaded

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hole is necessary, metal inserts with internal threads may be molded into, pressed into, or threaded into the part (depending on the design of the insert). These inserts provide a metal, female-threaded surface to hold the machine screw. The metal-on-metal contact provides greater strength and wear resistance than if one part were plastic which is useful where greater attachment force or large numbers of assembly and disassembly cycles are necessary.

5-7.3.2 Self-Threading Screws

Self-threading screws cut or form the internal threads as they are inserted. Use of self-threading screws eliminates the need to form the internal threads on molded parts and thus reduces molding costs and increases the production rate from the molding machine. Self-threading screws can be removed and reinserted.

These screws produce threads, either by a cutting action similar to that of a tap used to cut threads in a round hole or by a forming action during which the material is displaced by the wedging action of the tapered screw as it is driven into the hole. The amount of effort necessary to insert self-threading fasteners is higher than that necessary to insert a threaded fastener into a threaded hole.

This type of attachment is not recommended if a large number of assembly and disassembly cycles are needed.

5-7.3.3 Press-Fit Joining

Press fitting is the forcing of a protrusion of one part into an opening in another so there is an interference fit. The parts are held together by the friction forces on the mating surfaces of the two parts. The friction forces are quite large because the material is under compression caused by the interference fit. Significant force is required to join the pieces. Because there is no fusion of the material, however, the pieces can be separated with a similar amount of force. There is, therefore, some disassembly and reassembly capability.

Press fitting is usually used to join nylon parts to parts made of other materials. It represents an economical attachment method that provides a strong joint. Because of the resiliency of nylon, the parts to be joined should be designed with more interference than would be used for interference fits on metallic pieces. Care should be taken to ensure that the amount of interference is maintained both under conditions near the time of manufacture when the part is dry as molded and after the part has absorbed moisture or expanded due to elevated temperature during operation.

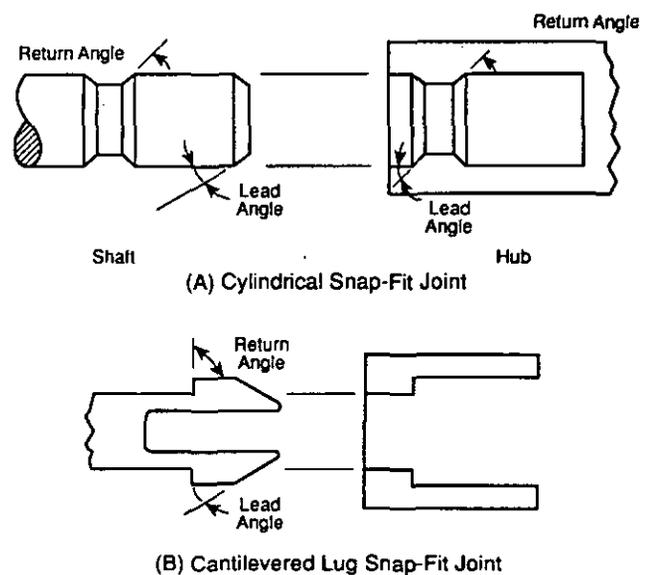
Since the press-fit joint is in continual compression, the tendency of the nylon material to "creep" under stress leads to a reduction in the effective interference at the press-fit joint and a reduction in the joint strength in smooth surface press-fit connections. If the surface of the metallic component that is mated with the nylon part is roughened or knurled, however, the creep tendency of nylon causes it to conform to the roughened or knurled surface and thus increases the holding power of the joint.

5-7.3.4 Snap-Fit Joining (Refs. 2 and 4)

Snap-fit assembly is similar to press fitting except that positive detents are molded into the mating surfaces so the parts do not have to remain in compression and the tendency to creep is reduced. Usually the detent consists of an undercut machined or molded into one surface and a protrusion on the other surface that mates with the undercut when the parts are joined. The parts should be designed so that the material can deform elastically as they are mated and can snap into place when the protrusion on one piece meets the undercut on the mating piece. Snap-fit protrusions are often molded on the outer surfaces of split pins, where each half of the pin becomes a cantilevered hook that engages a recess in the sides of a hole in a mating piece. The protrusions can also be molded onto solid pins, where the resiliency of the material provides the elastic deformation necessary during mating and/or unmating.

The snap-fit connection is strong but is not usually capable of making a totally sealed connection between the mating pieces. If sealing is necessary, O-rings or other sealing mechanisms must be incorporated in the design.

Snap-fitted pieces will survive many assembly and disassembly cycles if the edges of the protrusion and undercut are beveled. However, if the edges of the return angle are at right angles to the mating surface, the connection may be permanent, i.e., destruction would be required of at least one of the pieces to separate them. Note that if the edges that make contact during insertion are beveled and the trailing edges have a larger return angle, the parts may be mated easily yet be difficult to remove. Examples illustrating some typical joints are shown in Fig. 5-3. Protrusions with extreme undercuts, which are used for permanent assembly, may be difficult to eject



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Figure 5-3. Snap-Fit Joint Terminology (Ref. 2)

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from the mold. Therefore, special ejection provisions in the mold design may be necessary to allow ejection of these parts.

Unlike press-fitted parts, the snap-fitted molded pieces are not under compression once joined and therefore are not subject to creep deformation. The holding power of the joint does not diminish with time. Many of the considerations for the design of press-fitted nylon pieces apply to snap-fitted pieces as well. The dimensions of the features used for snap-fit mating must be designed so that pieces may be inserted and withdrawn and still hold over the entire range of part dimensions that will be encountered with changing temperature and moisture levels.

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CHAPTER 6

EFFECTS OF ENVIRONMENT

Information is given on natural environmental factors, the heat resistance of nylon, the effects of hot water and steam, outdoor weathering (test methods and the effects of exposure at various climatic locations), permeability to chemicals and reagents, compatibility with propellants and explosives, fungal and bacterial resistance, and changes due to irradiation.

6-1 EFFECTS OF NATURAL ENVIRONMENTAL FACTORS

Although nylon exhibits many desirable characteristics when compared to other engineering materials, it is more susceptible to environmental degradation under certain conditions than other engineering materials, especially metals. To ensure effective use of nylon materials, the designer must understand the environmental effects and provide for them in the design. To predict the effects of the environment on nylon in a new application, three things are required:

1. A knowledge of the material that includes its composition and crystallization and the presence of fillers and modifiers, etc.
2. A knowledge of the anticipated environment that includes its temperature and humidity levels and the presence of other chemicals, applied stresses, etc.
3. The response of the specific nylon to the environmental factors in the application.

A complete knowledge of the behavior of the nylon is useful for determining the effect of the environment on the nylon part and for designing the part or selecting the material composition to produce a part more immune to degradation from environmental factors. A more reliable source of information is the history of the performance of nylon in the same or similar applications. For example, experience with nylon in automotive applications can be used to select compositions that are tolerant of exposure to gasoline, diesel fuel, lubricants, antifreeze, hydraulic fluids, and salts. This experience has been documented and thus represents a resource available to confirm material selection (Ref. 1).

Nylon parts for military systems such as obturators have demonstrated the capability to function in the harsh military environment over a wide temperature range, -54 to 49°C (-65 to 120°F), with high-stress loading and in the presence of propellants, explosives, and certain chemical warfare agents such as blistering and nerve agents, e.g. distilled mustard (HD) and soman (GD), and decontaminating solutions DS2 and supertropical bleach (STB). However, certain nitro groups (such as nitroglycerin, trinitrotoluene, etc.) in the energetic formula, especially the double- and triple-base propellants, caused long-term storage degradation of most nylon compositions.

The remainder of this chapter contains information intended to provide a better understanding of environmental effects on various nylon compositions, especially the effects of elevated temperatures, water, outdoor environments, and chemicals.

6-2 RESISTANCE OF NYLONS TO HIGH TEMPERATURES

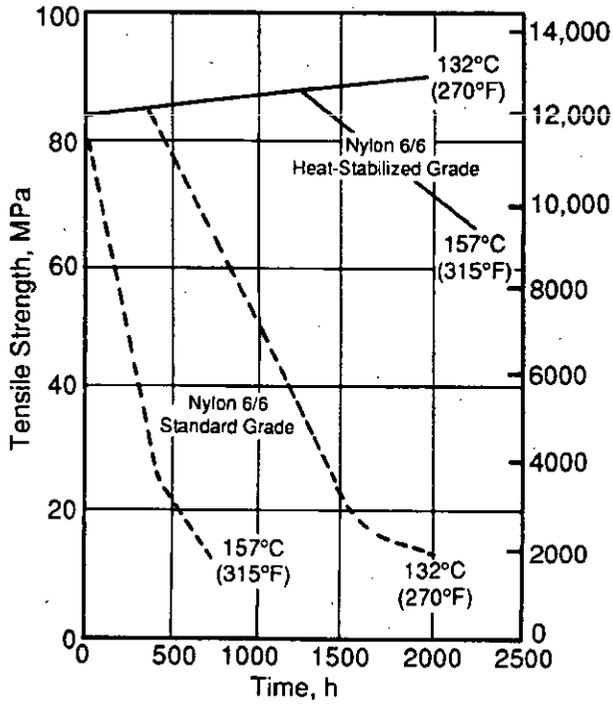
Upon exposure to high temperatures, typical nylon materials oxidize. Such oxidation produces a reduction in tensile strength, impact strength, and flexibility, and the effect accelerates as temperature increases. This relationship is the basis of accelerated life tests, i.e., samples are exposed for a relatively brief time to temperatures higher than those expected in service in order to determine indirectly the expected degradation of properties over long periods at normal temperatures. The ability to predict the degradation of properties on the basis of accelerated life tests is dependent on the validity of an assumed relationship between the temperature of the accelerated life test over the normal extremes for the application and the increased rate of material degradation. This technique is used extensively for material testing and provides useful results that are consistent with the results obtained in normal service testing. It is preferable, however, to verify the tolerance of nylon (or any other material) at the actual temperature extremes likely to be encountered in the application because testing at expected temperatures provides a more reliable measure of service life and temperature effects.

The primary properties of nylon evaluated for temperature effects are tensile strength and impact strength because these determine the load-bearing strength and the ability to withstand mechanical shocks without failure. The ability of a material to retain these properties is essential in many applications, but if degradation is expected from prolonged exposure, additional safety margins must be included in the design to avoid failure of the product.

6-2.1 ALIPHATIC NYLON TYPES

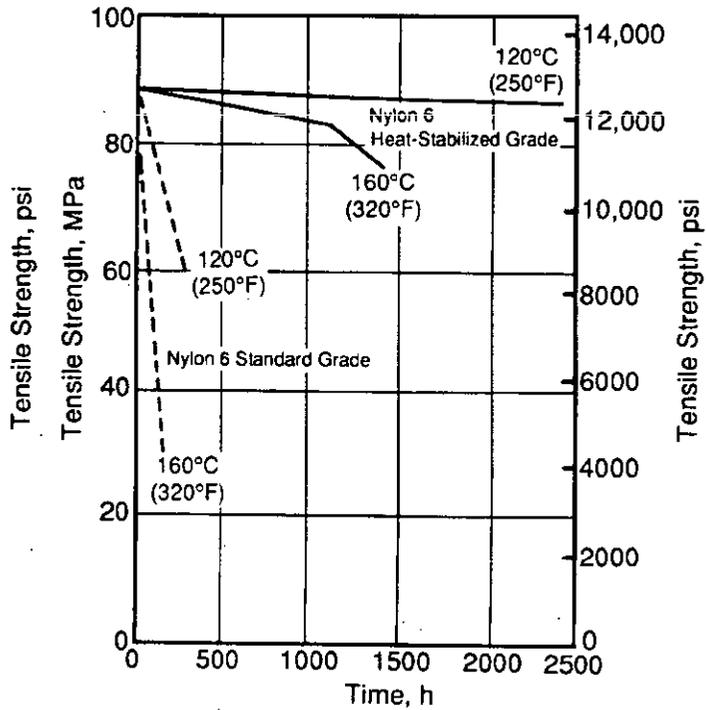
Data on properties of aliphatic nylons 6/6 and 6 have been plotted in Figs. 6-1 and 6-2 (Ref. 2). The data show the effects of exposure at different temperatures on tensile strength and impact strength as a function of time for the basic formulation and for a heat-stabilized grade.

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(A) Nylon 6/6

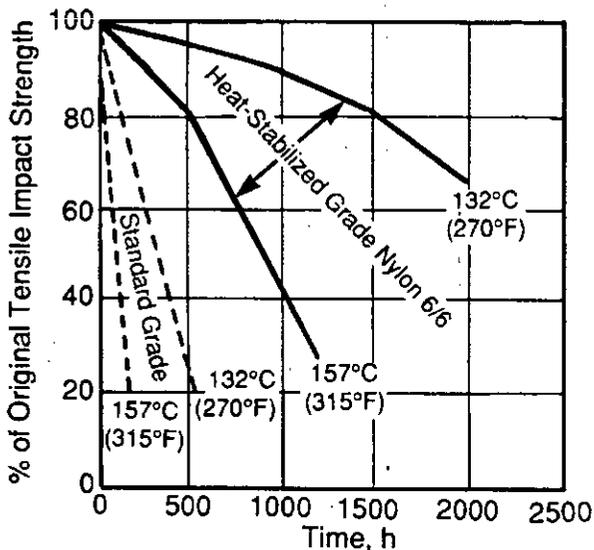
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(B) Nylon 6

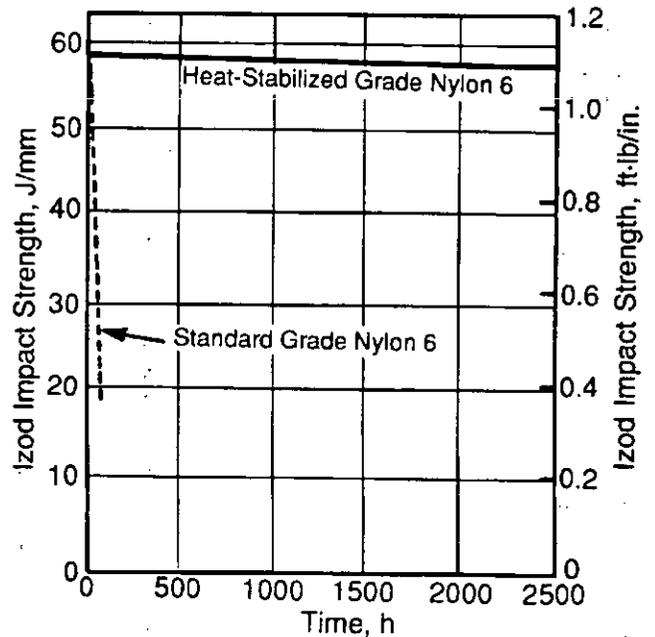
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Figure 6-1. Effects of Temperature and Stabilizers on the Tensile Strength of Nylon 6/6 Exposed in a Circulating Air Oven and Nylon 6 Exposed to Air Oxidation (Ref. 2)



(A) Nylon 6/6

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(B) Nylon 6

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Figure 6-2. Effects of Temperature and Stabilizers on the Impact Strength of Nylon 6/6 in a Circulating Air Oven and Nylon 6 Exposed to Air at 120°C (250°F) (Ref. 2)

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6-2.2 AROMATIC NYLON TYPES

The investigation of new high-temperature materials, including the aromatic polyamides, has been greatly accelerated to meet both military and civilian demands (Ref. 3). These interests are being generated by the highly specific requirements of space exploration and supersonic subpace flight for a broad spectrum of uses from structural composites to protective coatings. In general, high-temperature materials must have a high degree of flexibility, good thermal stability, an outstanding modulus-to-weight ratio, as well as a high strength-to-weight relationship at service temperatures of 540 to 1090°C (1000 to 2000°F). Generally, polymeric fibers meet all of these requirements except one, thermal stability. However, a new generation of polymers that includes the aromatic polyamides has been developed and is rapidly being improved. Thus their thermal properties are approaching those of glasses and metals. Comparison of thermal capabilities are shown on Fig. 6-3.

6-3 RESISTANCE OF NYLON TO WATER AND STEAM

Throughout this handbook the effects of moisture on the manufacturability and physical properties of nylon have been emphasized. The presence of steam imposes a somewhat more severe condition caused by the combination of moisture effects and elevated temperature, which negatively affect the mechanical properties of nylon. The combination

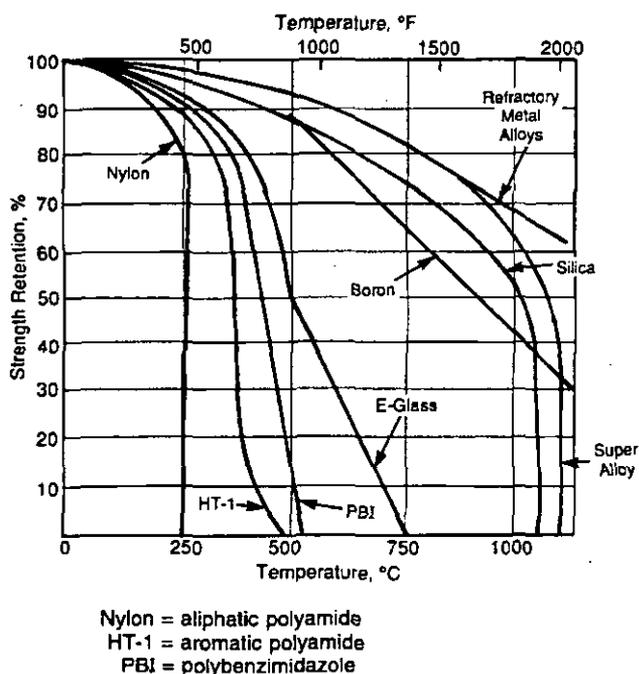
of these influences makes the prediction of service life or mechanical properties after a period of exposure difficult. In this case end-use testing is especially valuable. Testing under controlled conditions expected during end-use provides representative data on evaluation of nylon formulations and safety factors that should be incorporated into the design to compensate for the reduction in physical properties.

Historical data on the nylon valves used in home appliances indicate that these components undergo a continuous degradation in properties resulting in a finite service life for these components. A combination of factors including exposure to water, elevated temperatures, and the presence of oxygen dissolved in the water causes the degradation and results in the hydrolysis and oxidation of the nylon valve materials. It has been observed that exposure of nylon to hot, stagnant water which is free of dissolved oxygen causes degradation more slowly than fresh, running, hot water containing dissolved oxygen. Thus oxygen is a key ingredient in this process. Elevated temperatures contribute an increase in the rate of oxidation and the resulting embrittlement. Although increasing the temperature by 14 deg C (25 deg F) may reduce the useful life of a part by 40 to 50%, this contribution is sometimes not as significant as the effect of oxygen concentration in the water. The result of both mechanisms is an increase in the embrittlement of the nylon materials. The allowable amount of embrittlement depends on the nature of the application. Water-mixing and shutoff valves generally must withstand great impacts from the "water hammer" produced by the momentum of a moving water stream that is abruptly turned off. Testing under operational conditions is necessary to determine the adequacy of the design and materials used in the components. (Refs. 4 and 5). Compositions of nylon formulated to retard oxidative and hydrolytic degradation can be used to obtain a longer service life (Ref. 2).

Service life may be adversely shortened if the nylon components are subjected to elevated temperatures during storage prior to being placed in service. The problem is worse if the parts are moisture conditioned, placed in sealed containers, and then exposed to high temperatures for an extended period. Brittleness of the parts can result. Control of the temperature in storage areas is necessary to prevent this problem.

6-4 WEATHERING

Weathering refers to the changes that occur in a material when it is exposed to the natural elements, which include humidity, precipitation, atmospheric pollution, and sunlight. For most nylons, weathering causes degradation of mechanical properties and appearance. Specific changes include a reduction in tensile strength, embrittlement, and change in appearance. These changes are produced primarily by exposure to the ultraviolet component of sunlight, which breaks down the nylon molecules. The resulting de-



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Figure 6-3. Thermal Capabilities of Fibers (Ref. 3)

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crease in the molecular weight of the nylon material reduces the strength and toughness.

Nylon 6/6 can be compounded for extended use in outdoor applications, usually by the addition of carbon to screen out ultraviolet (UV) light. These compounds have been used in outdoor service for 20 yr or more with negligible degradation. Thus for long-term exposure to weather, these weather-resistant compounds should be used.

6-4.1 TESTING PROCEDURES

Testing of a nylon material is performed by exposing samples in an outdoor environment and comparing the mechanical properties measured after exposure with those of unexposed control samples. Alternatively, similar tests can be performed by mounting samples in exposure facilities that simulate the outdoor environment. Loss of strength is evaluated by conducting tensile tests on the exposed samples and controls and then comparing the tensile and yield strengths for each. Change in toughness is evaluated by comparing the area under the stress-strain curve of exposed and control samples. An alternative evaluation is measurement of the effective molecular weight of the material before and after exposure since higher molecular weight correlates with greater strength and toughness.

The location at which the samples are exposed has some effect on the outcome of the tests due to differences in humidity, the level and duration of daily ultraviolet radiation, and other climatic variations. For testing in the United States, Florida is a desirable location because its southern location provides greater exposure to the environmental factors that lead to weathering, i.e., ultraviolet radiation along with warm temperatures and high humidity. Arizona and Delaware are alternatives for evaluation of the weatherability in a dry climate with high ultraviolet radiation and a northern climate with seasonal variations, respectively. These tests typically represent a more severe exposure than is expected in service because the samples are placed on racks and oriented at 45 deg so they absorb maximum ra-

diation from the sun. Most outdoor applications have less exposure, although there are some applications that will have more (Ref. 6).

Exposure testing in a simulated environment is conducted in exposure facilities that generate concentrations of ultraviolet light at levels found in sunlight while controlling other environmental factors, such as temperature and humidity. Data from such a facility are presented in subpar. 6-4.3.

6-4.2 WEATHERING IN VARIOUS LOCATIONS

Weather exposure tests have been conducted in numerous locations. Presented in this paragraph are data from tests conducted in Florida, Arizona, and Delaware (Refs. 4 and 5).

Table 6-1 summarizes the data collected from weather exposure tests conducted in Florida. The following conclusions may be drawn from this table:

1. Basic nylon 6/6 material that has not been formulated to tolerate excessive amounts of UV light loses toughness but retains tensile strength after a 15-yr exposure to weather.
2. Nylon 6/6 with carbon material added for UV resistance retains toughness and tensile strength after a 15-yr exposure to weather.
3. White nylon 6/6 (conventional nylon with titanium dioxide added) was tested more recently and retains toughness and tensile strength after a 3-yr exposure to weather.

Tests in Arizona conducted over a 1.5-yr period showed the degradation was more pronounced on samples of nylon 6/6 with titanium dioxide than with carbon black. The results of the Arizona tests are summarized in Table 6-2.

Ultraviolet radiation is less intense in Delaware than in Arizona or Florida, so as expected, exposure tests conducted in Delaware showed less degradation than tests conducted in either Florida or Arizona. Data from the Delaware tests are shown in Table 6-3.

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TABLE 6-1. WEATHERING OF NYLON* IN FLORIDA (Ref. 4)

COMPOSITION	PROPERTY	MONTHS										
		0	6	12	24	36	60	84	96	108	180	
Zytel® 101 (6/6 nylon, not stabilized)	Yield Strength, MPa (psi)	57 (8,200)	**	**	**	**	**	**	**	**	**	**
		Tensile Strength, MPa (psi)	73 (10,600)	37 (5,380)	35 (5,140)	31 (4,480)	—	23 (3,380)	16 (2,300)	19 (2,800)	24 (3,500)	24 (3,500)
	Elongation, %	300	10	6	6	—	5	5	5	—	—	
Zytel® 105 BK-10A† (6/6 nylon, light stabilized, black)	Yield Strength, MPa (psi)	50 (7,300)	62 (9,060)	66 (9,560)	55 (7,990)	—	56 (8,050)	47 (6,800)	48 (7,030)	46 (6,700)	41 (6,000)	
		Tensile Strength, MPa (psi)	63 (9,100)	62 (9,060)	66 (9,560)	55 (7,990)	—	56 (8,050)	47 (6,800)	48 (7,030)	46 (6,700)	41 (6,000)
	Elongation, %	160	60	41	32	—	35	41	51	50	32**	
Zytel® 101 WT-07 (6/6 nylon, with titanium dioxide)	Yield Strength, MPa (psi)	54 (7,930)	43 (6,300)	45 (6,500)	46 (6,600)	41 (6,000)	—	—	—	—	—	
		Tensile Strength, MPa (psi)	72 (10,400)	61 (8,900)	46 (6,700)	46 (6,600)	41 (6,000)	—	—	—	—	—
	Elongation, %	205	290	230	65	30	—	—	—	—	—	

*Tensile bars tested as received; moisture contents ranged from 2-3%. The use of Zytel®, the E. I. Du Pont de Nemours and Co. trademark for nylon, does not constitute endorsement by the US Government.

**No yield

†Weathering data based on a predecessor of similar characteristics. All accelerated data have shown the current composition to be equivalent in resistance to ultraviolet light.

**Material still tough at conclusion of test and can be bent 180 deg around 3.2-mm (18-in.) steel mandrel

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TABLE 6-2. WEATHERING OF NYLON* IN ARIZONA (Ref. 4)

COMPOSITION	PROPERTY	MONTHS			
		0	6	12	18
Zytel® 105 BK-10A** (6/6 nylon, light stabilized, black)	Yield Stress, MPa (psi)	92 (13,400)	90 (13,100)	83 (12,100)	88 (12,800)
		Tensile Strength, MPa (psi)	92 (13,400)	90 (13,100)	83 (12,100)
	Elongation, %	25	20	25	25
Zytel® 101 WT-07** (6/6 nylon, with titanium dioxide)	Yield Stress, MPa (psi)	81 (11,800)	No Yield	No Yield	No Yield
		Tensile Strength, MPa (psi)	81 (11,800)	42 (6,100)	26 (3,800)
	Elongation, %	45	5	5	5

* All test bars exposed in dry-as-molded condition. After 12 months, Zytel® 101 and 101 WT-07 show surface cracking and a broad range in tensile properties.

** Weathering data based on a predecessor of similar characteristics. All accelerated weathering data have shown the current composition to be equivalent in resistance to ultraviolet light.

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TABLE 6-3. WEATHERING OF NYLON* IN DELAWARE (Ref. 4)

COMPOSITION	PROPERTY	MONTHS				
		0	6	12	18	24
Zytel® 101 WT-07 (6/6 nylon, with titanium dioxide)	Yield Stress, MPa (psi)	55 (8,000)	42 (6,100)	46 (6,600)	43 (6,200)	45 (6,500)
	Tensile Strength, MPa (psi)	71 (10,300)	48 (7,000)	46 (6,600)	43 (6,200)	45 (6,500)
	Elongation, %	295	250	95	70	65
Zytel® 105 BK-10A** (6/6 nylon, light stabilized, black)	Yield Stress, MPa (psi)	66 (9,600)	52 (7,600)	56 (8,100)	53 (7,700)	56 (8,100)
	Tensile Strength, MPa (psi)	66 (9,600)	53 (7,600)	56 (8,100)	53 (7,700)	56 (8,100)
	Elongation, %	215	200	70	45	45

* Bars contained 2.5% moisture at start of test.

** Weathering data based on a predecessor of similar characteristics.

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6-4.3 ARTIFICIAL WEATHERING TESTS

Tests are performed under simulated environmental conditions whenever it is necessary to control closely the conditions of the test, when it is desired to test for environmental conditions that do not exist at locations convenient for testing, or when it is desired to "accelerate" the test by imposing conditions more severe than those the item will encounter in service. In artificial tests to simulate some desired environment, environmental factors such as ultraviolet light, temperature, humidity or precipitation, and wind may be controlled in an exposure chamber. Typically, accelerated testing should not match a simulated environment so closely that laboratory facilities are unavailable for extended periods; however, the environmental conditions

must not be so much more severe than the normal environment that failure or degradation occurs by mechanisms which would not occur during normal service, e.g., failure that would occur by melting of the material.

An example of accelerated aging data for tensile bars 3.2 mm (0.125 in.) thick is shown in Table 6-4. The X-W Weather-Ometer® data in this table are taken from a commercially available exposure facility that used the wet-dry cycle. Although the exact correlation between tests in this facility and outdoor exposure tests cannot be precisely defined, it is believed that a test in this facility provides an amount of environmental stress to the nylon material equivalent to that from exposure to the outdoor environment in Florida for one year.

*Use of Atlas Electric Devices, Chicago, IL, product name does not imply endorsement by the US Government.

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TABLE 6-4. EXPOSURE OF NYLON* TO WEATHER-OMETER® (Ref. 4)

COMPOSITION	PROPERTY	HOURS						
		0	200	600	1000	2000	3000	6000
Zytel® 101	Yield Stress, MPa	54	58	No Yield				
	(psi)	(7,860)	(8,370)	No Yield				
	Tensile Strength, MPa	70	62	53	42	33	39	39
	(psi)	(10,100)	(9,030)	(7,650)	(6,130)	(4,740)	(5,660)	(5,600)
	Elongation, %	300	310	10	10	10	10	40
Zytel® 101 WT-07 (6/6 nylon with titanium dioxide)	Yield Stress, MPa	55	58	59	55	60	61	65
	(psi)	(8,000)	(8,410)	(8,500)	(8,020)	(8,640)	(8,860)	(9,400)
	Tensile Strength, MPa	71	66	56	46	No Yield	No Yield	No Yield
	(psi)	(10,300)	(9,580)	(8,070)	(6,620)	No Yield	No Yield	No Yield
	Elongation, %	300	315	290	210	54	43	28
Zytel® 105 BK-10A** (6/6 nylon, light stabilized, black)	Yield Stress, MPa	67	70	77	72	No Yield	76	90
	(psi)	(9,650)	(10,200)	(11,110)	(10,480)	No Yield	(11,010)	(13,000)
	Tensile Strength, MPa	51	51	53	50	64	No Yield	No Yield
	(psi)	(7,400)	(7,390)	(7,650)	(7,280)	(9,340)	No Yield	No Yield
	Elongation, %	210	105	60	46	10	14	118
Zytel® 408 BK-10** (Modified 6/6 nylon, light stabilized, black)	Yield Stress, MPa	59	—	64	—	66	—	—
	(psi)	(8,500)	—	(9,300)	—	(9,500)	—	—
	Tensile Strength, MPa	59	—	64	—	66	—	—
	(psi)	(8,500)	—	(9,300)	—	(9,500)	—	—
	Elongation, %	39	—	45	—	25	—	—
Zytel® ST 801 ("Supertough" 6/6 nylon)	Tensile Strength, MPa	41	—	—	36	34	—	30†
	(psi)	(6,021)	—	—	(5,260)	(5,000)	—	(4,300)†
	Elongation, %	215	—	—	59	56	—	61†
Zytel® ST 801 BK-10 ("Supertough", light stabilized, black)	Tensile Strength, MPa	—	—	—	42	39	—	37†
	(psi)	—	—	—	(6,089)	(5,716)	—	(5,400)†
	Elongation, %	—	—	—	215	222	—	187†

* Based on specimens conditioned to equilibrium at 50% relative humidity (RH)

** Weathering data based on a predecessor of similar characteristics.

† 10,000 hours

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6-5 PERMEABILITY AND RESISTANCE TO CHEMICALS AND REAGENTS

An important characteristic of the materials used in containers, tanks, pipes, sealable bags, and packaging films is their ability to act as a barrier to various liquids and vapors in the environment by either preventing their escape from a confined area or preventing contamination by these liquids and vapors. Another important characteristic is the resistance of these materials to attack by gases or liquids with a subsequent reduction in their ability to act as a barrier. The ability of materials such as nylon to act as a barrier is the permeation rate, which expresses the rate of flow of a specified liquid or gas through a unit area of a sheet of

the material when a differential pressure of the permeating liquid or gas is applied between the sides of the sheet.

6-5.1 PERMEABILITY DATA FOR NYLON

Because of its polar, semicrystalline structure, nylon is an excellent barrier material to many gases and liquids; however, there are some gases and liquids that will permeate through nylon sheets at a measurable flow rate. Table 6-5 (Ref. 7) lists the permeation rate of several types of nylon films for common gases and liquids, and Table 6-6 (Refs. 4 and 5) gives the permeation rate measured through a thicker nylon material, i.e., a 2.54-mm (0.1-in.) thick bottle. These data can be used to evaluate the loss from, or likeli-

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TABLE 6-5. PERMEABILITY OF NYLON FILMS (REF. 7)

PERMEANT	UNIT*	% RH	NYLON			
			6/6	6/10**	6†	12
Oxygen	cm ³ mil (100 in. ²) ⁻¹ day ⁻¹ atm ⁻¹	0	--	--	2.6	--
		50	2	4.3	6	--
		100	12	7	--	--
		Unspecified	--	--	--	52-92
Carbon dioxide	cm ³ mil (100 in. ²) ⁻¹ day ⁻¹ atm ⁻¹	0	--	--	9.7	--
		50	10	--	25	--
		Unspecified	--	--	--	156-336
		0	--	--	0.9	--
Nitrogen	cm ³ mil (100 in. ²) ⁻¹ day ⁻¹ atm ⁻¹	50	0.7	--	2(2)	--
		Unspecified	--	--	--	12.8-18
		50	0.9	0.9	0.6	--
		100	20†	14	19-20	--
Water vapor	g mil (100 in. ²) ⁻¹ day ⁻¹	50	0.9	0.9	0.6	--
		100	20†	14	19-20	--
		Unspecified	--	--	--	0.7
					at 100°F (38°C)	
Gasoline	g mil (100 in. ²) ⁻¹ day ⁻¹	50	0.2	--	--	--
Motor oil at 125°F (52°C)	g mil (100 in. ²) ⁻¹ day ⁻¹	50	0.1	--	0.00	--
Toluene	g mil (100 in. ²) ⁻¹ day ⁻¹	50	2	--	--	--
Trichloroethylene	g mil (100 in. ²) ⁻¹ day ⁻¹	50	--	--	0.05	--

* The unit of permeability corresponds to quantity lost (volume for a gas, weight for a liquid) × thickness per unit area × time (× pressure difference if the permeant is a gas). Many combinations of units are found in the literature. Conversions of the above units to others commonly encountered follow:

$$\text{cm}^3 \text{ mil (100 in.}^2\text{)}^{-1} \text{ day}^{-1} \text{ atm}^{-1} \times 0.394 = \text{cm}^3 \text{ mm m}^{-2} \text{ day}^{-1} \text{ atm}^{-1}$$

$$\text{cm}^3 \text{ mil (100 in.}^2\text{)}^{-1} \text{ day}^{-1} \text{ atm}^{-1} \times 6 \times 10^{-13} = \text{cm}^3 \text{ cm cm}^{-2} \text{ s}^{-1} \text{ (cm of mercury)}^{-1}$$

$$\text{cm}^3 \text{ mil (100 in.}^2\text{)}^{-1} \text{ day}^{-1} \text{ atm}^{-1} \times 6 \times 10^{-3} = \text{barriers}$$

$$\text{g mil (100 in.}^2\text{)}^{-1} \text{ day}^{-1} \times 0.394 = \text{g mm m}^{-2} \text{ day}^{-1}$$

** The permeability of nylon 6/12 has not been reported but is most likely comparable to that of nylon 6/10.

† Extracted

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TABLE 6-6. PERMEATION FACTORS OF VARIOUS LIQUIDS THROUGH 2.54-mm (0.1-in.) THICK BOTTLES MADE OF EXTRUSION-GRADE NYLON 6/6 (Ref. 4)

LIQUID	PERMEATION FACTOR,	PERMEATION FACTOR at 1 atm,
	g/24 h/m ² /mm	(g/24 h/100 in. ² /mil)
Kerosene	0.08	0.2
Methyl salicylate	0.08	0.2
Motor oil (SAE 10)	0.08	0.2
Toluene	0.08	0.2
Fuel oil B (isooctane-toluene blend)	0.2	0.5
Water	1.2-2.4	3-6
Carbon tetrachloride	2.0	5
VMP naphtha	2.4	6

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hood of contamination into, a sealed container. Note that the permeability of nylon is higher for liquids with polar molecular structures such as water, alcohol, and carbon tetrachloride. Of special interest to the military are the permeation rates of nylon for hazardous chemical warfare agents. Nylons 6, 6/6, and 12 show no permeation to HD (bis [2-chloroethyl] sulfide), a blistering agent, and GD (pinacolyl methylphosphono-fluoridate), a nerve agent (Ref. 8). Nylons 6/6 and 11 also provide an impermeable barrier to the nerve agents VX and VX-hexane (Ref. 9).

6-5.2 MEASUREMENT OF PERMEABILITY

Permeability can be measured by various techniques depending on the phase of the permeative material being investigated. In a test for the permeation of water vapor, a desiccant-filled dish is covered with a film of the material to be evaluated, weighed, placed in a humidity chamber for a specified period of time, and then reweighed. The increase in weight of the covered dish is proportional to the amount of water vapor that permeated through the cover of the dish and was absorbed by the desiccant. Measurement of gas permeability can be done in an apparatus consisting of two chambers separated by a window of the material to be evaluated for permeability. One chamber is filled with a specified gas while the other is evacuated. Observation of pressure in the evacuated side provides a measure of the amount of gas that has permeated through the test sample (Ref. 10).

Permeability of a material depends on many environmental conditions, e.g., temperature and pressure, as well as the

condition of the material being tested. Even under ideal conditions, it is difficult to obtain repeatable measurements of permeability. Therefore, the data presented in subpar. 6-5.1 should be used to estimate permeation rates through nylon and not to calculate precisely. With these reservations in mind, the permeation data in Table 6-6 can be used for nylons other than the extrusion-grade material, on which the data are based.

6-5.3 CHEMICAL RESISTANCE OF NYLON

A characteristic of nylon that contributes to its popularity is its tolerance of a wide range of organic and inorganic compounds with no degradation. Some compounds have a minor impact on the dimensions of nylon parts and on the mechanical characteristics of the material, and a small number of chemicals result in the drastic degradation of the mechanical characteristics and the surface finish of nylon. In this subparagraph the effects of a number of materials on nylon are discussed, beginning with those that do not have a significant detrimental effect on its physical characteristics. Table 6-7 lists many solvents and reagents and their specific effect on the properties of nylon 6/6, unless otherwise specified (Refs. 4 and 5). In most cases in which absorption is indicated, the absorption of the chemical shown in the table causes a slight dimensional increase and has a plasticizing effect on the nylon material. Thus a reduction in strength and an increase in toughness occur. Table 6-8 summarizes the effects of commonly encountered materials by grouping them into broad categories based on their effect on nylon (Ref. 4).

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TABLE 6-7. CHEMICAL RESISTANCE OF NYLON RESINS (Ref. 4)

CHEMICAL	CONCENTRATION, %	NYLON* (ZYTEL® 101 UNLESS OTHERWISE SPECIFIED)	EXPOSURE CONDITIONS			WEIGHT CHANGE**	% LENGTH CHANGE	CHEMICAL† RESISTANCE			COMMENTS
			TEMPERATURE		TIME (DAYS)			EXCELLENT	SATISFACTORY	UNSATISFACTORY	
			°C	°F							
Acetaldehyde	90		52	125				X			
Acetic acid	5		23	73	30	H	+1.4		X		
	5		23	73	90	H	+1.7			X	
	5	Zytel® 158L	23	73	90	M	+0.5		X		
Acetone	100		23	73	365	L	+0.0		X		
	100		50	122	365	M	+0.3		X		
	100	Zytel® 158L	23	73	90	M	+0.2		X		
Aluminum salts of mineral acids	10		23	73					X		
	10		52	125						X	
Ammonia, liquid	100		-33	-28	7			X			
	100		-33	-28	14			X			
	100		24	+75	200				X		
Ammonium chloride	10		52	125						X	
Ammonium hydroxide	10		23	73	365	H	+1.7	X			
	10		70	158	365	H	+1.3			X	
n-Amyl acetate	100	Zytel® 151L	98	208	45					X	
Antimony trichloride	10		24	75						X	
"Aroclor" 1242	100		23	73	30	L		X			
Barium chloride	10		24	75						X	
Benzene	100		23	73				X			
	100	Zytel® 151L	23	73	90			X			
Benzoic acid	10		24	75						X	
Boric acid	7		35	95	316					X	
Bromine	100		24	75						X	
Buffer solution pH 4	100		70	158	30	H	+1.6	X			
	100		70	158	90	H	+1.5		X		
	100		70	158	365	H	+1.4			X	
Buffer solution pH 7	100		70	158	365	H	+1.3	X			
Buffer solution pH 10	100		70	158	90	H	+1.6		X		
	100		70	158	365	H	+1.5			X	

* Zytel® 101 = nylon 6/6

Zytel® 151L = lubricated nylon 6/12

Zytel® 158L = same as 151L except higher melt viscosity and toughness

Zytel® 408 = nylon 6/6 with added impact resistance and flexibility

Zytel® ST = supertough nylon

** Low = <1%, Moderate = <1-4%, High = 4-9%, Very High = >9%

† Based on physical property measurements

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TABLE 6-7. (cont'd)

CHEMICAL	CONCENTRATION, %	NYLON* (ZYTEL® 101 UNLESS OTHERWISE SPECIFIED)	EXPOSURE CONDITIONS			WEIGHT CHANGE**	% LENGTH CHANGE	CHEMICAL RESISTANCE			COMMENTS
			TEMPERATURE		TIME (DAYS)			EXCELLENT	SATISFACTORY	UNSATISFACTORY	
			°C	°F							
n-Butanol	100	Zytel® 151L	50	122	45			X			
	100	Zytel® 158L	23	73	90	M	+0.3		X		
Butyric acid	10		24	75						X	
Calcium chloride	5		60	140						X	Stress cracks at high temperatures
Calcium hypochlorite	saturated		35	95	77					X	
Calcium thiocyanate	50									X	Swells nylon
Calcium tetrachloride	100		50	122	365	L	+0.1	X			
	100	Zytel® 158L	23	73	365	L	0.0	X			
Cetane	100		23	73	365	H	+1.7	X			
Chlorine water	dilute conc		23	73					X		
			23	73						X	
Chloroacetic acid	10		24	75						X	
Chloroform	100		23	73	56	H	+0.3	X			
	100	Zytel® 158L	23	73	90	VH	+4.1		X		
Chlorosulfonic acid	10		24	75						X	
Chlorox	100		23	73	10				X		
Chromic acid	10		24	75						X	
Citric acid	10		35	95	77				X		
Copper chloride	10		24	75						X	
m-Cresol	100	Any	23	73						X	Solvent for nylon
Diethylene glycol	90		24	75				X			
Ethanol	95		23	73	365	H	+2.4	X			
	95		50	122	365	H	+2.8	X			
	95	Zytel® 158L	23	73	90	VH	+3.2	X			
Ethyl acetate	95		50	122	365	L	0.0	X			
Ethylene dibromide	100	Zytel® 151L	50	122	45				X		
Ethylene dichloride	100		66	150	7	M	+0.3	X			
Ethylene glycol	100		23	73	56	M	0.0	X			
Formalin	38		23	73	14			X			
Formic acid	90		23	73						X	Solvent for many nylons including type 6/6

* Zytel® 10 = nylon 6/6

Zytel® 151L = lubricated nylon 6/12

Zytel® 158L = same as 151L except higher melt viscosity and toughness

Zytel® 408 = nylon 6/6 with added impact resistance and flexibility

Zytel® ST = supertough nylon

** Low = < 1%, Moderate = < 1-4%, High = 4-9%, Very High = > 9%

† Based on physical property measurements

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TABLE 6-7. (cont'd)

CHEMICAL	CONCENTRATION, %	NYLON* (ZYTEL® 101 UNLESS OTHERWISE SPECIFIED)	EXPOSURE CONDITIONS			WEIGHT CHANGE**	% LENGTH CHANGE	CHEMICAL* RESISTANCE			COMMENTS
			TEMPERATURE		TIME (DAYS)			EXCELLENT	SATISFACTORY	UNSATISFACTORY	
			*C	*F							
FREON 11**	100		23	73	365	L	+0.8	X			
FREON 12	100		23	73	365	L	0.0	X			
FREON 21	100		23	73	365	H	+0.5	X			
FREON 22	100		23	73	365	L	0.0	X			
FREON TE	100		23	73	8	L	+1.2	X			
Glycolic acid	70				200					X	Stress cracking agent
Hexafluoroisopropanol	100		23	73						X	Solvent for Zytel® 101
Hydrochloric acid	2.5		23	73	10			X			
	5		77	170	5					X	
	10		25	77	60					X	
Hydrogen peroxide	5		43	110	30					X	
Hydrogen sulfide (aq)	conc		23	73						X	
"Hylene" T	100		23	73	10			X			
Isooctane	100		23	73	365	M	0.1	X			
	100	Zytel® 408				L	0.1	X			
	100	Zytel® ST				M	0.2	X			
Lactic acid	10		35	95	316			X			
	25		23	73	90				X		
Lanolin suspension	10		35	95	77			X			
Methanol	100		23	73	56	H		X			
	100		23	73	365	H	3.0	X			
	100	Zytel® 408	23	73	365	H	2.4	X			
	100	Zytel® ST	23	73	365	H	2.2	X			
Methyl chloroform	100		72	162	4			X			
Methyl isobutyl ketone	100	Zytel® 151	23	73	14			X			
Methylene chloride	100		23	73	28	VH	+4.1		X		
Naphtha (VMP)	100	Zytel® 151L	98	208	45			X			
Nitric acid	10		23	73	60					X	
Nitromethane	100		23	73	30			X			
2-Nitropropane	100		49	120	30			X			
"Nujol"	100		70	158	365	L		X			
Perchloric acid	10		24	75						X	

* Zytel® 101 = nylon 6/6

Zytel® 151L = lubricated nylon 6/12

Zytel® 158L = same as 151L except higher melt viscosity and toughness

Zytel® 408 = nylon 6/6 with added impact resistance and flexibility

Zytel® ST = supertough nylon

** Low = <1%, Moderate = <1-4%, High = 4-9%, Very High = >9%

† Based on physical property measurements

†† Du Pont's registered trademark for fluorocarbons

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TABLE 6-7. (cont'd)

CHEMICAL	CONCENTRATION, %	NYLON* (ZYTEL® 101 UNLESS OTHERWISE SPECIFIED)	EXPOSURE CONDITIONS			WEIGHT CHANGE**	% LENGTH CHANGE	CHEMICAL† RESISTANCE			COMMENTS
			TEMPERATURE		TIME (DAYS)			EXCELLENT	SATISFACTORY	UNSATISFACTORY	
			°C	°F							
"Perciene"	100		23	73	365	M	3.0	X			
	100	Zytel® 408	23	73	365	M	2.4	X			
	100	Zytel® ST	23	73	365	M	2.2	X			
Phenol	90		23	73						X	Solvent for nylon
Phosphoric acid	5	Zytel® 151L	98	208						X	
Potassium carbonate	20	Zytel® 151L	98	208	45			X			
Potassium hydroxide	30		93	200	8				X		
Potassium permanganate	5		23	73	10					X	
Potassium thiocyanate	conc									X	Solvent for nylon
Sodium acetate	conc		38	100				X			
Sodium bicarbonate	conc		24	75				X			
Sodium carbonate	2		35	95	77			X			
Sodium chloride	10		23	73	365	H	+1.0	X			
Sodium hydroxide	10		70	158	30	H	+1.2	X			
	10		70	158	365					X	
Sodium hypochlorite	5		23	73	10				X		
Sodium nitrate	5		24	75	10			X			
Stannic chloride	10		24	75						X	
Stannic sulfate	10		24	75						X	
Sulfur dioxide gas			38	100	100					X	Limited service satisfactory
Sulfuric acid	30		23	73	30					X	
Sulfurous acid	10		23	73				X			
2,2,3,3 Tetrafluoropropane	100									X	Solvent for nylon
Toluene	100		50	122	365	M	0.0	X			
	100		23	73	365	M	0.1	X			
	100	Zytel® 408	23	73	365	M	0.1	X			
	100	Zytel® ST	23	73	365	M	0.2	X			
Tricresyl phosphate	100			150	7	L	0.2	X			
Xylene	100		23	73				X			
"Zerex"	40		104	220	92				X		Small surface cracks develop

* Zytel® 101 = nylon 6/6

Zytel® 151L = lubricated nylon 6/12

Zytel® 158L = same as 151L except higher melt viscosity and toughness

Zytel® 408 = nylon 6/6 with added impact resistance and flexibility

Zytel® ST = supertough nylon

** Low = <1%, Moderate = <1-4%, High = 4-9%, Very High = >9%

† Based on physical property measurements

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TABLE 6-8. CHEMICAL RESISTANCE BEHAVIOR OF NYLON (Ref. 4)

CHEMICAL BEHAVIOR	COMPOUND
Excellent resistance	Brake fluids Lubricants automotive, power steering fluids Oil Grease Hydrocarbons: aliphatic aromatic Paints Lacquers Detergents Fats: animal and vegetable Alkalies: up to 40% (high concentration) Gasoline
Unsatisfactory use with nylon resins	Phenols Trichloroacetic acid Fluoroalcohols: (some) Strong acids Calcium thiocyanate Calcium bromide Calcium chloride Potassium thiocyanate Zinc chloride Mineral Acids: strong Oxidizing agents: strong, high temperature
Increase in toughness, elongation with reduction in tensile strength	Alcohols Water Methylene chloride Chloroform Ethylene dichloride
Some dimensional change, physical properties unimpaired	Aldehydes: (most) Ketones Esters: (most) Chlorinated aliphatics: (most) Aromatic materials: (most)

} high concentration (50-80%)
and elevated temperature

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Nylons exhibit high resistance to attack by most organic and inorganic compounds. They are essentially inert when used with lubricating oils, greases, and aliphatic and aromatic hydrocarbons (including conventional fuels); therefore, they are used extensively in automotive and aircraft applications. Because nylon can tolerate moderately high temperatures concurrently with exposure to these vehicular fluids, high service temperatures are allowable on nylon parts. However, certain lubricant additives may affect nylon characteristics at temperatures above 66°C (150°F). Although tests have been performed on a variety of brake fluids, vehicular fuels, and vehicular lubricants, tests should be performed each time a new fluid formulation is used in a military vehicle to verify its compatibility with nylon at the maximum service temperature. This verification is especially necessary for those fluids which might contain additives that are not as compatible with nylon, such as the previously mentioned lubricant additives and ethanol, which is sometimes added to gasoline. Typically, nylon parts are compatible with commercially available fuels. In tests involving fuel samples from all major suppliers, nylon shows an average weight increase of 0.57% and an average dimensional change of +0.009% after 270 days of exposure at 23°C (73°F) to high- and low-test fuel samples from major suppliers.

Nylon is also resistant to many other products such as paints, lacquers, cleaning detergents, and foods. Therefore, nylon is used for containers and other packaging materials for all of these products, tools for the application of paints and lacquers, utensils for handling foods, and tools used for cleaning. Tests conducted at 82°C (180°F) have shown that nylon resins have excellent resistance to standard detergent and soap formulations.

Nylons are resistant to organic compounds such as aldehydes, ketones, monohydroxyl alcohols, most esters, and most chlorinated aliphatic and aromatic materials. Some of these materials may be absorbed into the nylon material and will act as plasticizers. Thus the strength of the nylon will decrease, and its elongation and toughness will increase. These materials include alcohols and partially halogenated hydrocarbons, such as methylene chloride, chloroform, and ethylene dichloride.

In general, nylon is not susceptible to corrosion in the same manner as metals, even in corrosive environments such as salt spray and industrial environments. This characteristic makes nylon an inexpensive replacement for metals in those environments. Its resistance to alkalis allows the use of nylon components in alkaline batteries.

Nylons 6/6, 6/10, and 6/12 exhibited no change in physical appearance and no significant changes in physical properties when exposed to direct contact for up to 24 h with military decontaminants DS2 and STB (Ref. 11). DS2 is a mixture of diethylenetriamine, methyl cellulose, and sodium hydroxide. STB is used in either powder or slurry form. The powder is a mixture of calcium oxide and cal-

cium hypochlorite, and the slurry consists of the powder mixed with water and detergent. These decontaminants are used to neutralize chemical warfare agents that may be deposited on military materiel.

Nylon is not immune to negative effects from all commonly encountered materials. For example, chlorinated water, found in most cities, has a detrimental effect on the service life of nylon components. Exposure tests of nylon in chlorinated water with a chlorine content of 8 ppm revealed that microcracking may be induced in the nylon and a reduction in service life of 20 to 30% may occur.

Although nylons are very resistant to attack from a wide variety of chemical agents, a few inorganic salts can cause stress cracking. Both calcium thiocyanate and zinc chloride will attack nylon, especially in higher concentrations, i.e., 50 to 80%. Nylons having higher molecular weight are less susceptible to attack. Zinc chloride, for example, is especially harmful to nylon 6/6 but has a lesser effect on nylon 12. Therefore, specific tests should be run to test nylon compatibility for specific applications.

When organic compounds attack nylon, the attack generally occurs through solvent action. Phenols are powerful solvents used to cement nylons (See subpar. 5-7.2.6.). Trichloroacetic acid and some fluoroalcohols attack nylon in a similar manner. Organic acids frequently attack nylon. Acetic acid, a relatively mild acid, slowly attacks nylon, whereas stronger acids degrade nylon more vigorously. Higher fatty acids, such as stearic acid, present no problem. Strong mineral acids and oxidizing agents rapidly attack nylon; the rate of attack increases with temperature. Use of nylon with these solutions may be tolerable at normal temperatures, but tests should be performed to verify compatibility before regular use with these solutions is attempted.

In some cases, some degree of chemical incompatibility can be tolerated. Situations such as low-temperature operation, intermittent exposure, low stress loading, and low surface area contact reduce but do not eliminate the effects of material incompatibility. On the other hand, operation at higher temperatures increases the rate at which incompatible materials attack nylon. Each increase of 15 deg C (27 deg F) may reduce the service life by 25 to 30% due to attack by incompatible materials. Under these conditions verification of material compatibility by testing becomes more important.

6-6 PROPELLANTS AND EXPLOSIVES

Military end-items are often used in contact with an explosive and/or propellant. The effectiveness of the end-item or energetic material can be seriously impaired by a chemical or physical interaction between the two. The interaction can lead to development of a nonstandard or hazardous condition or to the spontaneous ignition of the explosive material. Therefore, if the end-item is to be used with an explosive or propellant, it is necessary to conduct tests to determine the effect of the inert material (in this case nylon)

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on the energetic material and conversely the effect of the energetic material on the inert material. The most common test to determine the effect of the inert material on the energetic material is the vacuum stability test. The effect of the energetic material on the inert material is determined by long-term storage tests, as described in Ref. 12.

The vacuum stability test consists of heating together equal weights of energetic and inert materials and measuring the amount of gas evolved after a prescribed period of time. The degree of reactivity is determined by comparing the evolution of gas from the inert energetic mix with that of controls. (The materials tested separately are used as controls.)

When it has been determined that the polymer (nylon) does not affect the energetic material excessively, one or more tests to determine the effect of the energetic material on the polymer may be run. In these tests, specimens, usually tensile bar specimens, are immersed in the explosive or propellant and stored at elevated temperatures, usually 66°C (150°F). The properties of the test specimens are determined as a function of time in the energetic material and compared with the properties of control specimens stored apart from the energetic material. Time periods of several weeks, several months, or a year are sometimes required. The effects most often measured are visual changes, and changes in weight, hardness, tensile strength, and elongation. End-item requirements determine which properties are of greatest importance in each ordnance application. Accordingly, the significance of all changes in the properties of the polymer must be interpreted in terms of the particular application under consideration.

When tested in accordance with these procedures, the nylon types show good short-term compatibility with propellants and explosives. The presence of nitro groups (such as nitroglycerine, trinitrotoluene, dinitrotoluene, nitromethane, etc.) in the energetic formula, especially the double- and triple-base propellants, however, leads to long-term degradation of the nylons. They may become brittle due to the oxidizing atmosphere (NO₂, HNO₂, HNO₃, etc.) generated by the decomposition of the nitro compounds (especially if stored for prolonged periods at elevated temperatures), or they may become flexible due to plasticization caused by migration and absorption of compounds such as nitroglycerine. In some cases these effects will not be observed until storage times exceed 12 months at 66°C (150°F).

Long-term storage tests, i.e., 12 months, show nylons 6 and 6/6 to be unsatisfactory with the double- and triple-base propellants. Satisfactory results, however, were obtained with the explosives TNT and RDX (Ref. 13). A 43% glass-filled nylon 12 was compatible with the triple-base propellant M30 after 18 months of storage. This nylon composition is used as the cartridge case material for the medium caliber/automatic antiarmor cannon (MC/AAAC) 75-mm system (Ref. 14).

No discussion on the use of such data is complete without a precautionary warning on the use of such data. Compatibility data are valid only for the materials studied. Property data are considered transferable only when a material is specified by a manufacturer's identification number or by a precise and unwavering chemical formulation.

6-7 BACTERIA AND FUNGI: SOIL AND UNDERGROUND CONDITIONS

Polyamides are considered to be generally resistant to biological attack, particularly in relation to the polymeric constituents of the compounded polymers. However, additives such as plasticizers, lubricants, stabilizers, fillers, and other materials may change the biological resistance of both the polymer and finished composition. Considerable work with plasticizers has been documented, and the indications are that choice of the improper plasticizer can directly affect the durability of the finished product, i.e., the plasticizer can be attacked by bacteria and/or fungi (Ref. 15).

Test specimens of nylon 6/6 (extrusion grade) were buried at Landenberg, PA, for 3.5 years in termite-infested soil and then exhumed. Examination after exhumation showed no attack by termites and no apparent deterioration caused by fungi, insects, or other biological agents. Thus it was concluded that nylon was neither attractive to termites nor readily usable by fungi (Ref. 4). Some investigators (Ref. 16), however, have found that the bacterium *Pseudomonas aeruginosa* will start proliferation with nylon six weeks after initial contact.

Several types of nylons were tested microbiologically for their ability to support *Salmonella typhosa* growth. The test proved that these samples would not support the growth of this bacterium. Nylons were tested for resistance to fungal representatives of the following groups: (1) *Chaetomium globosum*, (2) *Rhizopus nigricans*, (3) *Aspergillus flavus*, (4) *Penicillium luteum*, and (5) *Memnoniella echinata*. Test bars exposed to active environments with respect to fungi showed no visual evidence of attack after cleaning and no lessening of their physical properties. Also no changes occurred in molecular weight.

6-8 IRRADIATION

Nylon is intermediate among plastic materials in resistance to radiation. A dose of 60,000 Gy (six megarads) of gamma radiation from a cobalt 60 source showed nylons 6/6 and 11 to be superior to polyethylene and polyvinylidene chloride but inferior to polystyrene and certain polyesters based on the amount of gas evolution (Ref. 17). Based on this study, nylon 6/6 can be considered for packaging food subjected to preservation by irradiation. Similarly, in the neutron-gamma radiation flux of an Oak Ridge National Laboratory nuclear reactor, nylons 6/6 and 6/10 retained their properties better than acrylics and cellulose but not as well as polystyrene and mineral-filled phenolics (Ref. 18). Aromatic nylons are more resistant than their aliphatic analogs.

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During irradiation both cross-linking and chain scission can occur to a degree that depends on the time and temperature of irradiation, the crystallinity and moisture content of the nylon, and post-irradiation treatment. Nylons 6/6 and 6/10 exposed to nuclear reactor radiation (Ref. 17) show little initial change in tensile strength and flexural modulus, but the modulus rapidly increases with increased time of exposure. Specific gravity and water absorption are also affected little initially but eventually show an increase at an exposure similar to that at which the modulus begins to change rapidly. Elongation and impact strength, however, decrease at low-dosage levels.

The immediate consequences of irradiation are the breaking of chemical bonds and formation of free radicals. Hydrogen is the chief gaseous product because the hydrogen atoms adjacent to the amide nitrogen are those most easily removed. Carbon monoxide, carbon dioxide, and methane are also produced.

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CHAPTER 7

SAFETY ASPECTS OF NYLON

The topics discussed in this chapter are the ecology, toxicology, and flammability issues related to the manufacture and application of nylons.

7-1 ECOLOGY

Because of the durability of nylon and the existence of cheaper products that are satisfactory for packaging, most nylon resin is used to produce durable products for automotive, appliance, and electrical applications. Most nylon products are placed in service and remain there for extended periods; only worn-out products enter the solid-waste disposal system. Only 20% of nylon production are products that are disposed after a small number of uses, e.g., brush bristles, oven cooking bags, and shipping container straps. Scrap material generated during the molding process is reground and added to virgin resin; thus this material does not enter the solid-waste disposal stream.

All of the nylon production in the United States (U.S.) equals about 0.01% of the refuse entering the waste disposal process. Consequently, there is insufficient nylon waste to warrant a recycling program to divert and reuse used nylon products.

Nylons that remain exposed slowly degrade in the presence of sunlight. The products evolving from this decomposition process are organic acids, aldehydes, carbon monoxide, and carbon dioxide. Buried nylon decomposes more slowly because of its resistance to bacteria and fungus. Because of this extremely slow rate of decomposition, there is little information available on the chemical products of this process (Ref. 1). This slow, almost nonexistent, decomposition makes nylon an inert product in landfills; it contributes no hazardous products that can leach into ground water.

Nylons emit products no more noxious when incinerated than other naturally occurring fibrous materials, such as wool, silk, or leather. When incinerated at normal conditions, i.e., 800°C (1470°F), nylon produces carbon dioxide, carbon monoxide, and small amounts of ammonia and hydrogen cyanide. The actual level of hydrogen cyanide is less than that produced by the combustion of silk under similar conditions. Incineration of nylon is an exothermic reaction. As the nylon burns, it releases energy that aids in the incineration of other waste products being disposed at the same time. At temperatures lower than those necessary for incineration, i.e., <305°C (581°F), nylon 6 or 6/6 breaks down into products that are even less noxious: carbon dioxide, water, ammonia, and small amounts of amines (Ref. 2).

In summary, there is no problem, present or anticipated, with the disposal of nylon because of the low volume of nylon produced for applications that lead to disposal and

because of the inert characteristics of nylon materials when buried in landfills. When burned, nylon produces products no more hazardous than do naturally occurring materials. Hence the use of nylon, even with increased consumption, is not expected to be an environmental concern.

7-2 TOXICOLOGY

Pure nylon is insoluble in body fluids and is biologically inert; however, additives and the residue of unprocessed monomers that did not polymerize can be a biological hazard for products that are to be used in the body.

Certain nylons have been approved by the Food and Drug Administration for use in food preparation as long as the specified criteria for purity and freedom from certain additives are met (Ref. 3). These include nylons 6/6, 6/10, 6, and 11 as well as some copolymers. Nylon 6 must be treated to reduce the unpolymerized monomer that remains after polymerization, and processing conditions must be monitored to reduce the chance of a reaction that would reverse the polymerization and produce the caprolactam monomer. The ϵ -caprolactam monomer is a poisonous material that induces convulsions when ingested in sufficient doses (Ref. 4). The hydrolyzed product of this monomer, ϵ -aminocaproic acid, is not toxic.

Basic nylon material is nonallergenic. Additive and residual monomers, however, can induce an allergic skin reaction in sensitive persons after extended contact (Ref. 5). Nylon has been successfully used for sutures; however, its use in situations involving long duration contact, e.g., implants, is not recommended because of the possibility of deterioration over time.

7-3 FLAMMABILITY

Concern over safety has prompted several studies to investigate the flammability of plastics (Refs. 6, 7, and 8). Tested according to American Society for Testing and Materials (ASTM) D 635 (Ref. 9), unmodified nylon is rated as self-extinguishing and is classified SE-2 (self-extinguishing class 2) by Underwriters Laboratories. Nylons having additional carbon atoms, such as nylon 12, show a greater tendency to burn and are classified between slow burning and self-extinguishing when tested by the ASTM procedure. Also the addition of other modifiers, such as glass fibers and plasticizers, causes the nylon to test as slow burning. There are modifiers that can be added to improve the flammability rating of the nylon material.

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The oxygen index is a measure of the amount of oxygen necessary to support combustion in materials and is another method used to rate the flammability of a material. Oxygen index tests performed according to ASTM D 2863 (Ref. 10) on nylon 6/6 produced an index of 28 to 29, which indicates that nylon is difficult to burn. Also nylons do not generate excess amounts of smoke when burned.

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CHAPTER 8

APPLICATIONS OF NYLONS

Information is given on the properties of nylons and the importance of these properties for particular applications, both civilian and military. The examples given concern automotive, textile, household, office, and military applications.

8-1 RELATIONSHIP OF APPLICATIONS TO PROPERTIES

The value of nylon as an engineering material is a result of combining its desirable characteristics, which include toughness, abrasion resistance, heat resistance, solvent resistance, and low friction. The suitability of nylon or any other material for a particular application is determined by the match between the material requirements of the application and the characteristics of the nylons, i.e., materials; being considered. Suitability for a particular application is not generally determined by a single characteristic but by a combination of requirements, such as toughness, low friction, and ability to tolerate petroleum-based lubricants. Economic and manufacturing considerations are also important in material selection as is the degree to which the properties of the material may be modified by fillers or other modifiers to adapt it to the requirements of the application.

Table 8-1 lists the characteristics that often qualify nylon for selection as the desired material for a specific application. If other characteristics are required in combination with one or more of those listed, they can be obtained by adding materials to the nylon. For example, increased tensile strength and reduced mold shrinkage can be obtained by adding glass fibers to the resin.

The remainder of this paragraph discusses specific applications for which various nylon compositions are used. The applications presented are grouped according to the nylon property from Table 8-1 that makes nylon an appropriate material choice for that application.

8-1.1 TOUGHNESS

The toughness, or impact resistance, of nylon (in combination with the strength of the material) is one of its more

TABLE 8-1. KEY PROPERTIES OF NYLON
(Ref. 1)

Toughness
Fatigue resistance
Low friction
Abrasion resistance
Resistance to oils and solvents
Stability at high temperature
Fire resistance
Creep resistance

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significant properties. It depends on the composition of the nylon and varies with moisture content. Tougher compositions can be formed by creating copolymers with various nylon compositions, adding plasticizers, or reinforcing with glass fibers. (Glass-fiber reinforcement can increase or decrease toughness depending on the amount of fiber incorporated, the orientation, and the adhesion between the fiber and the nylon material.)

Examples of nylon applications that take advantage of the toughness of nylon include football face guards, hammer handles, door striker parts, gears, and oscillating machinery parts. Because of its toughness, Nylon 6 is used for football face guards. Glass-reinforced nylon 6/6 is used for hammer handles. Nylon is also used for a variety of consumer appliance and tool housings because of its ability to withstand rough treatment and accidental dropping onto hard surfaces and its capability to be colored and finished in a variety of surface finishes.

Some military applications requiring great toughness that use nylon resins include obturator bands, rotating bands, and cartridge cases for small and large caliber weapons. For these applications the parts must function properly under high rates of loading or stress at extreme temperatures of -40 to 49°C (-40 to 120°F) and under all climatic conditions. Obturator bands for the 105-mm fin-stabilized discarding sabot anti-tank rounds include a centrifugally cast and machined nylon 6/6, and those for the 120-mm discarding sabot rounds use extruded and machined nylon 6/12. An injection-molded, 50% glass-filled nylon 12 is used as the cartridge case for the medium caliber/automatic antiarmor cannon (MC/AAAC) 75-mm round.

8-1.2 RESISTANCE TO FATIGUE AND REPEATED IMPACTS

Resistance to fatigue and repeated impacts is the capability of nylon to withstand a series of impacts, which individually are less than the level necessary to damage the material. The fatigue introduced by the stress repetition or reversal would lead to failure of materials with lower resistance to fatigue. For example, in a comparative test of nylon and a polycarbonate material, both of which exhibit strong single-impact strength, test samples were subjected to repeated impacts having a magnitude of 6% of that necessary to fracture the material in a single blow. The polycarbonate material fractured on the 37th impact, but the nylon was unbroken after 250 impacts. (Ref. 2)

Resistance of nylons to fatigue and repeated impacts makes

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it an excellent material choice for hammer handles, automobile door latch parts, gears, and other machine parts. Additional applications include a textile machine shuttle made from nylon 6/6 and a backing plate for a printing press made from a terpolymer, which includes nylons 6, 6/6, and 6/10.

8-1.3 LOW FRICTION

The low coefficient of friction of nylon with other metals makes it an excellent choice for bushings, bearings, sprockets, gears, cams, guides, and other similar applications with or without lubricants. Its low friction without lubricants allows its use where lubricants could contaminate other materials, such as in food processing. Bearing capacity is increased by reinforcing the nylon with metal or using the nylon as a coating over a stronger substrate.

The already low coefficient of friction can be reduced even further by addition of modifiers to increase the natural lubricity of nylon. These modifiers include molybdenum disulfide, graphite, and polytetrafluoroethylene (PTFE) resin. For example, addition of molybdenum disulfide to nylon 6/6 for use in the handrails of escalators reduces the coefficient of friction by a third in comparison to components made from the unmodified nylon material.

8-1.4 ABRASION RESISTANCE

When their *PV* (pressure \times velocity) limitations are not exceeded, nylons exhibit very good resistance to wear, and moderate abrasion does not generate a residue of ground nylon that contaminates lubricants or products being processed. Example applications in which the abrasion resistance of nylon can be used to advantage include sliding wear plates (gibs) used in elevators, guide tubes for abrasive yarns in textile mills, coatings for automotive timing gears and machinery parts, and wire jackets.

The elevator gibbs are pads located on the sides of elevators that ride against vertical metal rails affixed to the sides of the elevator shaft. The gibbs keep the elevator aligned in the shaft and prevent tilting when it is unevenly loaded. Nylon gibbs have replaced metal and synthetic rubber gibbs used in the past and eliminated the need for lubrication other than an annual application of a rust-inhibiting coating to the metal parts. The nylon parts slide for thousands of miles before replacement is necessary.

Some timing chain sprockets in automobile engines have nylon 6/6 teeth molded onto an aluminum hub. The aluminum provides the rigidity to the gear, and the nylon allows quieter operation and minimizes the wear to both the gear and the metal chain that runs around it. A similar gear construction is used in food processing conveyers, except that nylon 6/10 is used because of its low water absorption. In the latter application no lubrication is allowed because it would contaminate the food being processed, and the nylon allows long-term operation without lubrication.

In the manufacture of carpets 6.4-mm (0.25-in.) tubes are used to guide the carpet fibers from the spools to the tufting

machine over distances of about 30 m (100 ft). The nylon withstands the abrasion of the carpet fiber and shows no significant wear after five years. Nylons 6/10 and 6/12 are used in this application because they are less likely to swell; swelling would buckle the tubing and increase the tension of the yarn.

Nylons 6, 6/66 copolymer, 6/10, and 6/12 are used as a jacket over softer wire insulation materials, such as polyvinyl chloride. The tough outer layer of nylon allows a smaller overall diameter of the insulated wire with no sacrifice in protection. This smaller diameter allows wiring to be more densely installed in conduit, and the lower friction of the nylon makes installation easier.

Using nylon 11 to coat the sliding components of a slip spline used in the driveline of a truck increases the life of those components by a factor of eight. The resiliency of the nylon coating allows a more even distribution of force over the whole contact area between both parts of the spline assembly and thus prevents penetration of the film of lubrication applied to the splines and the accelerated wear which would accompany that.

Another application of nylon that illustrates its resistance to abrasion is the use of machined nylon for large screws used to slide bottles along a horizontal channel and position them for filling. The nylon material does not show any significant wear and does not mar the coatings of the containers being positioned.

8-1.5 RESISTANCE TO OILS AND SOLVENTS

Nylons are not significantly degraded by oils and solvents, except for strong acids. They absorb moisture and trace amounts of hydrocarbons, but as long as small dimensional changes can be tolerated, they are compatible with both. Also they have low permeability to gases.

A significant feature of nylon materials is their compatibility with lubricants and both ester- and hydrocarbon-based hydraulic fluids. This allows components fabricated with nylon to be used either in brake systems or in the engine drivetrain of vehicles. The elastomeric materials used in automotive hoses do not have this capability. If care is not taken to select a hose for a particular automotive application that is made from compatible material, disastrous results might occur. For pressurized automotive applications extruded nylon tubing made from plasticized nylon 66/6 copolymer is overbraided with wire or yarn to produce a flexible hose capable of high-pressure operation over a wide temperature range. Tubing of this construction can be used for hydraulic lines, air-conditioning hoses, fuel lines, or oil lines and can reduce the inventory of parts necessary.

Nylons 6 and 11 can be used for rotational molding of fuel tanks for vehicles in any shape and produce a tough, flexible tank that is not affected by the fuel it contains.

The imperviousness of nylon to grease and fats and its low permeability to oxygen make it excellent material for films used to protect food products. Sealed nylon containers can be

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used for unrefrigerated storage of processed food products. Its high-temperature capability allows food packaged in nylon bags to be cooked directly in the bag.

Nylons 6, 6/6, and 11 are also used to package mechanical parts that have been lubricated. The packaging material is not affected by the lubricant and completely contains it, and the toughness of the material prevents accidental tearing.

8-1.6 STABILITY AT HIGH TEMPERATURES

The stability of nylon at high temperatures makes it an obvious material choice for applications requiring a tolerance for heat without degradation of mechanical properties. Examples of applications that take advantage of the high-temperature capability of nylon include cooking utensils, handles for pans, cooking bags, dishwasher parts, coil forms for coils subject to heating from current flow, and oil seals for automobile engines.

The resistance to heat together with the freedom from toxic additives make nylon materials ideal for use in cooking utensils, especially for parts that contact food. Kitchen utensils such as spatulas, spoons, and bowls can withstand many cycles of use in hot grease and hot detergent solutions. Handles for pans are made of glass-reinforced nylons because of their ability to remain stiff when exposed to high temperatures and their tolerance of grease. Nylon bags used to package food allow sterilization after the product is packaged. Also meats and poultry can be cooked in similar bags.

The combination of resistance to heat and high electrical resistance allows nylon to be used for coil forms or bobbins when electrical current flow may heat the coil hot enough to soften other insulating materials. These forms are usually made from nylon 6/6 treated with an antioxidant. If high-temperature operation is expected, glass reinforcing can be used to enhance the rigidity of the material at higher temperatures.

Oil seals must withstand the temperatures of the upper part of an automobile engine without degradation. Glass-reinforced nylon treated with an antioxidant is used for this application.

8-1.7 RESISTANCE TO CREEP OR RELAXATION

The amount of permanent deformation induced in a nylon component depends on the level of applied stress, the duration of its application, and environmental factors, the most important of which is temperature. Stress levels that are too low to cause immediate permanent deformation may lead to deformation if applied over a long period of time. The distortion is referred to as creep because of the gradual rate at which the deformation takes place.

Resistance to creep is generally required in conjunction with other characteristics. For example, sealing of liquid butane containers is performed by crimping a sheet metal cap over a nylon cylinder. The cylinder material must be resilient so that it seals to the crimped cap and does not fracture during the crimping operation. It also must not deform under the

continuing pressure of the cap or leaks will develop. Other applications for which resistance to creep is desired include nylon casters or wheels that are moved infrequently. Rigidity is required for the wheels to support the load, and resistance to creep is necessary to prevent the development of flat spots when the wheels are not moved for a period of time.

8-2 TYPICAL APPLICATIONS OF NYLONS

The nylons have offered an ever-broadening set of property combinations that have spurred steady growth in spite of a constant increase in the number of materials competing. Table 8-2 lists areas of nonmilitary-specific application of nylons. Military applications are covered in par. 8-3.

TABLE 8-2. NYLON APPLICATIONS (Ref. 1)

<u>Appliance</u>	<u>Electrical</u>
Laundry equipment	Industrial controls
Cooking equipment	Wiring and associated devices
Dishwashers and garbage disposals	Industrial connectors
Cooling equipment	Batteries
Consumer electronics	Telephone parts
Housecleaning equipment	Switches
Small kitchen appliances	
Sewing machines	<u>Hardware</u>
Personal care and grooming appliances	Furniture fittings
	Door and window fittings tools
<u>Automotive</u>	Lawn and garden implements
Chassis parts	Boat fittings
Power plant	
Decorative body parts	<u>Packaging</u>
Functional body parts	Aerosols
Electrical parts	Film and coated substrates
Fuel system	
Heating, ventilation, and air-conditioning	<u>Machinery</u>
Accessories	Agricultural
Lamp lenses	Mining and oil drilling
	Food processing
<u>Business Equipment</u>	Printing
Business machines	Textile processing
Vending machines	Pumps, valves, meters, filters, and air blowers
Office equipment	Material handling equipment
<u>Consumer Products</u>	Standard components
Kitchen utensils	gears
Toys	cams
Sporting goods	sprockets
Apparel fittings	bearings
Personal accessories	gaskets
Photographic equipment	pulleys
Musical instruments	brushes
Brush bristles	
Film for cooking	
Fishing line	

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8-2.1 AUTOMOTIVE USES

In the automotive industry nylons are used in a number of mechanical parts, including distributor gears, speedometer gears, windshield wiper gears, light-load bearings and cams, and clutch and brake pedal bushings.

A one-piece speedometer takeoff gear and shaft has been made possible by the use of nylon. The complete unit, including teeth, is injection molded in one operation. This part formerly required five production steps. A significant reduction in cost is achieved, and performance superior to that of the unit replaced is provided.

Such electrical parts as fuse holders and insulating bushings are made of nylon because it combines insulating properties with mechanical strength and heat resistance.

A number of automobiles have lenses made of nylon in overhead and other interior lamps. Its toughness and ability to be molded in very thin sections enable lenses of only 0.64 mm (0.025 in.) thick to withstand rough treatment in both assembly and service. The flexibility of the lenses permits them to be snapped into place easily without the use of gaskets required for lenses of more rigid materials. Nylon withstands the heat from the lamp and will not yellow with age.

8-2.2 TEXTILE MACHINERY USES

In many textile machinery parts nylon requires no lubrication; thus it eliminates a particularly troublesome problem. In these and other uses nylon provides economy, either in the initial part or in terms of long life with reduced maintenance costs.

The nylon bearings on the take-up rolls of yarn-twisting machinery run without oil and have shown no wear after years of continuous use. As a result, the yarn being handled stays free of spattered oil or metal particles from worn bearings.

Other uses of molded nylon in textile machinery include thread guides of many types, parts for drafting and spinning equipment, looms, and winding machines.

8-2.3 HOUSEHOLD APPLIANCE USES

Nylon is used in a large number of household appliances. The major advantages to such use are long life, quiet operation, ability to be operated with little or no lubrication, and economy.

Nylon gears used in a high-quality eggbeater were proved in tests to last 20 times as long as the metal gears previously used. The nylon gears are unaffected by salad oils and various other materials with which they come in contact, and they operate efficiently without the use of lubricants.

Rollers and slides made of nylon for drawers in kitchen cabinets and stoves use no lubrication and provide quiet and easy operation. In most cases tests indicate that these parts will operate smoothly for the life of the equipment.

A key part of many electric shavers is a connecting rod, which transmits power from the motor to the cutting blade. Molded of nylon, the part reciprocates at speeds from 15,000 to 17,000 half-cycles per minute with an almost negligible

amount of lubrication applied at the factory. The nylon part absorbs vibration and shock and gives long, trouble-free service.

Other uses of nylon in household equipment include mixing machine gears, washing machine parts, fan parts, refrigerator door rollers, cutlery handles, and rollers and slides for windows and drapes.

8-2.4 OFFICE EQUIPMENT USES

Parts molded of nylon have been widely adopted in business machines. In one calculating machine, nylon dials, ratchets, and cams give more durable service than the parts they replaced, eliminate the need for lubrication and subsequent dial cleaning, and provide quieter, smoother operation. An intricate cam formerly required 20 production steps; the cam presently used is made of nylon in a single injection-molded shot. Nylon is also used for the drawers of many types of cabinets and desks.

8-2.5 ELECTRICAL COMPONENT USES

Nylon is used in the electrical industry for molded components and jacketing on wire and cable. In most cases nylon is used primarily because of its toughness, abrasion resistance, heat resistance, and insulating properties.

Coil forms comprise a particularly important use of nylon. Strength in very thin sections, ability to be molded into intricate shapes, and heat resistance are the major reasons for this use. Because of its toughness, nylon coil forms will not break in the winding operation.

For certain aircraft many miles of cables jacketed with nylon are used in each airplane. These cables include low-voltage wires, coaxial cables, and transmission lines. The nylon jacketing provides protection against high-octane gasoline and oil and outstanding resistance to abrasion (as demonstrated by its use in military and civilian field-wire jacketing). Nylon also protects against fungi, increases the heat resistance of the cable, and reduces plasticizer volatilization from the primary insulation. Its toughness permits the use of thinner coatings. Jackets on these cables range from 0.13 to 0.46 mm (5 to 18 mil) in thickness. The thin coatings, coupled with low specific gravity, permit important savings in weight. Nylon also has good flexibility, even at temperatures below -51°C (-60°F).

Other electrical uses of nylon resins include strain-relief grommets, wire connectors, switch components, insulated tools, and mechanical parts.

8-2.6 OTHER INDUSTRIAL APPLICATIONS

Nylon has a number of other industrial uses, including faces for soft-impact hammers used in metalworking, pressure gage parts, valve seats, telephone equipment, battery cases, and gears, cams, and bearings for cameras and projectors.

The use of molded nylon for the battery case of the lamp on a miner's cap has permitted the manufacturer to design a 4-cell model with no appreciable increase in size or weight

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over the 3-cell unit. Nylon provides insulation between the cells of the battery and is unaffected by the electrolyte solution. As an outer case nylon combines light weight and compactness with resistance to abrasion, impact, and corrosive mine waters. Nylon has solved a particularly troublesome problem involving check valves in the hydraulic lift of a farm tractor. Because of its resiliency, the nylon check valve provides a tight seal, even if there are slight imperfections in the mating surface. It does not become worn or grooved after repeated contact with the bushing, it withstands the high temperature of the oil in the system, and it retains its dimensions. The part is injection molded in one piece and needs no machining to provide a smooth seat within close tolerances.

8-2.7 MEDICAL AND PERSONAL APPLICATIONS

Because of its toughness, physiological inertness, and ability to withstand repeated sterilization in a steam autoclave, nylon is used in a number of medical applications, including hypodermic needle parts, parts for blood transfusion kits, inspiratory valves, and surgeons' scrub brushes.

Nylon is also used in combs, brush backs, tumblers, and table utensils. Buttons and zippers of nylon are tough, colorful, and resistant to dry-cleaning solvents and ironing.

8-3 MILITARY APPLICATIONS

Conventional equipment in military service uses nylon. These items include appliances, automotive vehicles, electrical components, hardware, packaging, general consumer products, aircraft parts, and mechanical components listed in Table 8-2. Specific military applications of nylon are in Table 8-3.

TABLE 8-3. MILITARY APPLICATIONS USING NYLON

The military applications of nylons include many of the applications already listed in Table 8-2 in one capacity or another, plus applications in current weapons systems, training rounds, and training systems. These include

- Boat hulls and masts
- Cartridge cases
- Obturator
- Rotating bands
- Sabots
- Handguards for small arms weapons
- Butt plates for rifles
- Magazines for ammunition
- Coatings for metal bipods on submachine guns
- Training and practice munitions and related training aids, which include
 - Targets
 - Scoring devices
 - War game paraphernalia
 - Computer-aided instruction devices

When materials are selected for military hardware, consideration must be given to the environments to which the item is to be subjected; these environments may vary considerably from the environments encountered for civilian applications. Table 8-4 (Ref. 3) lists the environmental conditions (parameters) to which military material may be subjected during its lifetime. It is extremely important that the environmental conditions in Table 8-4 be considered when nylon ma-

TABLE 8-4. MILITARY ENVIRONMENTAL CONDITIONS (Ref. 3)

PARAMETER	REMARKS
Storage	Required shelf life may extend to 10 yr at controlled conditions of 29°C (85°F) and 70% relative humidity in a dark container.
Temperature	Environment for extended periods may be 49°C (120°F) at 50% relative humidity and/or -54°C (-65°F), which encompasses both storage and operational conditions. Temperatures in short-term storage may reach 74°C (165°F).
Vibration	Item will be subjected to vibration during transportation, handling, and use.
Acceleration	Item will be subjected to acceleration when used.
Humidity	Item will be subjected to humidity during manufacturing and assembly and will be subjected to humidity extremes unless packaged within a sealed container.
Shock	Item will be subjected to shock loads during transportation and handling and in operation.
Operation	Most applications, e.g., fuzes and timers, require one-time operation for very short periods. Possibility exists for applications requiring continuous operation. Loading conditions or load capacity varies with application and should be considered accordingly.
Compatibility	Material must be compatible with environmental media, i.e., solvents, explosives, propellants, chemical warfare agents, decontaminants for agents, etc.
Fatigue	In applications involving continuous operation, fatigue factors are considered.
Other	Item will be subjected to aging factors and environments that affect plastic materials: sunshine, radiation, and general weathering. Related to these are materials characteristics such as creep, cold flow, and dimensional stability.

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materials are examined for use in military weapons systems and munitions, e.g., large caliber, small caliber, small arms, and training or practice ammunition.

8-3.1 LARGE CALIBER AMMUNITION

Some current uses for nylon include obturator bands for the 105-mm and 120-mm discarding-sabot antitank rounds. Nylon is the only current plastic material to qualify for use at the extreme temperatures and high rates of loading experienced in the gun tube. Nylon also has the ability to break up into nonlethal pieces upon sabot discard once the round leaves the gun tube. For obturator materials the 105-mm round uses a centrifugally cast and machined nylon 6/6, and the 120-mm round, an extruded and machined nylon 6/12. The nylon obturator for the 105-mm round is designed so the fin-stabilized projectile can be fired from either a smooth bore or rifled barrel. An injection-molded, 50% glass-filled nylon 12 is the only plastic material tested to date that has met the requirements for the MC/AAA 75-mm cartridge case. The toughness of nylon at the extreme temperatures of the test and its compatibility (Ref. 4) with M30 propellant, with which it is in direct contact, qualified it as the material of choice for this round.

Plastic rotating bands for use on the 203-mm (8-in.) spin-stabilized, extended-range-ammunition (ERA) projectile were evaluated as possible replacements for the metal bands (Ref. 5). These plastic bands were designed to obturate, impart proper spin, and disintegrate into nonlethal fragments at the gun muzzle. A nylon 6/12 and a nylon 12 were included in the test evaluation. The nylon 12 was of prime interest because of its good cold-temperature properties. The tests were conducted at -40°C (-40°F) and 60°C (140°F). Preliminary tests on these rounds with the nylon plastic rotating bands showed that the average particle size and velocity of the fragments from the discarding band pose no hazard to friendly troops downrange of the firing piece, that certain plastic designs tested are far superior in obturation to a metallic band with or without an obturator, and that nylon rotating bands will substantially reduce gun wear when compared to barrel wear caused by copper-banded projectiles. Nylons 6/12, 11, and 12 have also been successfully used as rotating bands by the Air Force (the 30-mm GAU-8 cartridge) and the Navy (a high-fragment projectile) (Ref. 6).

8-3.2 SMALL CALIBER WEAPONS

Nylon parts for small arms, small caliber weapons, have also become universally accepted because of their good performance under extreme conditions of temperature and rough handling in the field. Their cost, availability, ease of fabrication, appearance, and feel also support their acceptance.

The use of nylon plastics for small arms (Ref. 7) includes unfilled plastic grips of nylon 6/6 or 6/12 for the US Army M9 9-mm Beretta Model 92F pistol. The Steyer Aug (Armeegewehr, i.e., Universal Army Rifle) SA (semiautomatic) uses a glass-reinforced nylon 6/6 stock. This nylon

composition met the requirements in deformation tests at temperatures up to 100°C (212°F) and in notched-bar impact tests at temperatures down to -40°C (-40°F). The carrying handle and tube sleeve of the M249, 5.56-mm light machine gun, squad automatic weapon (SAW), is a molded, unreinforced rigid nylon 6, and the butt filler, pistol grip, and handguard are a 30% glass-reinforced nylon 6. The butt stock and pistol grip of the M16A2, 5.56-mm US military rifle, is a molded, high-impact 33% glass-filled, lubricated, black-pigmented nylon 6/6, and the US assault rifle (AR)-18, 0.223-caliber weapon, has a stock made of nylon 6/6. A steel bipod that can be attached to the M16 is coated with a nylon 11 applied by the fluidized-bed technique. Metal surfaces coated with nylon are resistant to corrosion and have excellent abrasion resistance.

A nylon 6/12, Zytel[®] 158 by Du Pont, and a carbon-black-filled nylon 6/12, Zytel[®] 157 HSL BK-10 by Du Pont, were successfully used as rotating bands on 20-mm ammunition (Ref. 8). These nylon compositions were applied to the round by injection molding over the cleaned, primed, induction-heated steel interfaces of the projectile. The Zytel[®] 158 performed satisfactorily on projectiles without a band seat, whereas Zytel[®] 157 required a shallow band seat. Both materials were tested successfully at -54°C (-65°F), 21°C (70°F), and 71°C (160°F) at muzzle velocities up to 1220 m/s (4000 ft/s).

The feasibility of using plastic rotating bands on 25-mm ammunition was studied. The tests showed that nylon 6/12 without glass-fiber reinforcement performed exceptionally well throughout a wide temperature range. Glass-filled nylons 6/12 and 6/6, however, exhibited brittle failure and were unable to withstand the high-rate barrel-engraving loads (Ref. 9). The Naval Surface Weapons Center has published a general handbook on plastic rotating bands (Ref. 10). The emphasis in this handbook is on nylon 6/12.

8-3.3 TRAINING AND PRACTICE MUNITIONS

Plastics, particularly nylons, are used extensively in training munitions. They provide reduced costs, improved performance and safety characteristics, and add appropriate realism to the "service" item. Nylons 6, 6/6, 6/12, and 12 have been used in these munitions. Typical applications in which nylon has been used successfully for practice munitions are described in the following summary of relevant reports (Ref. 11):

1. Anonymous, "Shells and Bullets of Plastics—Here's Why", *Modern Plastics* 30, No. 12, 80-82, 186, 189 (December 1960).

This article makes reference to a caliber .38 training round, the body of which was molded from Zytel[®] 101 nylon 6/6 by Du Pont. These reusable nylon rounds successfully withstood hundreds of firings.

2. T. G. Stastny, Sr. and M. M. Rottenberg, *Development of a 20-mm Plastic Frangible Projectile*, AFATL-TR-74-53 (AAI-ER-7736), (US Government Only), AAI Corpo-

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ration, Cockeysville, MD, for US Air Force Armament Laboratory, Eglin Air Force Base, FL, February 1974.

A 43% glass-filled nylon 6/12 projectile with an integral rotating band was capable of being fired from a standard 20-mm Mann gun barrel at standard muzzle velocity (1006 m/s (3300 ft/s)). In all cases the frangible projectile performed well and broke up on impact.

3. M. G. Popik and R. W. Schnepfe, *Development of 20-mm and 30-mm Plastic/Aluminum Cartridge Cases*, AFATL-TR-72-201, AAI Corporation, Cockeysville, MD, for US Air Force Armament Laboratory, Eglin Air Force Base, FL, October 1972.

Basic feasibility was established for the 20-mm and 30-mm plastic/aluminum cartridge cases. The plastic body was an injection-molded part of 50% glass-reinforced nylon 12. Work on the 30-mm case was limited to Mann gun barrel firings, whereas the 20-mm case was fired in both a Mann gun barrel and an M61 automatic gun at a rate of 4300 rounds per minute. Satisfactory performance of the 20-mm case was established at temperatures of -54°C (-65°F), ambient, and 74°C (165°F) when fired in the M61 gun. Test firings of the 20-mm case in the M39 gun, however, were unsuccessful.

4. *20 mm Nonricochet Target Practice Ammunition*, AFATL-TR-78-26, (US Government Only), Aeronutronics Division, Ford Aerospace and Communications Corporation, Newport Beach, CA, for US Air Force Armament Laboratory, Eglin Air Force Base, FL, March 1978.

The rotating band used on this projectile was an injection-molded nylon 6/12. The projectiles were fabricated by a zinc die-casting method to lower manufacturing costs. The test results show that the accuracy of the shell was primarily a function of the type of rotating band and the band rifling configuration used. Projectile bodies were die-cast from zinc alloy 5 by using a permanent mold, and the nylon 6/12 rotating bands were injection molded on the projectile bodies.

5. *25-mm Plastic Telescoped Cartridge Case Development Program*, AFATL-TR-75-16, (US Government Only), US Air Force Armament Laboratory, Eglin Air Force Base, FL, January 1975.

This report describes a joint exploratory development program by the US Air Force Armament Laboratory and the US Army Armament Command to provide a 25-mm automatic cannon for tri-service application. The cartridge case and seal materials most compatible with the ballistic environment were Hüls 38% glass-filled nylon 12 and Zytel® 151 nylon 6/6 by Du Pont. The feasibility of a nylon cartridge case using molded propellants and a telescoped projectile was demonstrated successfully at ambient temperatures and at -54°C (-65°F). Experimental investigations showed that the cartridge case will withstand peak chamber pressures greater than 690 MPa (100,000 lb/in.²) and still extract from the gun chamber without difficulty. The chamber seal was observed to have a significant effect on ballistic performance, and a compatible nylon seal was demonstrated successfully

at peak chamber pressures up to 552 MPa (80,000 lb/in.²). The manufacturing feasibility of a zero-draft, injection-molded case was also demonstrated successfully.

6. W. L. Black, *Development of a Plastic Cartridge Case Utilizing a Low-Pressure Ballistic System for a Family of 40-mm Cartridges*, AAI-ER-7107, (US Government Only), AAI Corporation, Baltimore, MD, for Picatinny Arsenal, Dover, NJ, November 1972.

The objective of this program was to produce a practical design for a 40-mm cartridge case that could be molded in plastic. The case would replace the M-118 metal used in a family of 40-mm cartridges. A suitable design was achieved for the plastic cartridge case and the low-pressure ballistic system that performed as well as the current M-118 production cartridge case. Three nylon types were tested in this design: a 43% glass-filled nylon 6/12, a 40 to 45% glass-filled nylon 6/10, and a 40% glass-filled nylon 6/6. The former was selected as the prime material with nylon 6/10 as the alternate. The nylon 6/6 was inferior in moisture absorption and dimensional stability. The following handling and environmental tests from MIL-STD-331 were passed by the nylon cartridge cases:

- Vibration (Test 104, Procedure 1, ambient temperature only)
- Seven-Foot Drop Test (Test 111)
- Forty-Foot Drop Test (Test 103)
- Temperature-Humidity Test (Test 105).

7. W. L. Black, *Development of a Plastic Cartridge Case for the M406 Cartridge Utilizing a Unique Low-Pressure Ballistic System*, AAI-ER-6187, (US Government Only), AAI Corporation, Baltimore, MD, for US Army Armament Research and Development Command, Dover, NJ, April 1970.

Low-pressure ballistic systems allow for the use of relatively low-strength case materials. However, because of the thin section required where the case mates with the projectile, it was reasoned that a glass-filled, tough material was needed. A 40% glass-filled nylon 6/10 was selected. Firings of this material were successful and target velocities were attained.

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 9. *Final Report for Plastic Rotating Band Technology and Demonstration Program*, Ford Aerospace and Communications Corporation, Newport Beach, CA, 16 April 1979.
 10. R. J. Edwards et al, *Structural Technology for Rotating Band Evaluation (STROBE) Program—Plastic Rotating Bands—Handbook of Structural Analysis Methods and Material Properties*, Report PDA-TR-1438-00-05 (Revision B), Naval Surface Weapons Center, White Oak Laboratory, Silver Spring, MD, June 1982.
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Conditioning
Characteristics
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Environmental effects
Joining

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