MIL-HDBK-176
17 MAY 1972

MILITARY STANDARDIZATION HANDBOOK

GUIDANCE FOR FLEXIBLE FLAT MULTICONDUCTOR CABLE (FLAT CONDUCTORS)

FSC 6145

DEPARTMENT OF DEFENSE
WASHINGTON 25, D.C.

MIL-HDBK-176
Guidance for Flexible Flat Multiconductor Cable
17 May 1972

1. This standardization handbook was developed by the Department of Defense with the assistance of the National Aeronautics and Space Administration in accordance with established procedure.

2. This publication was approved on 17 May 1972 for printing and inclusion in the military standardization handbook series.

3. This document provides basic and fundamental information on FCC electrical interconnecting harnesses and manufacturing practices. It will provide valuable information and guidance to personnel concerned with the preparation of specifications and the procurement of FCC electrical interconnecting harnesses. The handbook is not intended to be referenced in purchase specifications except for informational purposes, nor shall it supersede any specification requirements.

4. Every effort has been made to reflect the latest information on FCC electrical interconnecting harnesses and manufacturing practices. It is the intent to review this handbook periodically to insure its completeness and currency. Users of this document are encouraged to report any errors discovered and any recommendations for changes or inclusions to U.S. Army Electronics Command, Attn: AMSEL-RD-ZS , Ft. Monmouth, N.J. 07703.

FOREWORD

The use of flat-conductor cable (FCC) offers technological and economical advantages. When the program managers and personnel responsible for the system design have properly evaluated the major FCC advantages of cost, space, and weight reductions, with increased system performance and reliability, the general use of FCC for both military and commercial programs will be assured. A number of independent surveys made by separate agencies have indicated that the use of FCC for interconnecting harnesses in all new design of aircraft, missiles, and ground equipment will be 40-55 percent by 1975.

FCC has seen limited use on many successful programs for a number of years. However, it is expected that, with its acceptance and general use, many new application techniques and hardware configurations will be developed.

New FCC technology has been reached. Even though the technology is still young, and much more is required for future development hardware and system application, the ultimate success of the system is assured.

This handbook is prepared for use by engineers, designers and technicians and is intended to serve as a text. The test presents pertinent information for hardware selecting, design, manufacture and quality control necessary for FCC interconnecting harness application.

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SECTION I. INTRODUCTION

1.1 General

This handbook was prepared from the National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC) technical memorandum X-53975. This memorandum was by McDonnell Douglas Corporation (MDC), Missile and Space Systems Division (MSSD).

1.2 Purpose

This handbook provides guidance in the design, manufacture, and quality control of FCC electrical interconnecting harnesses. Although this handbook is primarily for military applications, for both flight and ground support equipment, much of the information can be applied to commercial programs.

1.3 History

For many years, conventional round-wire cables (RWC) have been used for interconnecting components and electrical/electronic boxes in commercial, military, and scientific programs.

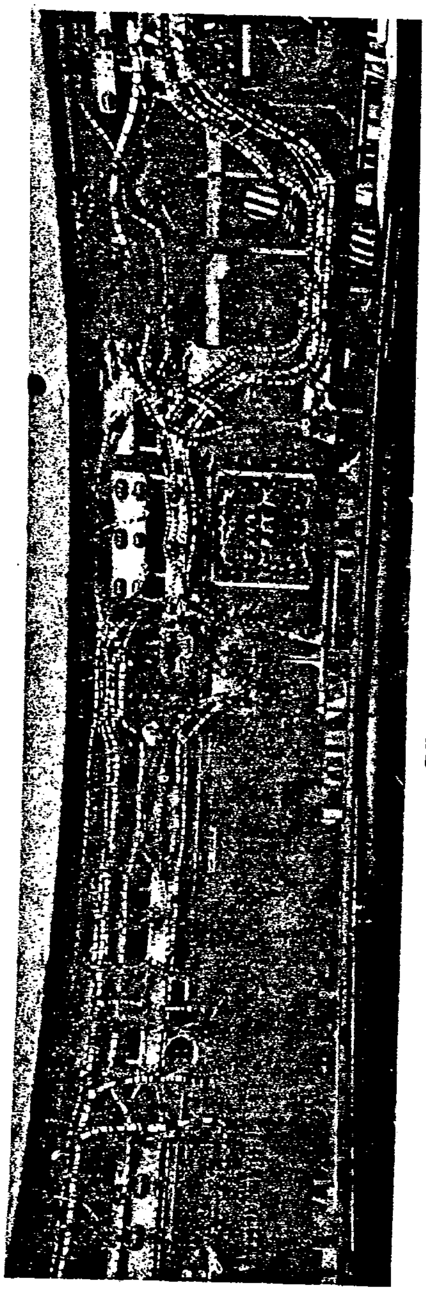
The 1950's saw the introduction of the rigid printed circuit (PC) board with its high packaging density, reduced costs, and improved reliability. The PC board provided the first significant step forward in the interconnection field. Its acceptance and success are now a legend.

Next came the flexible printed circuitry with solid rectangular conductors laminated between layers of high-performance insulation materials. This system is used extensively today for automobile dashboard wiring, computer section interwiring, and for many electronic packaging concepts used in space, missile, and aircraft systems. The flexible, printed-circuitry harnesses provide: reduced costs resulting from reduction of assembly times of up to 95 percent; major weight and space savings; and higher strength provided by the bonded, laminated insulating sheets, which in turn permits use of much smaller conductor cross-sections. Also, improvements in system performance and reliability are provided, resulting from the identity and repeatability of each harness and its installation.

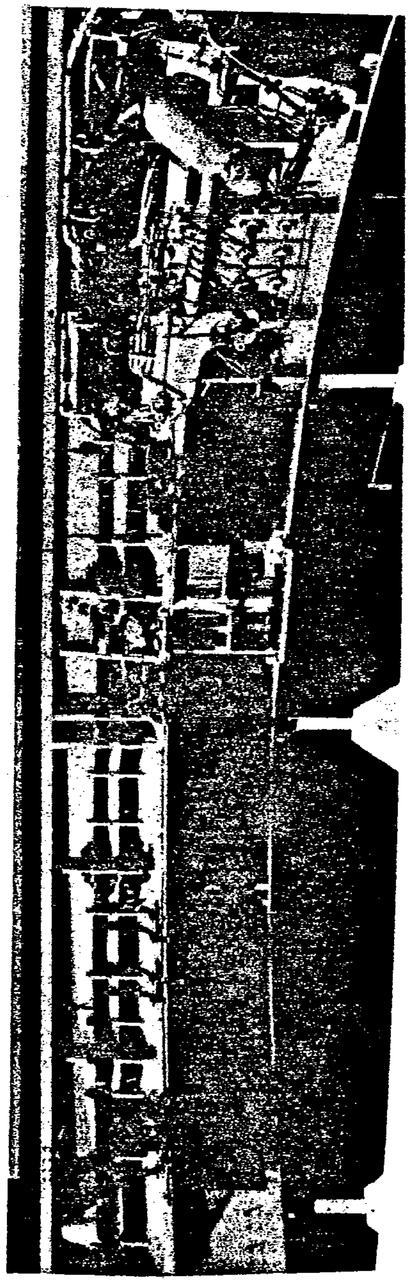
The use of continuous FCC to interconnect electrical/electronic units utilizing PC boards, flexible printed circuitry, and variations of these, logically follows the trend for improved interconnecting systems.

FCC development was begun in 1956 by the Army Ballistic Missile Agency at Redstone Arsenal, Huntsville, Alabama, in an effort to achieve weight and space savings, and increased reliability in rocket and missile cable systems. Effort has been continued by the same working group which has since been transferred to NASA/MSFC.

Figures 1-1 and 1-2 show the results of an FCC development study made by MDC for NASA/MSFC to determine the feasibility of using continuous FCC to interconnect electronic components in a modern space vehicle. The results of this study, an FCC applications study prepared by MDC for NASA/MSFC and other studies and applications indicate that the use of FCC offers many advantages in weight, space, cost, performance, and reliability for commercial, military, and space programs, for ground and airborne applications.



RWC INSTALLATION



FCC INSTALLATION

FIGURE 1-1. FCC versus RWC comparison, 180-degree section of Saturn S-IVB aft-skirt mockup.

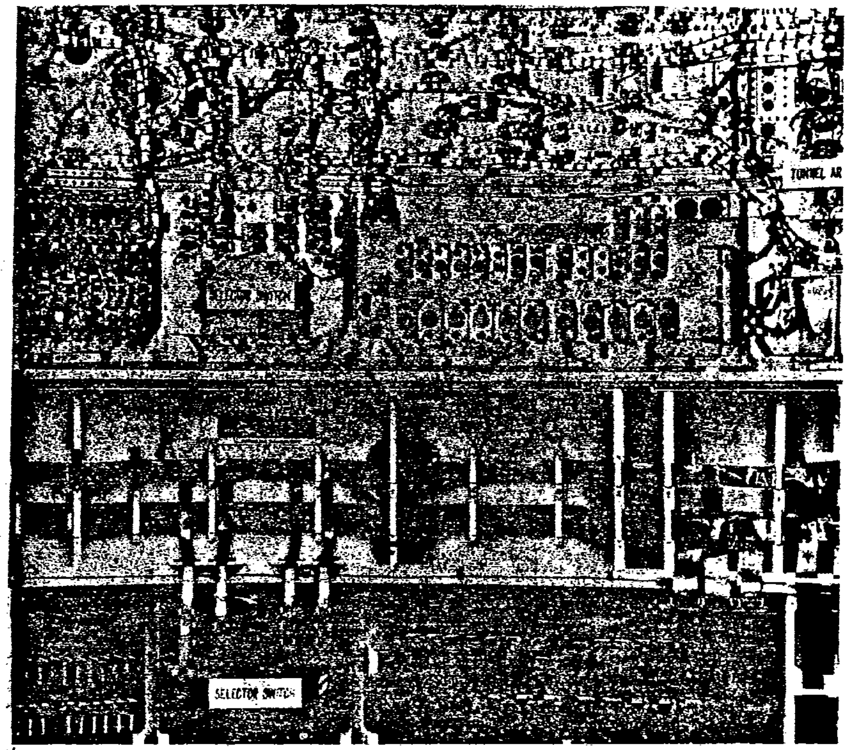


FIGURE 1-2. FCC versus RWC comparison, 60-degree section, Saturn S-IVB aft-skirt mockup.

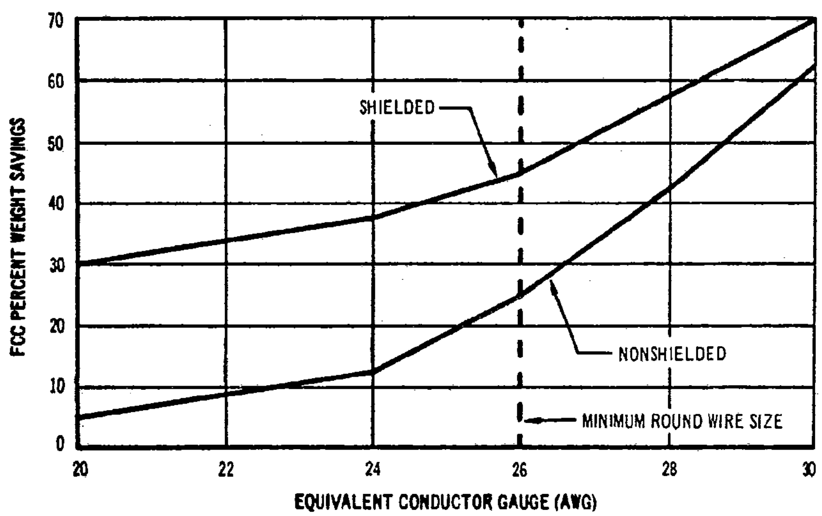


FIGURE 1-3. Weight-saving chart - FCC versus RWC.

1.4 FCC System Advantages

The FCC system offers appreciable advantages over the RWC systems in weight, space, and cost savings, as well as improved performance and reliability.

1.4.1 Weight Saving. From previous studies, the weights for FCC supports and clamps are considerably less than those used with RWC. This saving results primarily from cable stacking and simplification of clamping and supports for FCC. In addition, the NASA/MSFC conductor-contact connector system provides appreciable weight saving over the current miniature round connectors. However, the cable provides the major weight savings for the smaller conductors (Fig. 1-3). For comparison purpose, RWC per MIL-W-81381/2 with 7-mil H/film insulation and alloy conductors, and FCC cable per MIL-C-55543 were considered. High-density FCC was used for 20 and 22 equivalent AWG sizes. The FCC weight saving increases as the conductor cross-sections decrease. Future programs, with integrated circuit electronics, can be satisfied with wire-gauges of 26 and smaller in many circuits.

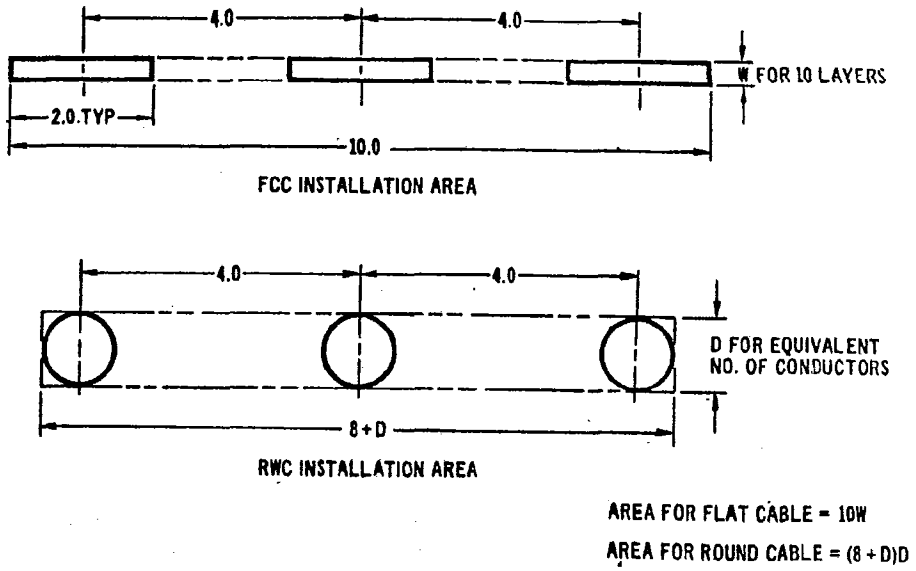
1.4.2 Space Saving. Figure 1-4 shows the space savings that can be achieved through the use of FCC. The areas compared are for typical interconnecting harnesses requiring three separate bundle runs. The 80 to 90 percent space savings shown are particularly advantageous in tunnel and other congested areas where a minimum height is available for harness runs. Major connector mounting-and-handling installation area savings are achieved by the FCC connector system. Figure 1-5 shows the area configurations, and Figure 1-6 shows the actual mounting and handling area required.

1.4.3 Cost Saving. To arrive at realistic cost comparisons, the cost of materials, design, development, harness fabrication, and installation must be considered. Table 1-1 lists these comparisons developed and verified by subsequent studies, and those performed by other agencies. The saving percentages shown are average and can vary from program to program. However, the 80 percent shown for recurring harness fabrication is realistic for all programs utilizing properly designed FCC systems.

TABLE 1-1. COST COMPARISON - FCC VERSUS RWC SYSTEMS

Item	Sub-item Percentage Of Major Item	FCC Cost Saving (%)[a]	
		Sub-item	Major Item
Engineering			-5
System	25	-10	
Harness Layout	25	-10	
Production Drawings	25	0	
Schematics, etc.	25	0	
Development			20
Materials			28
Cable	40	0	
Connectors	40	35	
Clamps	5	50	
Supports	15	75	
Harness Fabrication			80
Harness Installation			40

a. To realize the cost savings indicated, FCC must be applied early in the program to eliminate redesign, redevelopment, and requalification.



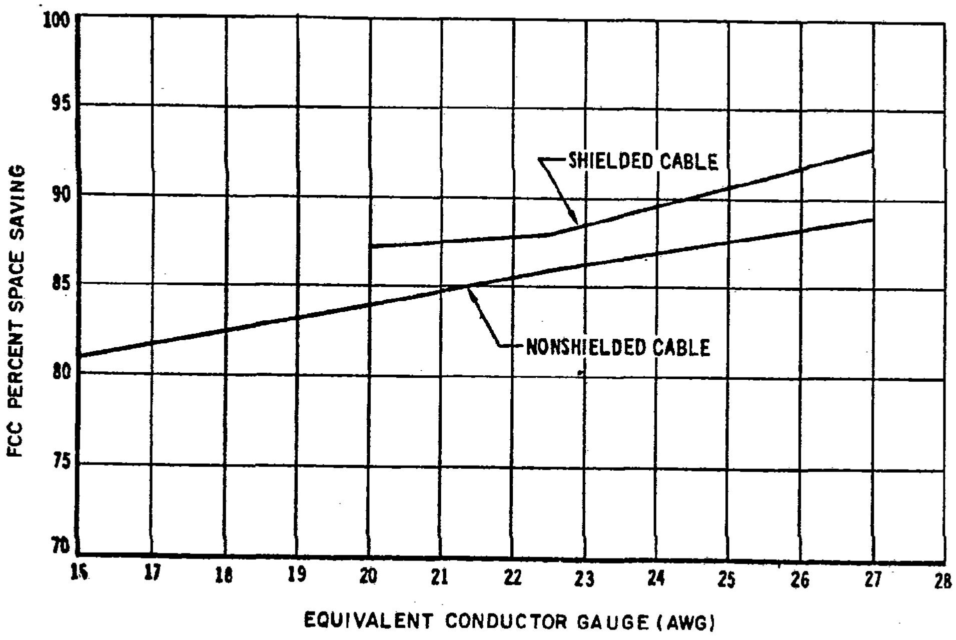
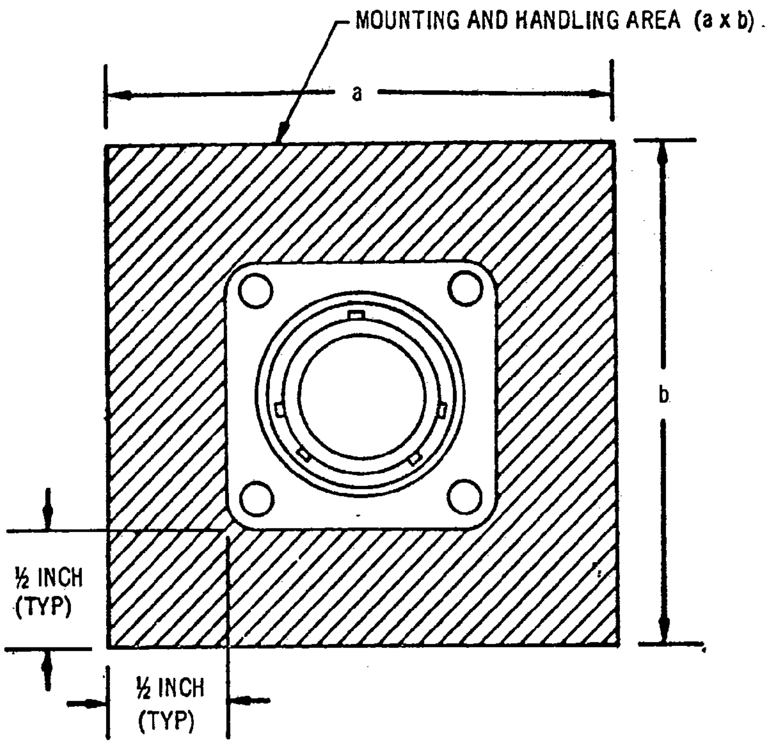
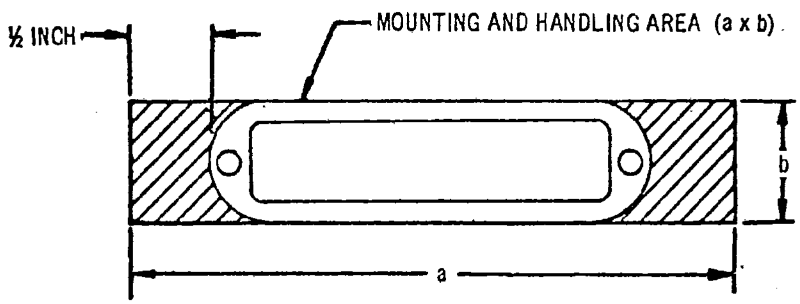


FIGURE 1-4. Space saving - FCC versus RWC.



RWC RECEPTACLE



FCC RECEPTACLE

FIGURE 1-5. Mounting and handling area configurations.

ROUND CONNECTORS	CANNON PV SERIES SHELL NO.	10	14	16	20	22	24	
	NUMBER OF PINS	6	12	26	39	55	61	
FCC CONNECTORS	NUMBER OF PINS	*6	*12	24	36	50	64	76

*NOTE: THESE CONNECTORS USE ROUND SHELL SIZES EQUIVALENT TO THOSE ABOVE.

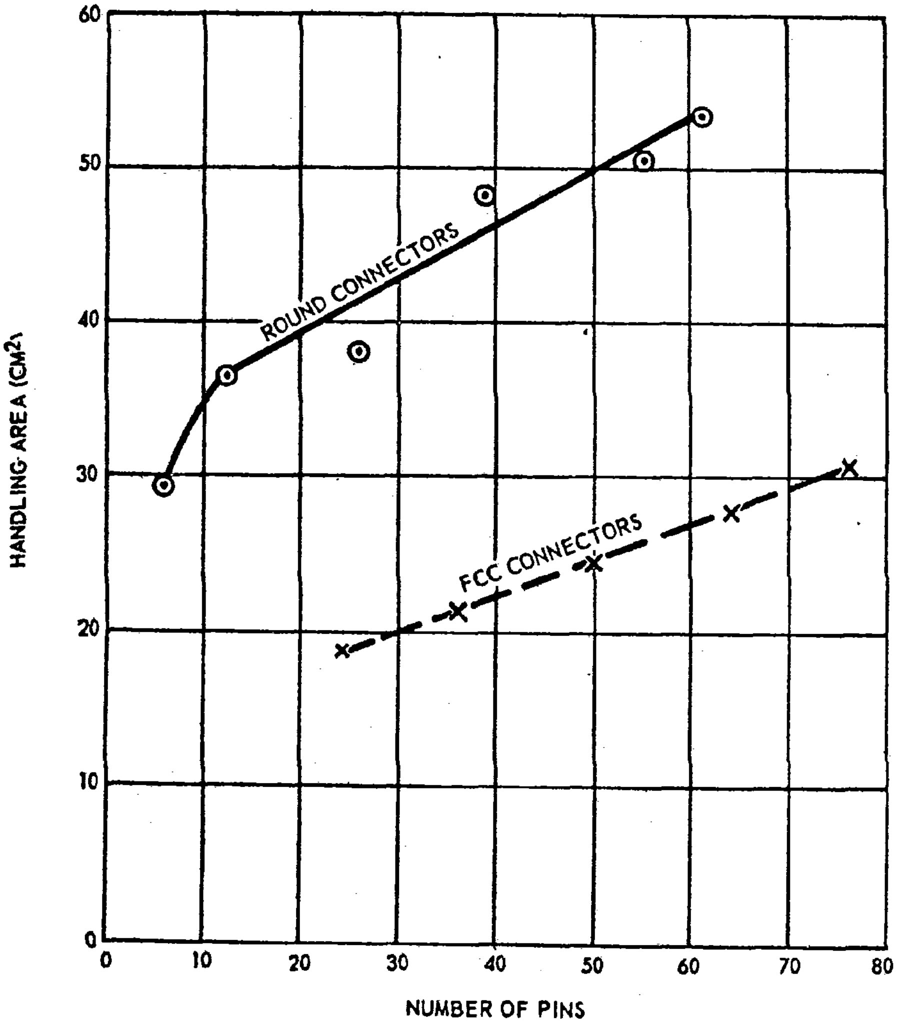


FIGURE 1-6. Mounting and handling area - FCC versus RWC connectors.

Figure 1-7 shows the cost comparison between FCC and RWC. The cables considered were the same as those used for the weight-saving comparison of Paragraph 1.4.1. The connector cost saving of 35 percent (Table 1-1) results primarily from the use of the NASA/MSFC molded-on plug assemblies.

1.4.4 Increased Thermal Capacity. Tests conducted by NASA/MSFC on both FCC and RWC equivalent bundles under ambient and vacuum conditions disclosed major thermal advantages for the FCC. The current-carrying capacity may be uprated for FCC for the same conductor cross-section as follows:

FCC Cable Configurations	Uprating Factor In Air	Uprating Factor In Vacuum
Single-Layer	1.50	1.55
Three-Layer	1.35	1.50
Ten-Layer	1.05	1.05

These tests, which are based on many electrical measurements, confirm the increased current-carrying capacity, or decrease in operating temperature, when equivalent conductor cross-sections are applied to the same electrical loads.

1.4.5 Improved System Performance. Major advantages in system performance can be realized through the use of FCC. The interconnecting harnesses can be designed for the required electrical characteristics that are predictable and repeatable. The control of the conductor cross-sections, their location in relationship to adjacent conductors, and the registration control of each cable in the interconnecting harness-runs provide the required system performance and assure repeatability from unit to unit.

1.4.6 Increased Reliability. The use of FCC for interconnecting harnesses provides increased reliability in a number of specific areas. The high tensile strength of the insulation layers and cable construction, which provides mechanical load-sharing, provides a major increase in effective strength. The percentage increase becomes even greater in the small conductor sizes. The abrasion resistance is greatly improved as a result of the geometry of the harness cross-section. The mechanized FCC termination system, made by cable layer, is simpler and more reliable, and quality control is much simpler. The FCC harness assemblies are simpler, lighter, and require less space. The improved heat dissipation assures lower operating temperature. System performance is improved as described in Paragraph 1.4.5.

1.5 Present Status of FCC

1.5.1 Specifications. Military specifications (MIL-C-55543 and MIL-C-55544) have been prepared and released for FCC and FCC connectors by the tri-service government agencies. Their issuance provided the program authority and the vendor guidance so badly needed in the past.

1.5.2 Available Hardware. Numerous manufacturers are currently making, or capable of making, FCC in accordance with the requirements of MIL-C-55543. Testing on typical, available cable has indicated that the specification requirements can be met. A complete line of conductor-contact connectors per MIL-C-55544 has been developed by NASA/MSFC. Tooling has been completed, and testing has been accomplished. Prototype samples of the pin-and-socket specification connector are currently undergoing evaluation testing. An FCC-to-RWC transition has been developed, tooled, and tested for use on the NASA/MSFC ATM program. Other wire-change devices, clamps, and supports have been developed for FCC use. All of the above are defined and further explained in Section II.

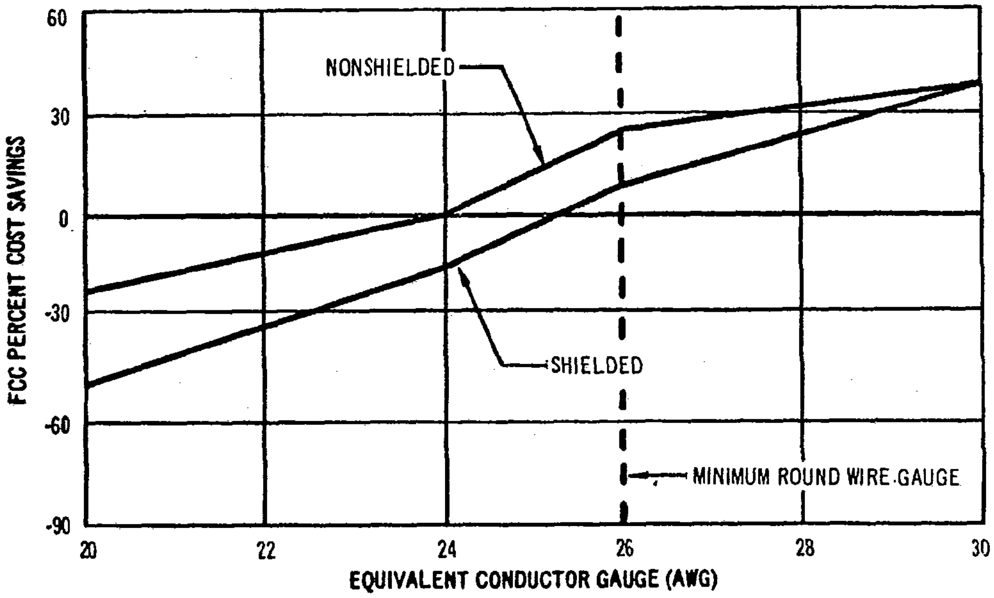


FIGURE 1-7. Cable cost saving — FCC versus RWC.

1.5.3 System Studies. MDC performed a development study and an application study for NASA/MSFC to determine the feasibility of applying FCC to a large missile stage.

The MDC Aircraft Division in St. Louis has prepared the functional FCC mockup shown in Figure 1-8. FCC was used to interconnect analog, digital, and high-frequency communication systems. Over 75 percent of the existing RWC shielding was eliminated, with a system performance equal to or better than that of the original RWC harnesses.

Lockheed Aircraft Corporation performed a similar study to determine the feasibility of using FCC harnesses in existing military aircraft. Their study indicated major weight and cost savings for the FCC system.

1.6 Predicted Future Use

The many advantages of the FCC system assure its increased use on future programs. Data from surveys made by various government, other prime contractor, and component manufacturer estimates indicate extensive use of FCC in the future.

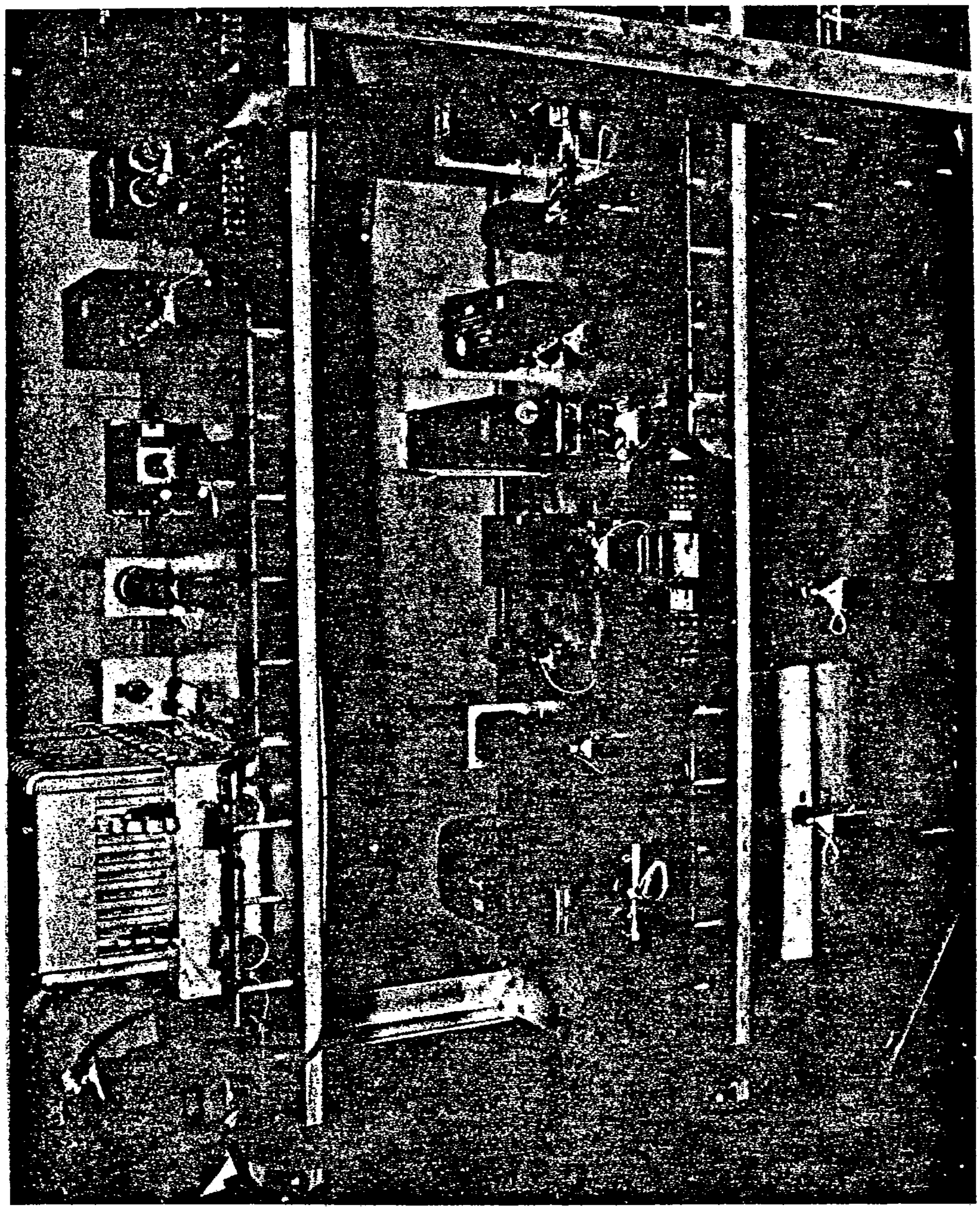


FIGURE 1-8. FCC harness installation for aircraft application evaluation (MDC).

1.7 Report Format

This handbook is divided into coordinated sections to provide the continuity required for overall FCC application. These sections are as follows:

Section I - Introduction and Familiarization

II - Hardware

III - Design Application

IV - Wiring Changes

V - Reliability

VI - Manufacturing and Installation Techniques

VII - Quality Assurance - Inspection and Test Procedure

The material presented covers the definition and application of current FCC systems including the NASA/MSFC and other conductor-contact connector systems and the pin-and-socket contact connector systems.

1.8 Trade Names

It is not the intent of this handbook to endorse trade names. Those materials referenced herein, with manufacturer's name and trademark, are well suited for the particular applications specified. The use of these materials should not be limited to the trade name used, provided other materials of equal quality, and suited to the particular application, are available.

SECTION II. FCC HARDWARE

2.1 Introduction

This section includes descriptive data on cable, plugs and receptacles, circuit change devices, fasteners, support brackets, and adhesives and tapes for use with FCC electrical interconnecting harnesses. MIL-C-55543, "Military Specification, Cable, Electrical, Flat Multiconductors, Flexible, Unshielded" and MIL-C-55544, "Military Specification, Connectors, Electrical, Environment Resistant, for use with Flexible Flat Conductor Cable, General Specification" may be used to complement this handbook.

Both nonshielded and shielded FCC are discussed. A military specification for shielded FCC will be available soon. The MIL-C-55544 NASA/MSFC conductor contact and the Picatinny Arsenal pin-and-socket contact connectors are included, as well as information on other existing, prototype, and proposed FCC connector systems.

Where applicable, part numbers and sources are given. In other instances, the information is general in nature to aid the designer in preparing drawings for the required hardware.

2.2 Cable

2.2.1 General Description. FCC is made up of solid, flat, rectangular conductors - usually bare or plated copper, but other conductor materials such as aluminum can be used - laminated between layers or sheets or high-performance insulating materials.

Figure 2-1 shows typical cross-sections of various nonshielded FCC constructions. The most widely used construction is the symmetrically laminated form (No. 1) with the individual conductors sandwiched between the plastic insulation sheets. An adhesive is used to keep the conductors properly spaced and to assure the integrity of the FCC when exposed to the various operating conditions. The extruded form (No. 2) is made with individual conductors similar to those used for the laminated construction. The insulation is applied by the extrusion process. This method would generally be applicable to ground application or for special electrical requirements where the weight of the added insulation thickness would be acceptable. Preinsulated and laminated (No. 3) is manufactured by the standard laminating process, except the conductors are first coated with an insulating varnish. This allows the conductors to be laminated in close proximity to each other while assuring maximum insulation integrity between adjacent conductors. FCC having etched conductors is shown in Nos. 4 and 5. Solid copper foil is bonded to the bottom insulation sheet, or the copper foil is spray or tower-coated with the insulation material. This assembly is then etched to provide the individual conductors. The top insulation layer is laminated (No. 4) or spray or tower-coated (No. 5) to complete the cable. Woven cable (No. 6) utilizes commercial weaving practices to apply the insulation thread, to space and securely hold the rectangular, solid conductors in place. The woven thread is later impregnated to provide a sealed and mechanically sound FCC.

Appendix III lists the various types of FCC cable described above, with names of vendors who have manufactured these types of cables (Appendix IV).

FCC can be further defined or categorized as standard-density and high-density low-power cables, power cables, and shielded cables. The power and shielded cables are covered in detail in subsequent paragraphs. The standard-density and high-density low-power cables are covered by the military specification sheets of MIL-C-55543. The standard-density FCC has a spacing between conductors of approximately 35 mils, while the high-density FCC has a spacing of approximately 10 mils.

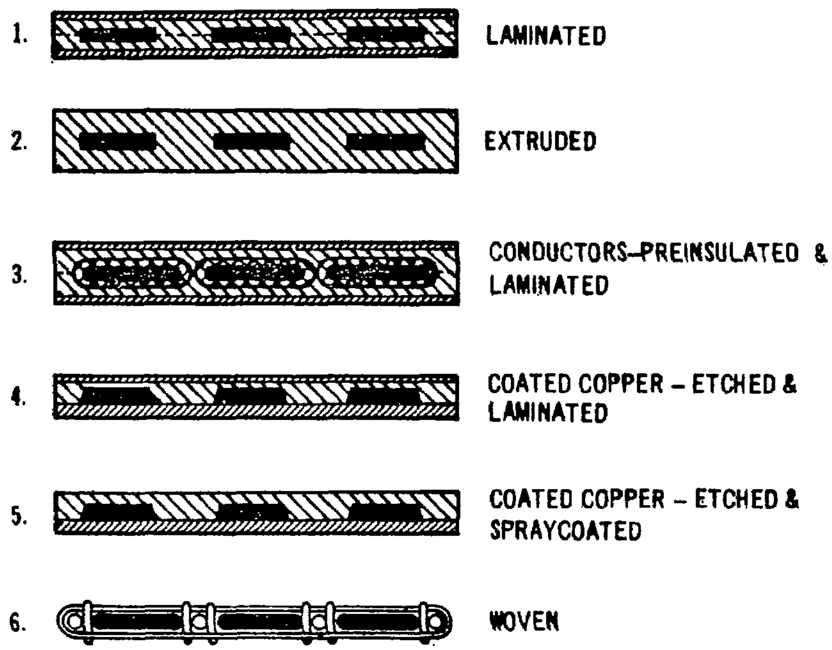


FIGURE 2-1. FCC cross-sections for various manufacturing methods.

2.2.2 Insulation Materials. The FCC system permits the use of many insulation materials in cable construction. Table 2-1 lists the detailed characteristics of many of the materials which have already been used or considered. An examination of Table 2-1 discloses the excellent comparative characteristic values of the polyester (Mylar[1]) and polyimide (Kapton[1]) which have been selected as the primary insulations for the MIL-C-55543 cable configurations.

Relatively low specific gravities of approximately 1.4 for weight reductions, high tensile strengths of approximately 20,000 psi, and high dielectric strengths of 7,000 volts per mil are among the more important characteristic advantages of these materials. The maximum service temperatures for polyimide (Kapton) and polyester (Mylar) are listed as 400°C and 150°C, respectively. When laminated into FCC with the required adhesives, the temperature rating of the finished cable is reduced to 200°C and 100°C, respectively.

Teflon[2], both TFE and FEP, has been used as the primary insulation on many FCC configurations. Specific electrical characteristics are achievable for special applications, and the improved flexing properties at extremely low temperatures are achievable. Both polyester (Mylar) and Teflon FEP can be used as heat-formable materials for making self-retractable corrugated and convoluted cable assemblies (Figures 3-77 and 3-78).

2.2.3 Conductors. Various types of conductor materials can be used successfully with FCC. Copper conductors, both bare and plated, have seen the most extensive use to date. For strip or laminated cable constructions, slit conductors in accordance with QQ-C576 and flattened round-wire conductors per QQ-W-343 or QQ-C-502 can be used. For etched conductor cable construction, soft or annealed, rolled copper foils or electrolytic deposited copper with a controlled minimum purity can be used. The copper conductors have been plated with nickel to improve resistance to oxidation at high temperatures, and to enhance subsequent termination processes.

The sealed construction of FCC makes the use of aluminum conductors feasible. Aluminum has a lower weight-per-conductivity ratio, is more economical, and is not affected by shortages or procurement priorities as copper often is. Aluminum conductors also have an improved resistance to nuclear radiation, which makes it a requirement on some programs.

Other conductor materials, such as iron and iron alloys for economy and special requirements, and special oxides for specific applications, are adaptable to the FCC constructions.

2.2.4 Nonshielded Cable.

2.2.4.1 General Description. The nonshielded FCC, as defined by MIL-C-55543, is suitable for aerospace, defense, and other government contracts requiring operation under various environmental conditions; minimum size with weight and space savings consistent with service requirements. Table 2-2 lists these various cable characteristics in comprehensive tabular form. It is anticipated that future revisions to MIL-C-55543 will add other insulation systems and conductor configurations; however, every attempt will be made to standardize a limited number of cable widths, insulation types, conductor spacings, and conductor sizes to eliminate an endless number of configurations and part numbers with their resultant problems in procurement and logistics. Similar cable with less stringent requirements have a very large application for commercial and less demanding programs.

The MIL-C-55543 specification has standardized on cable widths, conductor widths and thicknesses, number of conductors, and conductor centerline spacings. These data are tabulated in Table 2-3. Table 3-2 presents additional information on conductor cross-sections in square mils, nominal resistance, and resistance tolerances resulting from conductor cross-section tolerances. For resistance changes with conductor temperatures, use the correction factors from the curve of Figure 3-6.

1. Trademark E. I. Dupont de Nemours and Co., Inc.
2. Ibid.

TABLE 2-1. DETAILED CHARACTERISTICS OF VARIOUS INSULATIONS

Characteristic	TFE Teflon[a]	FEP Teflon[a]	Kapton[a] Polyimide	CTFE[b]	PVF Tedlar[a]	Polypropylene	Mylar[a] Polyester	Polyvinyl-Chloride	Polyethylene
Specific Gravity	2.15	2.15	1.42	2.10	1.38	0.905	1.395	1.25	0.93
Flammable	No	No	Self-Ext	No	Yes	Slow Burning	Yes	Self-Ext	Yes
Appearance	Translucent	Clear Bluish	Amber	White & Opaque	Clear	Clear	Clear	Translucent	Clear
Bondability with Adhesives	Good[c]	Good[c]	Good	Good[c]	Good[c]	Poor	Good	Good	Poor
Bondability to Itself	Good	Good	Poor	Good	Good	Good	Poor	Good	Good
Chemical Resistance	Excellent	Excellent	Excellent	Excellent	Good	Good	Excellent	Good	Good
Sunlight Resistance	Excellent	Excellent	Excellent	Excellent	Excellent	Low	Fair	Fair	Low
Water Absorption (%)	<0.01/24 hr	<0.01/24 hr	3/24 hr	0	0.5/2 hr	0.01	0.8/24 hr	0.10	0.01/24 hr
Volume Resistivity ohm - cm	>10^{18}	>$2x10^{18}$	10^{16}	$3.1x10^{16}$	$3x10^{13}$	10^{16}	10^{18}	10^{10}	10^{16}
Dielectric Constant 10^2 - 10^8 Hz	2.2	2.1	3.5	2.5	7.0	2.0	2.8 - 3.7	3.6 - 4.0	2.2
Dissipation factor 10^2 - 10^8 Hz	$2x10^{-4}$	$.4x10^{-4}$ $7.7x10^{-4}$	$3x10^{-3}$ $14x10^{-3}$	$15x10^{-3}$	$9x10^{-3}$ $41x10^{-3}$	$2x10^{-4}$ $3x10^{-4}$	$2x10^{-3}$ $16x10^{-3}$	$14x10^{-2}$	$6x10^{-4}$
Service Temperature									
Minimum (°C)	-60	-60	-60		-70	-55	-60	-40	-20
Maximum (°C)	250	200	400		105	125	150	85	80
Tensile Strength									
psi @ 25°C	3000	3000	25000	4500	13000	5700	20000	3000	2000
$N/m^2 \times 10^8$ @ 25°C	0.2067	0.2067	1.697	0.31	0.8825	0.3927	1.378	0.2067	0.1378
Modulus of Elasticity									
psi	58000	50000	510000	190000	280000	170000	550000		50000
$N/m^2 \times 10^8$	3.930	3.394	34.623	12.90	19.29	11.913	37.895		3.445
Thermal Expansion	(-30°C to 30°C)	(-30°C to 30°C)	(-14°C to 38°C)	(-195°C to 90°C)	(-30°C to 30°C)	(-30°C to 30°C)	(21°C to 50°C)		(-30°C to 30°C)
in./in./°F$x10^{-6}$	55	50	11	48	28	61	15	d	100
cm/cm/°C$x10^{-6}$	100	90	20	82	50	110	27		180
Dielectric Strength Volts/mil	800	3000	3600	2000	2000	750	3500	800[d]	1500
Sample Size (mils)	5	5	5	5	5	125	5	5	5

Notes: a. Trademark, E. I. Dupont de Nemours & Co., Inc.
b. Trademark, Minnesota Mining and Manufacturing Co., Inc.
c. Must be treated.
d. Depends on formulation (plasticizer)

The conductor temperature rise versus current for 1-, 3-, and 10-layer, 2-inch-wide cables with 4- by 40-mil conductors on 75-mil centers is shown in Figure 3-10 for operation in air, and Figure 3-11 for operation in vacuum. Table 3-3 gives correction factors for other conductor cross-sections and centerline spacing configurations.

2.2.4.2 Specification Requirements. Detailed specification performance requirements are given by MIL-C-55543. The military specification sheets define the various cable types or configurations as defined by Table 2-2.

In general, the specification dimensional tolerances are: ±5 mils for cable widths; ±5 mils for cable margin, the distance between the edge of the cable and outside edge of the outer conductor; ±5 mils noncumulative for conductor centerline spacing on standard density and ±2 mils for high density; ±1 mil for cable thickness; ±0.4 mil for conductor thickness; and ±2 mils for conductor width.

TABLE 2-2. MIL-C-55543 CABLE CONFIGURATION

Military Specification Sheet No.	Insulation	Conductor Plating	Cable Construction (Copper Conductor)	Voltage Rating (V)	Maximum Operating Temperature (° C)	Conductor Configuration (Density)
MIL-C-55543/1	Polyester	Nickel Plated	Strip	300	100	Standard
MIL-C-55543/2	Polyester	Nickel Plated	Strip	300	100	High
MIL-C-55543/3	Polyimide/FEP	Nickel Plated	Strip	300	200	Standard
MIL-C-55543/4	Polyimide/FEP	Nickel Plated	Strip	300	200	High
MIL-C-55543/5	Polyimide-Type Homopolymer/FEP	Bare	Etched	300	200	Standard
MIL-C-55543/6	Polyimide-Type Homopolymer/FEP	Bare	Etched	300	200	High
MIL-C-55543/7	Polyester	Bare	Strip	300	100	Standard
MIL-C-55543/8	Polyester	Bare	Strip	300	100	High
MIL-C-55543/9	Polyimide/FEP	Bare	Strip	300	200	Standard
MIL-C-55543/10	Polyimide/FEP	Bare	Strip	300	200	High
MIL-C-55543/11	FEP	Nickel Plated	Strip	300	175	Standard
MIL-C-55543/12	FEP	Nickel Plated	Strip	300	175	High
MIL-C-55543/13	TFE	Nickel Plated	Strip	300	200	Standard
MIL-C-55543/14	TFE	Nickel Plated	Strip	300	200	High

2.2.4.3 Tensile Strength. The tensile strength of FCC, with its insulation contributing to the cable collective strength, is exceptionally good (Section V). Figure 2-2 shows FCC elongation versus tensile load for various 1-inch-wide cables with copper conductors on 75-mil centers and 0.5-mil-thick solid copper foil for the shielded cables. The values shown will vary with other types of insulation and other conductor configurations.

2.2.4.4 Radiation Resistance. The polyimide and polyester insulations used for the MIL-C-55543 have very good resistance to nuclear radiation. Cables with these insulations were subjected to two phases of radiation exposure by NASA/MSFC. Phase I consisted of an average overall gamma dose of 7.03 by 10^5 roentgens (R) and an average flux of 7.7 by 10^{11} neutrons per square centimeter (N/cm^2) (# 0.5 MeV). The exposure time was approximately 1.25 hours. Phase II consisted of a total gamma exposure of 2.1 by 10^6 R and average neutron flux of 1.2 by 10^{14} N/cm^2. Exposure time was approximately 4 hours. There was no evidence of dielectric breakdown of insulation between conductors subjected to the above radiation and a potential of 2500 volts after radiation.

TABLE 2-3. MIL-C-55543 FCC DIMENSIONAL DATA

Cable Widths (in.)	Spacing (in.)	No. of Conductors
0.50	0.050	7
	0.075	6
	0.100	4
	0.150	3
1.00	0.050	17
	0.075	12
	0.100	9
	0.150	6
1.50	0.050	27
	0.075	18
	0.100	14
	0.150	9
2.00	0.050	37
	0.075	25
	0.100	19
	0.150	12
2.50	0.050	47
	0.075	32
	0.100	24
	0.150	16
3.00	0.050	57
	0.075	38
	0.100	29
	0.150	19

Centerline Spacing (in.)	Conductor Configuration	Conductor Size (in.)		Nearest AWG Size
		Width	Thickness	
0.050	Standard	0.025	0.003	30
			0.004	29
			0.005	26
	High Density	0.040	0.003	28
			0.004	27
			0.005	26
0.075	Standard	0.040	0.003	28
			0.004	27
			0.005	26
	High Density	0.065	0.003	26
			0.004	25
			0.005	24
0.100	Standard	0.065	0.004	25
			0.005	24
			0.006	23
	High Density	0.090	0.004	24
			0.005	23
			0.006	22
0.150	Standard	0.115	0.004	22
			0.005	22
			0.006	21
	High Density	0.140	0.004	22
			0.005	21
			0.006	20

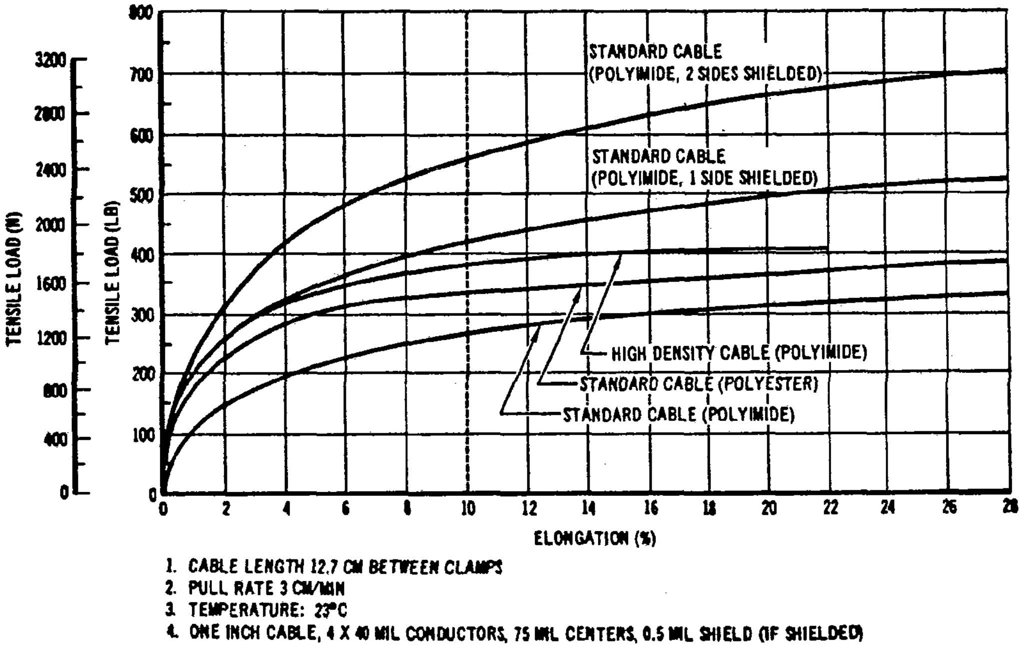


FIGURE 2-2. FCC elongation versus tensile load.

2.2.4.5 Cable Selection. The FCC selected will be dependent on the program requirements. Most high-reliability government contracts will require the use of the MIL-C-55543 cable. On those programs, where special configurations not covered by the specification are required, it is recommended that detailed procurement specifications be prepared to meet the general requirements of MIL-C-55543, together with the specific special configuration and requirements.

On those programs not requiring cable to military specifications, special consideration should be given to procurement of cable with insulation systems, construction tolerances, performance requirements, and qualifications commensurate with the program requirements.

Special electrical characteristic requirements can often be met with nonstandard cable cross-sections. Over-and-under conductors, different cross-section conductors in the same cable, special spacings and special insulation material, and thickness configurations can often be made to replace much larger and more expensive coax type RWC. Layer termination techniques can be used to further reduce the overall cost of the special interconnecting harnesses. Extensive use of these special FCC configurations is currently being made in interconnecting computer module planes with high-speed electronic circuits.

Special mechanical characteristics are also possible. An example of a low torque application for a NASA/MSFC program (ATM) is given in Section III, Paragraph 3.2.8.4.

2.2.5 Shielded Cable. Various types of shield configurations have been used on FCC. Perforated-copper shielded cable, manufactured by Hughes Aircraft and W. L. Gore, was used by General Dynamics on the standard missile. A copper alloy screen shield was used by Methode Electronics for a shielded cable configuration developed for NASA/MSFC. The openings or windows in the shield material provided the required bond between the adjacent insulation layers. However, the openings greatly reduce the shielding effectiveness at critical frequencies. These shielded configurations also had offset edge conductors with each edge conductor in contact with one shield (Fig. 2-3). The offset edge conductors complicated the cable stripping and preparations for plug termination.

Improved cable-bonding techniques permit the use of solid metal foil shields. Electrical testing has disclosed that continuous contact between the shields and edge conductors is not required for electrostatic shielding effectiveness; in fact varying resistance with cable flexing could be a source of noise. The shielded cable configuration utilizing a solid foil shield and non-offset edge conductors is shown in Figure 2-3. This configuration with 0.5-mil copper foil shields and polyimide/FEP insulation has been successfully manufactured. NASA/MSFC has performed cable flexing tests on this cable, at both low and high temperatures essentially in accordance with the requirements of MIL-C-55543 to verify the electrical and mechanical integrity.

2.2.5.1 Shielding Materials. From the development and testing described above it has been concluded that a solid shield, without openings, should be used. If the shielded FCC is to be used for general routing and interconnection in conjunction with nonshielded FCC, the shield thickness should be limited to approximately 0.5 mil. By using polyimide (Kapton) or polyester (Mylar) as the primary insulations, a cable thickness of approximately 19 mils can be achieved which will provide the required flexibility.

For electrostatic shielding, 0.5-mil annealed copper provides the shielding attenuation as described in Section II, Paragraph 3.2.3.2.3. The ductility of the annealed copper provides the elongation and compression required when the cable is bent or flexed.

For electromagnetic shielding, effectiveness throughout the operational frequency range a ferromagnetic material is required. In addition, recent tests at MDC have indicated that this shielding must be ferromagnetically continuous around both edges of the cable. A study conducted by Picatinny Arsenal for NASA/MSFC has indicated the desirability of having the shield made up of multiple layers of very thin materials alternating between nonferrous and ferrous layers. The shielding nomographs and discussion in Section III verify the effectiveness of this design approach.

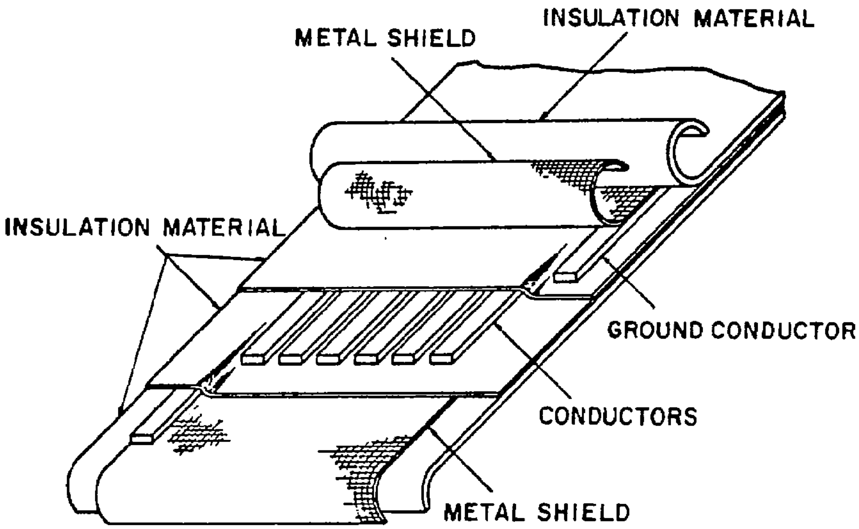


FIGURE 2-3. Shielded FCC with offset edge conductors.

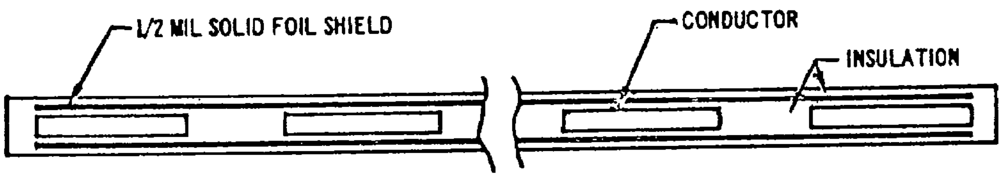


FIGURE 2-4. Shielded FCC with non-offset edge conductors.

A second approach investigated by MDC was to utilize a 0.5-mil fully annealed high permeability nickel-iron alloy shield plated with 50 microinches each of copper and nickel. Prototype samples of this material were made. Short samples were plated and longer nonplated samples were made into a 200-foot laminated shielded cable. However, the required continuous magnetic path around the edges of the cable was not provided, and the testing indicated inadequate magnetic shielding effectiveness.

The multilayer magnetic shield, continuous around the cable edges, could be achieved theoretically by several deposition methods.

A nonshielded FCC could have the shield applied directly to the outer insulation by vacuum deposition, electrolysis deposition, electrolytic deposition, or by gaseous deposition. An outer insulation layer could then be applied to complete the cable. The effectiveness of a prototype magnetic shield, continuous around the cable edges, should be verified before a development effort is expended on any of the above techniques. Then, the considerations for shield flexing, cable integrity under temperature cycling, and terminations must be made during the cable development.

An over-and-under conductor configuration can be used to reduce the effect of magnetic fields. There should be a minimum thickness of insulation between the conductor pairs. This method has been used successfully by Hughes Aircraft in a high-current shield application. If the high interconductor capacitance can be tolerated, this method provides a unique FCC application solution.

2.2.5.2 Stripping Considerations. Section VI describes various FCC stripping processes. The stripping of shielded FCC is generally much more difficult than the stripping of nonshielded FCC. This thickness of shield and the insulation between the shield and conductors, the greater bond strength required to the shield, and the insulation step between the edge of the shield and the conductors tend to complicate the stripping problems. For proper shield termination to a shielded FCC plug, it is necessary to prepare the cable end as shown in Figure 2-5.

After many cable constructions and many stripping methods were evaluated, the following cable construction is suggested. This applies to electrostatic shielded cable constructed as shown in Figure 2-4. The other insulation is tower-coated polyimide-amide or is polyester (Mylar). Both are chemically removable. The inner-cable construction is selected to meet the program requirements. The shield removal is accomplished in two separate chemical stripping operations. The first removes the outer insulations while the second removes the shield to provide the upper two steps shown in Figure 2-5. If subsequent stripping of the conductors is required, it can be accomplished by the technique established for nonshielded cable stripping. This simple approach assures the cable integrity after shielded cable stripping.

2.2.6 Power Cable. Power FCC configurations have been designed by NASA/MSFC and manufactured by Method Electronics. Various cable constructions with two and three conductors in 1-, 2-, and 3-inch cables are shown in Figure 2-6. Power cables, with equivalent conductor conductivities from 8 to 23 AWG, are designed for multiples of 75-mil centerline spacing. This permits them to be terminated in FCC connectors with 75-mil center contacts. By using special windows and shuttles for the NASA/MSFC molded-on plug, the stripped power-cable conductor can be formed to provide contact areas on both sides of the plug. This permits many parallel receptacle contacts to be used to complete each power circuit. Table 3-13 shows additional design data. Cables, copper and aluminum, have been made in sizes up to AWG 2/0 equivalent.

The advantages of the use of FCC power cables and other methods of application are discussed in Section III. Additional conductor cross-sectional requirements for various gages are given in Table 3-13, and Figure 3-60.

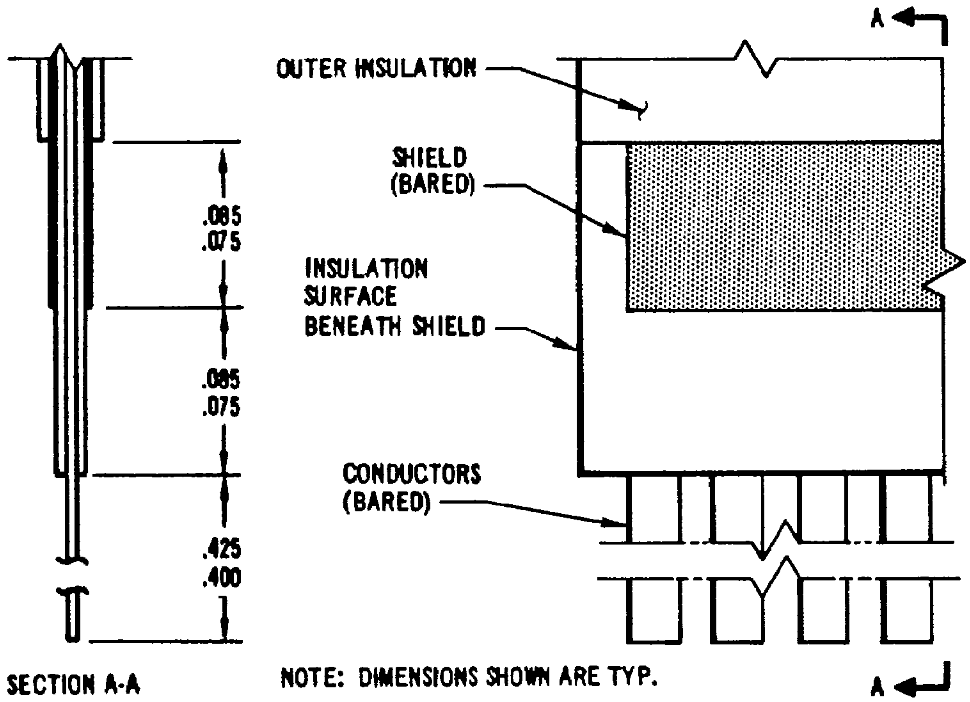
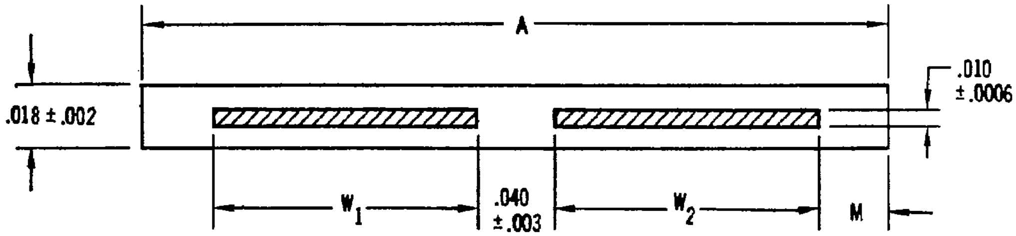
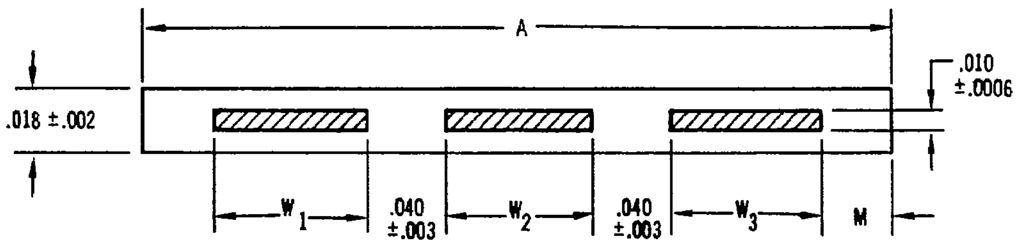


FIGURE 2-5. Shielded-cable preparation for plug termination.



A ±.010	W1 ± .002			W2 ± .002			M ±.008	WEIGHT lb/1000 ft
	WIDTH	EQUIV. AWG	Ω PER 1000'	WIDTH	EQUIV. AWG	Ω PER 1000'		
1"	.410	13	2.0	.410	13	2.0	.070	38
2"	.860	10+	.97	.935	9−	.90	.082	81
3"	1.385	8+	.61	1.385	8+	.61	.095	125



A .010	W1 ± .002			W2 ± .002			W3 ± .002			M ± .008	WEIGHT lb/1000ft
	WIDTH	EQUIV. AWG	Ω PER 1000'	WIDTH	EQUIV. AWG	Ω PER 1000'	WIDTH	EQUIV. AWG	Ω PER 1000'		
1"	.260	15	3.2	.260	15	3.2	.260	15	3.2	.070	37
2"	.560	12+	1.5	.635	11−	1.3	.560	12+	1.5	.082	80
3"	.935	9−	.90	.860	10+	.97	.935	9−	.90	.095	124

CONDUCTOR MATERIAL: HIGH CONDUCTIVITY COPPER, ANNEALED, NICKEL PLATED.
INSULATION MATERIAL: KAPTON 4 MIL, FEP BONDED.
APPLICABLE SPECIFICATION: MSFC-SPEC-220

FIGURE 2-6. FCC power cable configuration.

2.3 Connectors

2.3.1 Introduction. Numerous connector concepts have been developed for use with FCC. In other instances, existing RWC connectors have been adapted for FCC use. MIL-C-55544, "Connectors, Electrical, Environment Resistant, for use with Flat Conductor Cable, General Specification for," has been prepared to define the operational requirements of environmental connectors for use with FCC. This specification contains detail specification sheets for the NASA/MSFC conductor-contact connector and for the U. S. Army Picatinny Arsenal pin-and-socket contact connector. For purposes of this report, a connector is defined as a mated plug and receptacle. The receptacle contains the mounting provisions for attaching to a bracket or electronic unit.

To afford the users of this report a broader concept of connectors and termination systems which have been used, or are being prepared for use, the MIL-C-55544 connectors are discussed in detail in separate paragraphs, and general descriptions and illustrations are given for other connectors developed for and/or used with FCC.

2.3.2 Conductor-Contact Connectors (per MIL-C-55544). The conductor-contact FCC connector system was developed by NASA/MSFC. This system, which utilizes the cable conductor as the plug contact, eliminates at least one of the total connector junctions. In addition, it provides a light weight, simple, and economical FCC plug assembly. Production-type tooling has been developed by NASA/MSFC for a complete line of connectors, including five sizes for rectangular and two sizes for cylindrical configurations.

2.3.2.1 Plugs. Two types of conductor-contact plugs have been developed; molded-on and premolded nonshielded plugs by NASA/MSFC. The nonshielded plugs, which have all-plastic bodies, are capable of accepting shielded FCC if there are no requirements for the shield path to be carried through the connector in a continuous peripheral manner. The shield can be "floated" or carried through one or two connector contacts. All plugs of the same size are interchangeable, and all have integral polarity keys to prevent reversed insertion. All plugs have the capability of accepting a number of cable segments per cable layer, as shown in Figure 2-7. All of the above plugs are currently designed and tooled for 75-mil and centerline contacts. The design concepts shown are applicable for 50- and 100-mil centerline contacts. Two or more contacts can be used in parallel, with the FCC, having centerline spacings a multiple of 75 mils, prepared as shown in Figure 3-59. Another method of terminating wider conductors or power FCC in a plug is to remove window spokes and ridges of the shuttle of the premolded plug parts to provide for wide power-cable conductors (Fig. 2-8).

2.3.2.1.1 Molded-On.

2.3.2.1.1.1 Rectangular. Figure 2-9 shows a typical cross-section of the rectangular molded-on plug assembly, together with details which define the parts required and the control and outline dimensions for all five plug sizes. Section VI of this report (and MS 75079, Proposed Method Drawing, included with the MIL-C-55544 specification) defines the steps required for plug assembly. If the polysulfone molding material is used as shown in Figure 2-9, the operating temperature is limited to a maximum of 100°C. If PPO molding material is used, the maximum operating temperature is increased to 150°C, and the resistance to chemical solvents is increased. NASA/MSFC has production-type molding dies for the five plug sizes shown. Tooling drawings for these dies are available to qualified organizations on request.

2.3.2.1.1.2 Cylindrical. Molded-on cylindrical plug assemblies for 0.25- and 0.5-inch-wide cable are shown in Figures 2-10 and 2-11. These plugs are similar to the rectangular plugs described above except for the circular geometry. The plug assembly steps are defined in MS 75080, Proposed Method Drawing, included with the MIL-C-55544 specification.

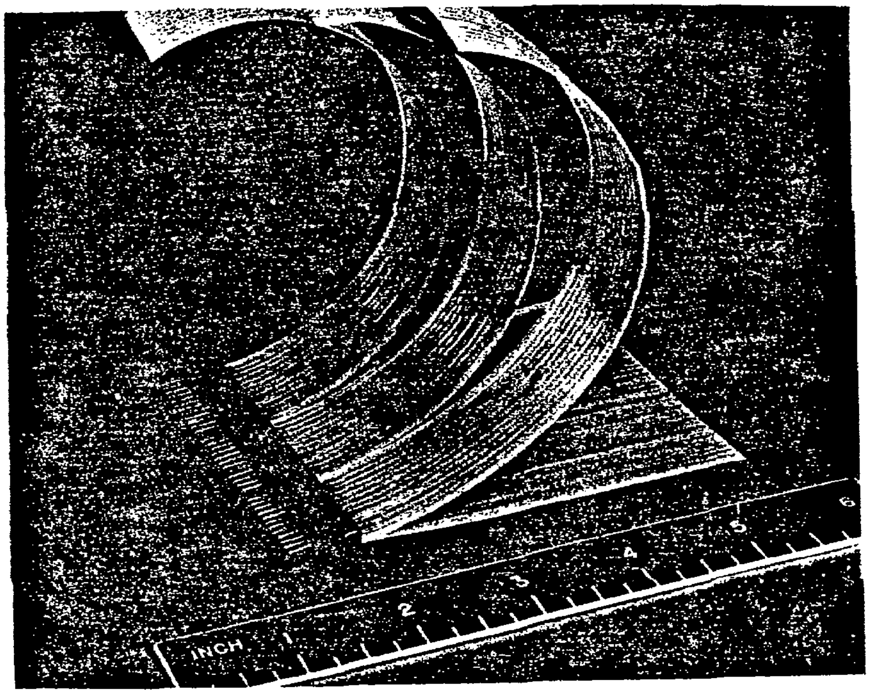


FIGURE 2-7. Multiple cable terminations in one layer.

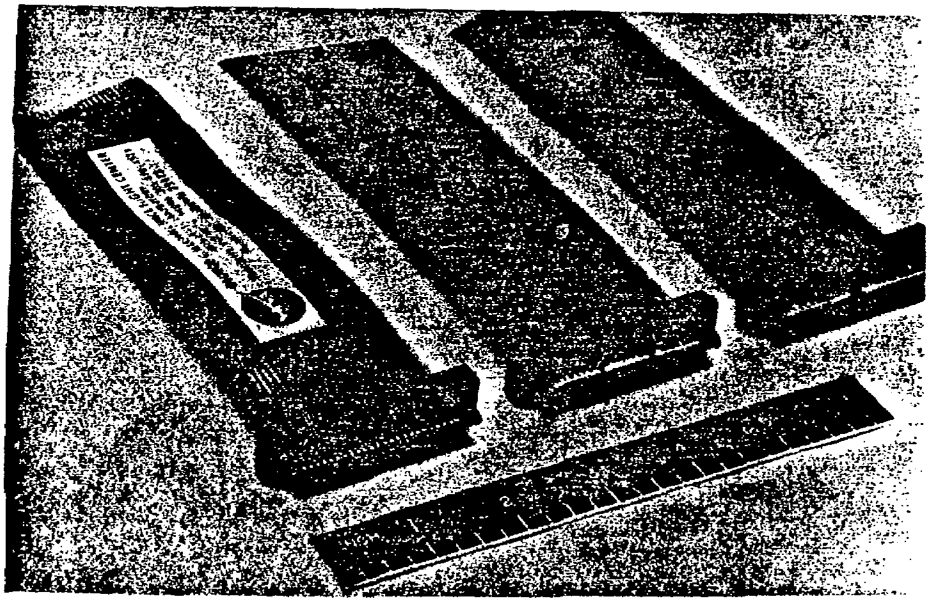
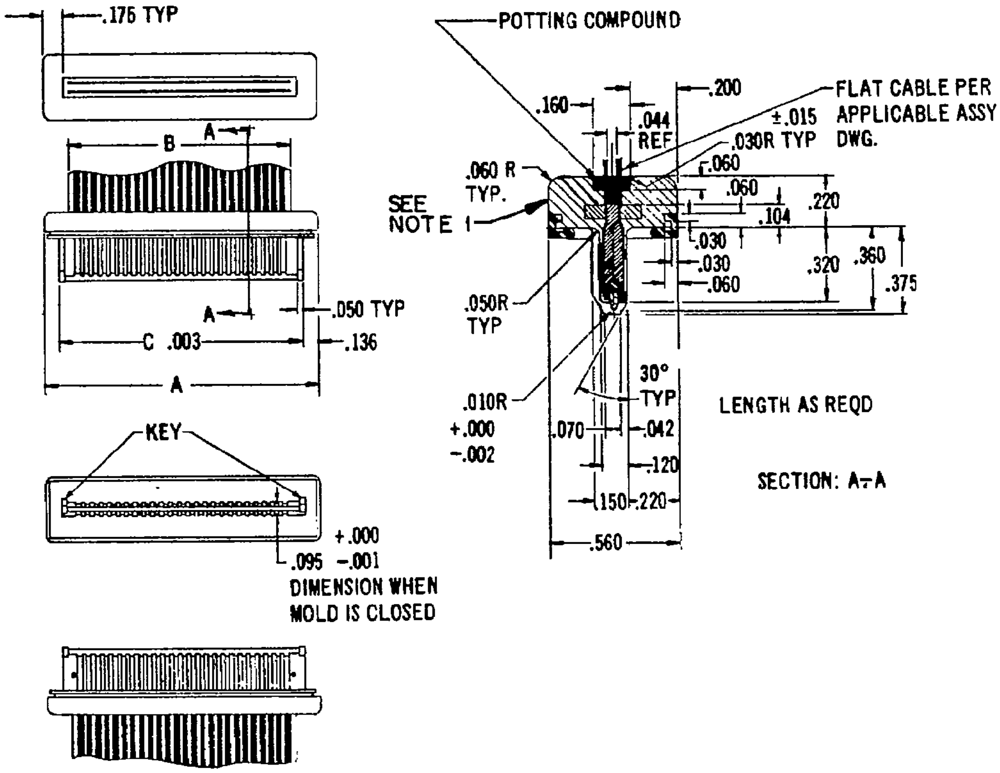


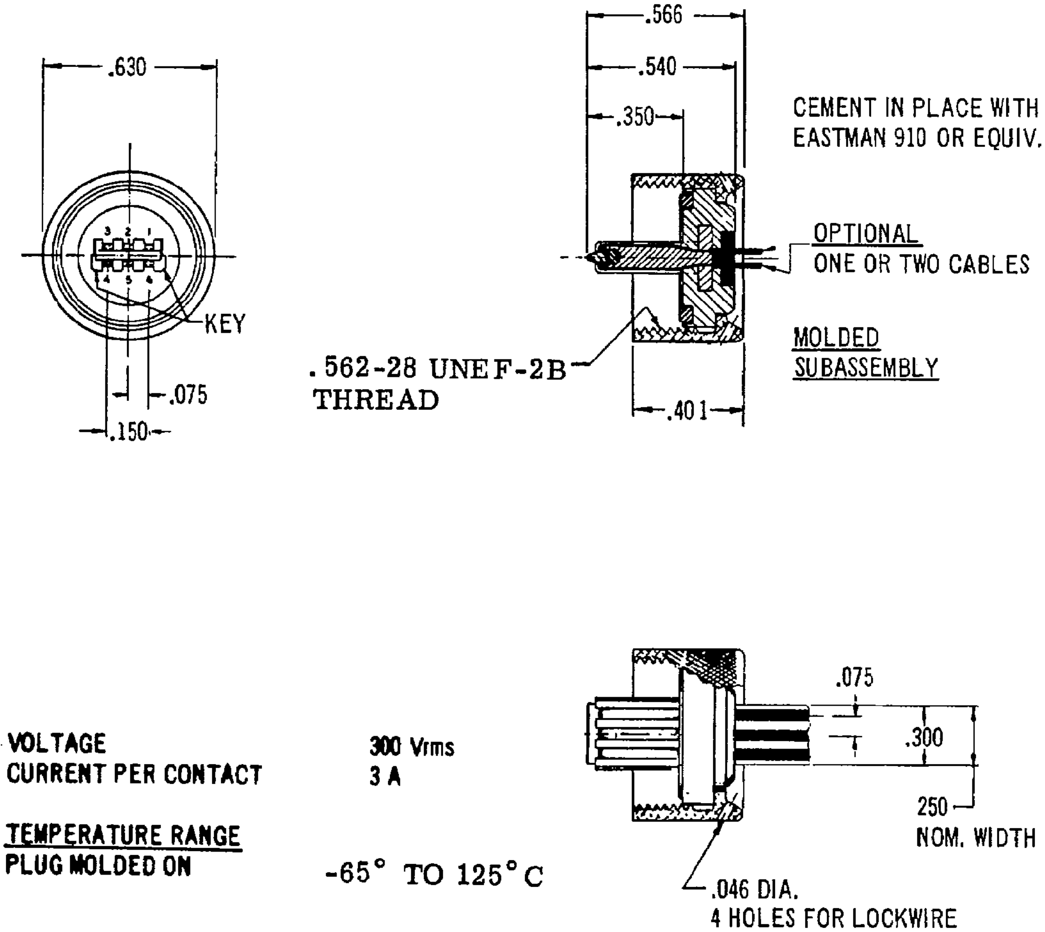
FIGURE 2-8. FCC power-cable termination.



A	B	C
1.409	1.000	1.137
1.859	1.500	1.587
2.384	2.000	2.112
2.909	2.500	2.637
3.359	3.000	3.087

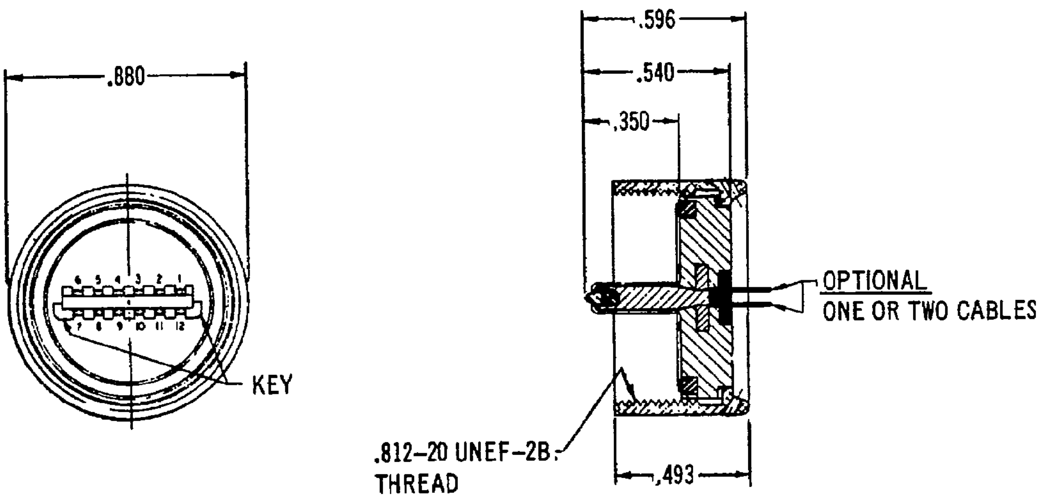
NOTES:
1. Polyphenylene oxide.
2. Cable and conductors may be trimmed as required.
3. Temperature range: -65° C to 125° C.

FIGURE 2-9. MIL-C-55544/7 Molded-on rectangular plug.



VOLTAGE	300 Vrms
CURRENT PER CONTACT	3 A
TEMPERATURE RANGE PLUG MOLDED ON	-65° TO 125° C

FIGURE 2-10. MIL-C-55544/9 Molded-on cylindrical plug assembly, .25-inch wide cable.



VOLTAGE	300 Vrms
CURRENT PER CONTACT	3 A
TEMPERATURE RANGE	
PLUG MOLDED ON	-65° TO 125° C

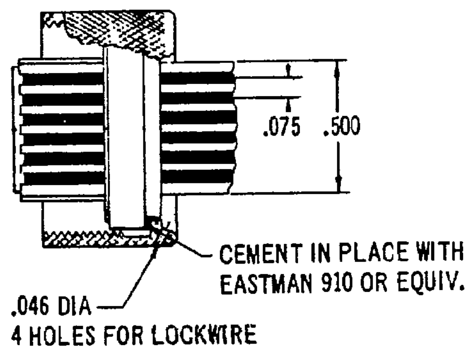


FIGURE 2-11. MIL-C-55544/9 Molded-on cylindrical plug assembly, 0.5-inch wide cable.

2.3.2.1.2 Premolded Plugs.

2.3.2.1.2.1 Nonshielded Rectangular. Figure 2-12 shows a typical cross section of the premolded plug assembly together with details which define the parts required and the control and outline dimensions for all five plug sizes. Section VI of this report and the MS 75078, Proposed Method Drawing (included with MIL-C-55544), define the steps required for plug assembly. The glass-filled epoxy molding material used for the premolded parts of this plug permits operating at a maximum of 200° C. Tooling has been developed for the five plug sizes shown, and parts are available from Methode Electronics.

2.3.2.2 Receptacles. Two types of receptacles have been developed for both the rectangular and cylindrical conductor-contact plugs described above; the "FCC to FCC" and the "FCC to RWC" (solder) types. The FCC to FCC mates with two identical FCC conductor-contact plugs. The solder type can be used for electronic units and feedthrough applications to effect a transition from an FCC plug to RWC. All receptacles have carefully designed contact springs with controlled radius, spring rate deflections, and contact force to achieve and maintain the required performance. Variations to the existing rectangular receptacles to provide conductive shell finish and conductive mounting gaskets would provide shielded receptacles.

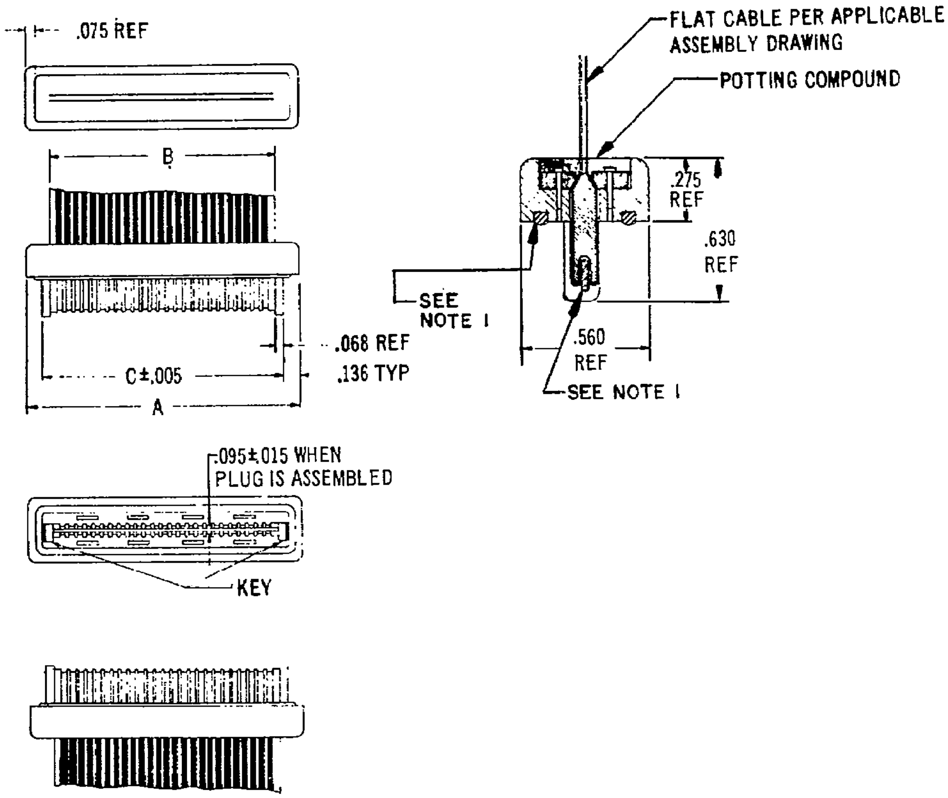
2.3.2.2.1 FCC to FCC, Rectangular. Figure 2-13 shows the five sizes of actual receptacles, a chart with tabulation data, a receptacle cross-section, and an enlarged contact-area view with a spring-force chart. Additional outline and control dimensions, performance, and marking information are given in the M55544/8 specification sheet included with MIL-C-55544. These production-type receptacles are manufactured by Amphenol, and are patterned after the original NASA/MSFC machined-shell receptacle. Qualification-type testing has been accomplished by two agencies to verify performance with the specification.

2.3.2.2.2 FCC to RWC, Rectangular. Figure 2-14 shows five sizes of receptacles, a data chart, and contact information. Additional outline and control dimensions, performance, and marking information are given in M55544/6 specification sheet included with MIL-C-55544. These production-type receptacles are: manufactured by Amphenol; patterned after the NASA/MSFC machined-shell design; and have passed specification qualification-type tests by two independent agencies.

2.3.2.2.3 FCC to FCC, Cylindrical. Figure 2-15 shows the cylindrical flat-cable to flat-cable receptacle for one-hole mounting with tabulation for 0.25- and 0.5-inch-wide cables. The cross section shows the mated plug and receptacle with contact details. Prototype receptacles of both sizes have been made and evaluated by NASA/MSFC. Similar receptacles with square flange mounting have also been made.

2.3.2.2.4 FCC to RWC, Cylindrical. Figure 2-16 shows the cylindrical flat-cable to round-wire receptacle for one-hole mounting, with tabulation for 0.25- and 0.5-inch-wide cables. The cross-section shows the mated plug and receptacle with contact details. Prototype receptacles of both sizes have been made and evaluated by NASA/MSFC. Similar receptacles with square flange mounting have also been made.

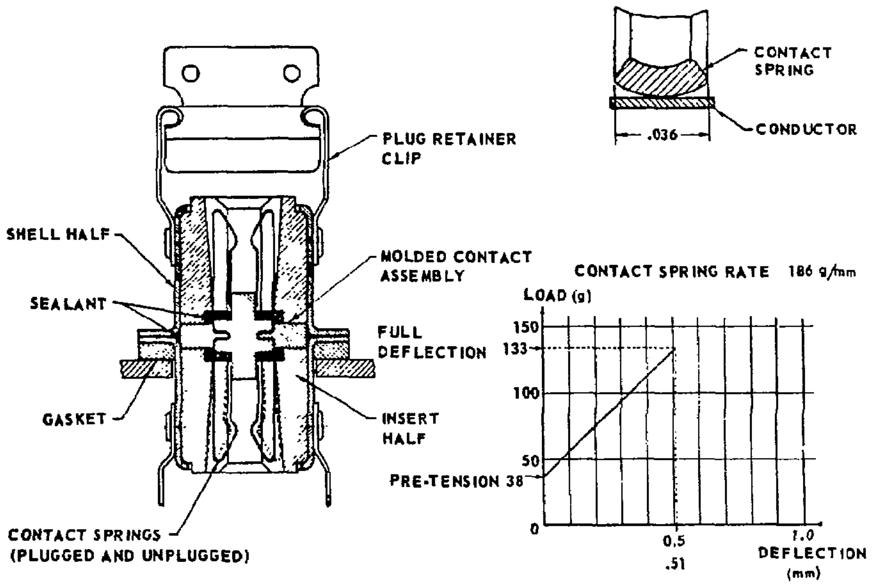
2.3.3 Pin-and-Socket (per MIL-C-55544). A pin-and-socket FCC connector system has been designed by the U.S. Army at Picatinny Arsenal, and a 2-inch cable size, single-layer, shielded version has been tooled, manufactured, and is undergoing evaluation testing. MIL-C-55544 contains two versions of this connector: shielded and nonshielded. The basic bulkhead-type receptacle and mating plug are capable of accepting either FCC or RWC, with different interchangeable back hardware. The specification requires crimp-removable contacts for the round-wire termination. The FCC terminations can be made by crimping to the stripped, preformed conductors by welding or by lap soldering. Termination by layer is possible in all termination systems. Peripheral-shield continuity is achieved in the cable-shield area by a compressed, silver-filled conductive gasket and at the plug interface by fingered conductive springs. Figure 2-17 shows this connector configuration.

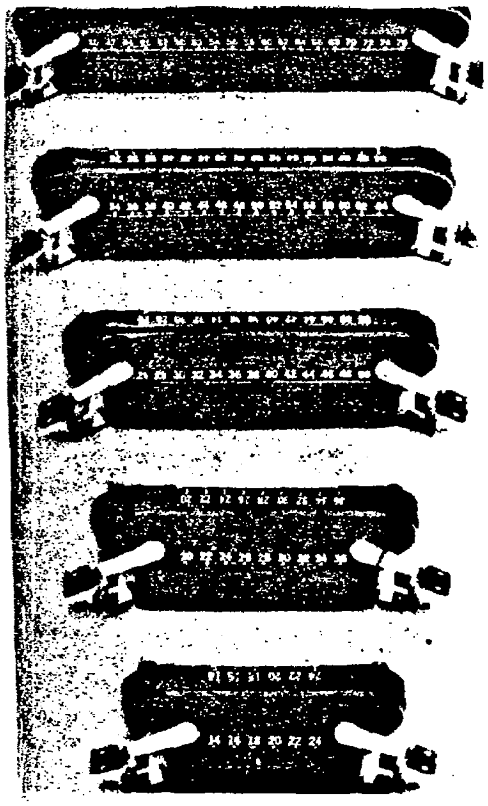


A REF	B REF	C REF
1.409	1.000	1.137
1.859	1.500	1.587
2.384	2.000	2.112
2.909	2.500	2.637
3.359	3.000	3.087

NOTES:
1. Cement wedge and seal in place with Dow Corning 140 or equivalent.
2. Temperature range: -65° C to 125° C.

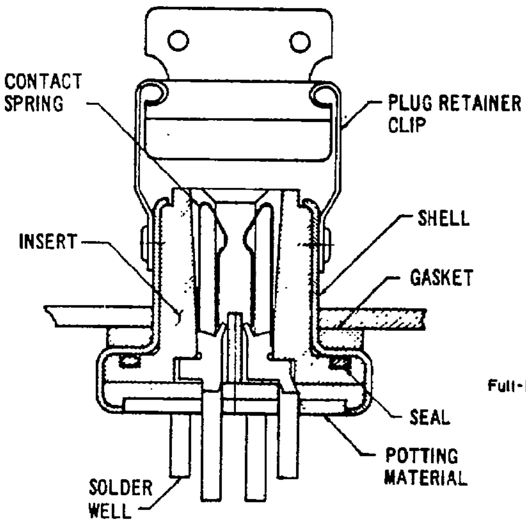
FIGURE 2-12. MIL-C-55544/5 Premolded rectangular plug.



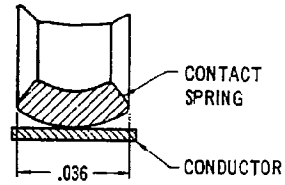


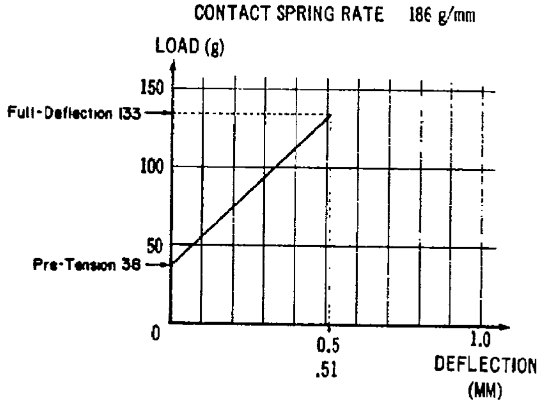
CABLE WIDTH INCHES	NUMBER OF CONTACTS	MOUNTING AREA INCHES	WEIGHT IN GRAMS	
			RECPT	PLUG EA
3	76	.9 X 4.2	67	17
2.5	64	.9 X 3.8	60	15
2	50	.9 X 3.3	50	12
1.5	36	.9 X 2.7	39	9
1	24	.9 X 2.3	32	7

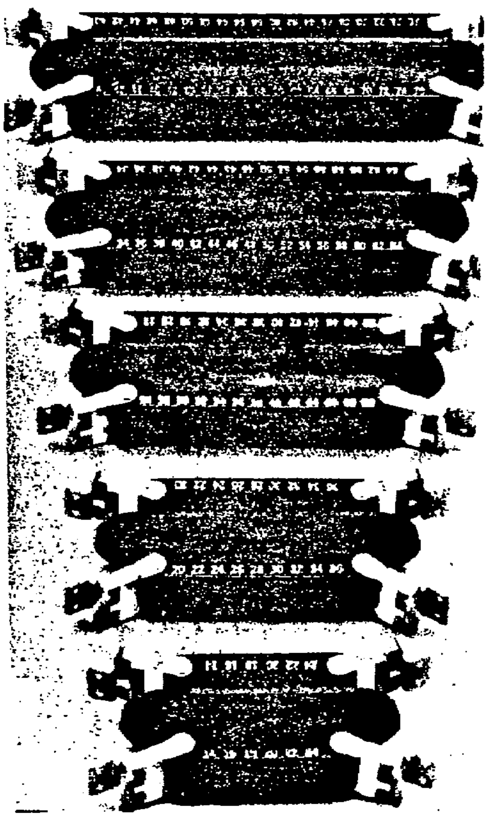
FIGURE 2-13. FCC to FCC receptacle, rectangular.



ENLARGED SECTION

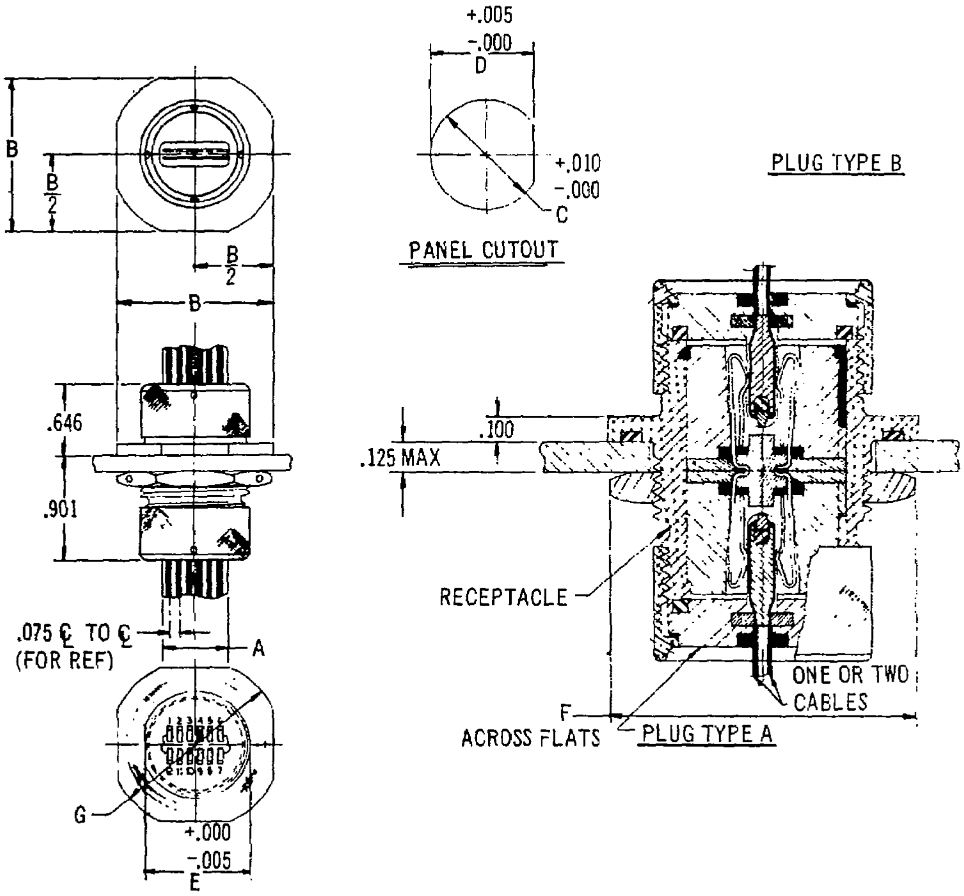






CABLE WIDTH INCHES	NUMBER OF CONTACTS	MOUNTING AREA INCHES	WEIGHT IN GRAMS	
			RECPT	PLUG EA
3	76	.9 X 4.2	57	17
2.5	64	.9 X 3.8	50	15
2	50	.9 X 3.3	40	12
1.5	36	.9 X 2.7	33	9
1	24	.9 X 2.3	28	7

FIGURE 2-14. FCC to RWC receptacle, rectangular.

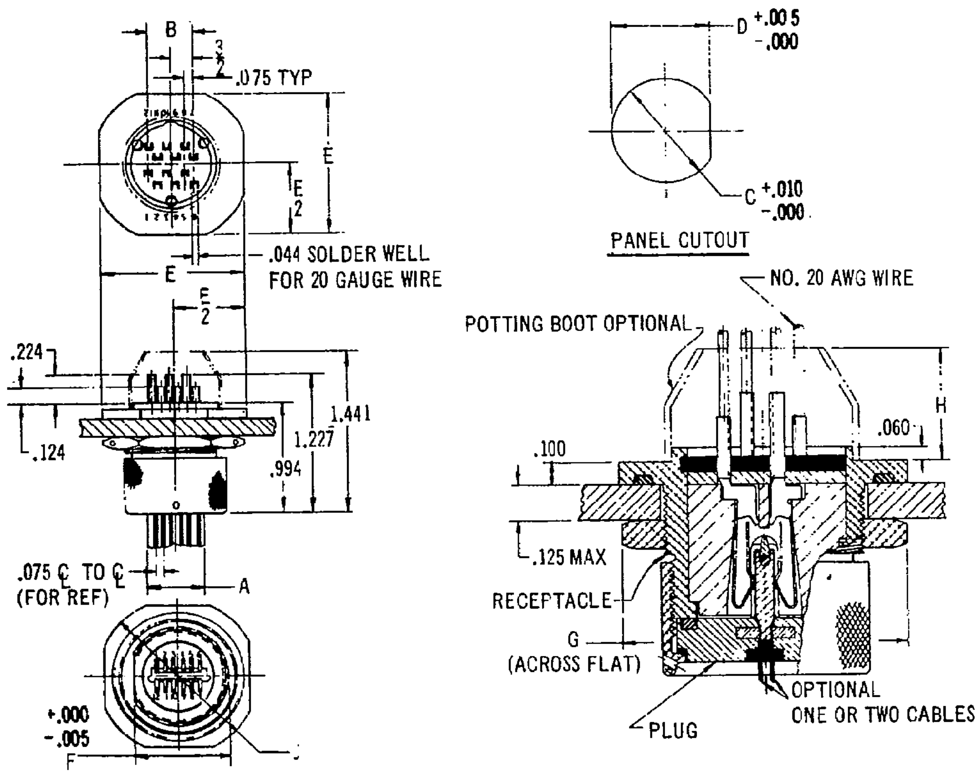


DIMENSION						
A	B	C	D	E	F	G
.300	.938	.572	.542	.540	.750	1.00
.500	1.250	.884	.830	.818	1.062	1.38

VOLTAGE -------------300V.RMS
CURRENT PER CONTACT----- 3A.
CONTACT RESISTANCE ------ .006 OHMS MAX.
TEMPERATURE RANGE
RECEPTACLE ---------- -65° TO 125°C

PLUG MOLDED ON -------- -65° TO 125°C
AIR LEAKAGE
RECEPTACLE ---------- LESS THAN 1 CU CM/HR AT 2 ATM. DIFF.
HUMIDITY ------------- MIL-STD-202 METHOD 106

FIGURE 2-15. MIL-C-55544/16 FCC to FCC receptacle, cylindrical.



DIMENSION								
A	B	C	D	E	F	G	H	J
.300	.150	.572	.542	.938	.540	.750	.500	1.00
.500	.375	.884	.830	1.250	.818	1.062	.750	1.38

VOLTAGE -----------300 V.RMS
CURRENT PER CONTACT -- 3 A
CONTACT RESISTANCE ---.006 OHMS MAX.
TEMPERATURE RANGE
RECEPTACLE ---------65 TO 125°C

PLUG MOLDED ON---65 TO 125°C
AIR LEAKAGE
RECEPTACLE------LESS THAN 1 CU CM/HR AT 2 ATM. DIFF
HUMIDITY--------MIL-STD-202 METHOD 106

FIGURE 2-16. MIL-C-55544/14 FCC to RWC receptacle, cylindrical

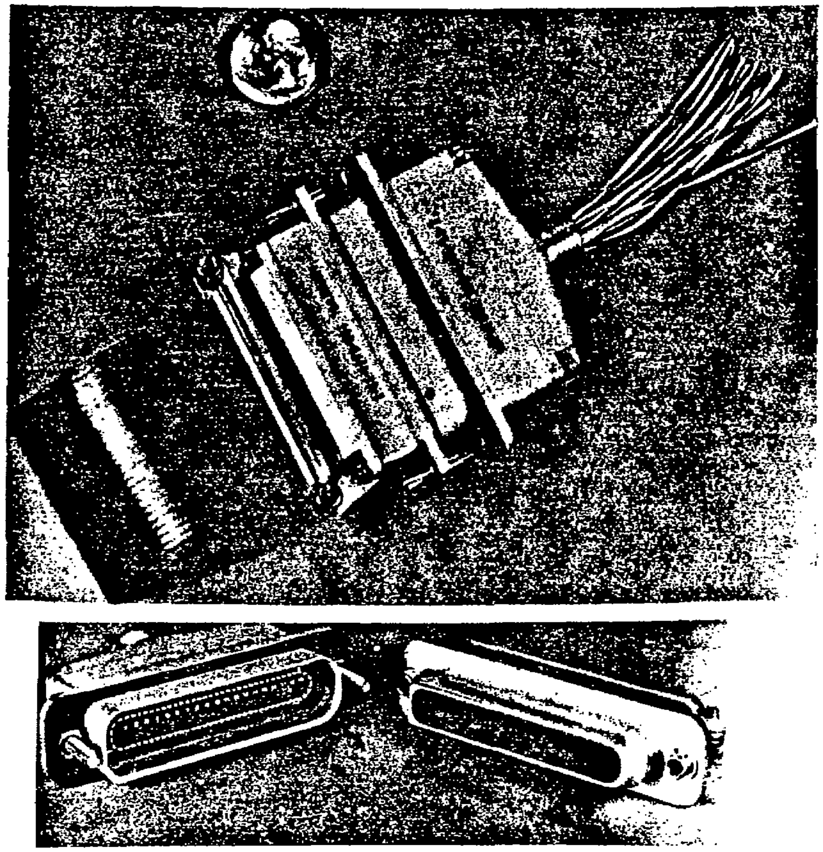


FIGURE 2-17. Pin-and-socket connectors (Picatinny Arsenal)

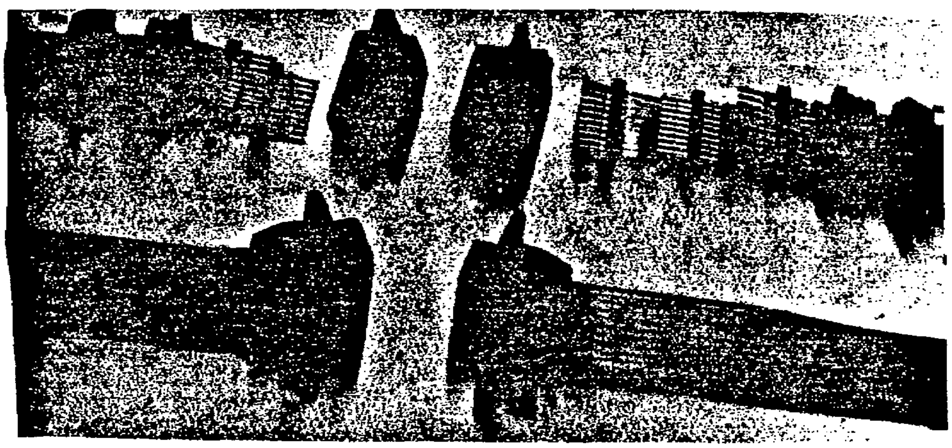


FIGURE 2-18. Multilayer connector, 16-gage contacts (ELCO).

The MIL-C-55544/1 and /3 specification sheets define the nonshielded and shielded plugs, and the /2 and /4 sheets define the nonshielded and shielded receptacles. All sheets are tabulated for 1-, 2-, and 3-inch cable widths, for 1, 2, and 3 layers of contacts, and for 50-, 75-, and 100-mil contact centerlines. This represents a total of 27 each different plug and receptacle configurations. If shielded and nonshielded versions are considered, then there are 54 different configurations for plugs and 54 for receptacles. So it can be seen that considerable more design, tooling, and qualification testing is required before this connector design approaches the availability status of the NASA/MSFC conductor systems.

2.3.4 Other FCC Connectors. To present a broader concept of connectors and termination systems that have been used, or being proposed, general descriptions and illustrations are given for other connectors developed for and/or used with FCC.

2.3.4.1 For Severe Environmental Conditions. Numerous connectors have been designed and developed for severe environmental conditions. Although the following connectors are not included in the existing draft of the MIL-C-55544 connector specifications, they meet many of the specification requirements.

2.3.4.1.1 Initial Development. Figure 2-18 shows a multilayer FCC connector developed by ELCO Corporation for Picatinny Arsenal. This was one of the first pin-and-socket type connectors designed for the termination of the FCC on a by-layer concept. Although the 16-gage pin-and-socket contacts and the 0.16 contact centerline spacing resulted in a contact density and connector weight generally not acceptable for flight-type connectors, many of the principles incorporated in this design were included in the high-density connectors which were to follow.

2.3.4.1.2 Prototype Connectors for the Poseidon Program. The Lockheed Aircraft Company Missile Division at Sunnyvale, California, had flat-cable prototype connectors developed for possible use in the Poseidon Missile tunnel. All connectors were for 2-inch-wide FCC with contacts on 100- and 150-mil centers. The connector system provided a production break and a transition from FCC tunnel wiring to RWC equipment area wiring. Electrical shielding provisions were included for both the FCC and RWC connector parts. Sealed contact wafers for each FCC cable layer were used for connector assembly. Each wafer could be replaced for repair or rework, as required.

Figure 2-19 shows the prototype built by Cannon IT&T. Figure 2-20 shows a cross section of the design submitted by Bendix. A prototype version was also manufactured by ELCO Corporation. All designs utilized terminations in the flat-cable portion of the connector, made by welding through the insulation.

2.3.4.1.3 High-Density FCC Connectors. Figure 2-21 shows a Mark II Micro Dot connector manufactured by Cannon IT&T. This connector has FCC contact centerline spacing of 50 mils with a contact-layer spacing of 44 mils to provide a contact density of over 400 per square inch. It has metal backshells plus interfacial and intercontact seals. Recommended termination is welding through the FCC insulation, followed by encapsulation. This connector is available in 9-, 15-, 21-, 25-, 37-, and 51-contact layouts.

Figure 2-22 shows a Micro Dot type MMD, high-density flat-cable connector. This prototype connector accommodates three 1-inch-wide standard FCC's on 50-mil centerline. Contact termination is made by welding through the insulation to contact wafers which are subsequently assembled into the connector backshell. Interfacial and intercontact sealing as well as provisions for keying and electrostatic shielding are provided.

Figure 2-23 shows a 50-mil center multilayer-prototype connector made by Cannon IT&T. It incorporates metal shells, separately sealed, removable wafers for each cable layer, interfacial and intercontact seals, and electrostatic shielding provisions. This connector was designed specifically to meet the requirements of MIL-C-55544.

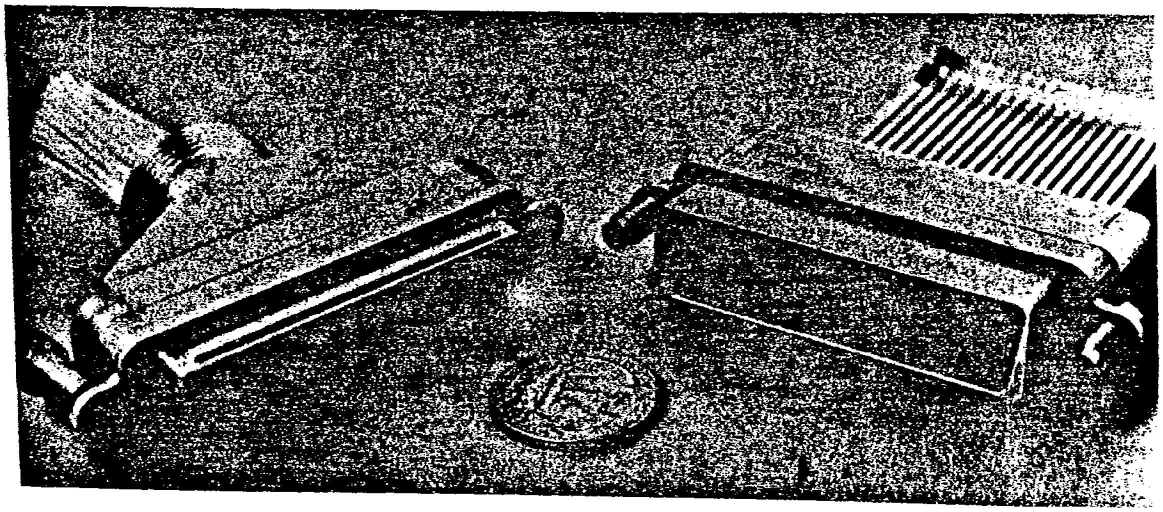


FIGURE 2-19. Multilayer connector prototype for Poseidon (Cannon IT&T).

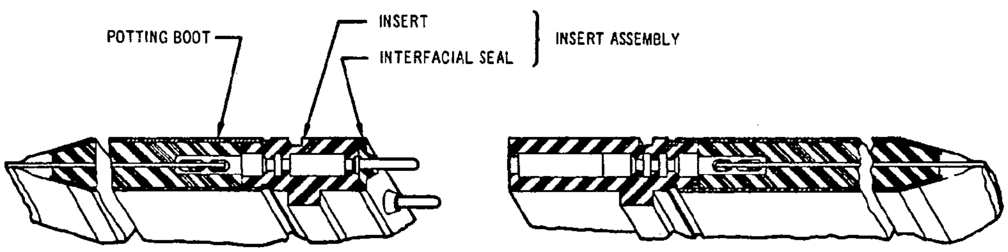


FIGURE 2-20. Multilayer connector cross-section for Poseidon (Bendix).

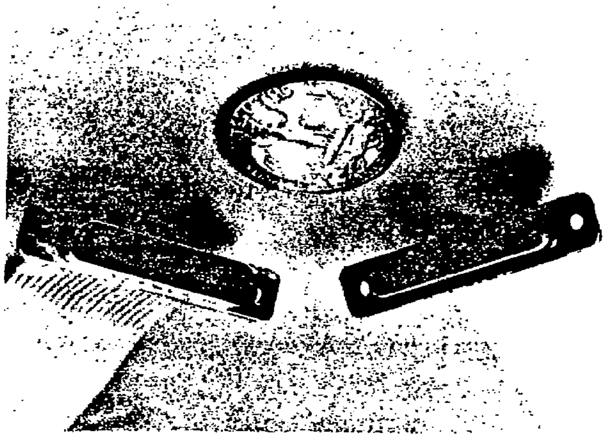


FIGURE 2-21. MARK II Micro Dot high-density connector (Cannon IT&T).

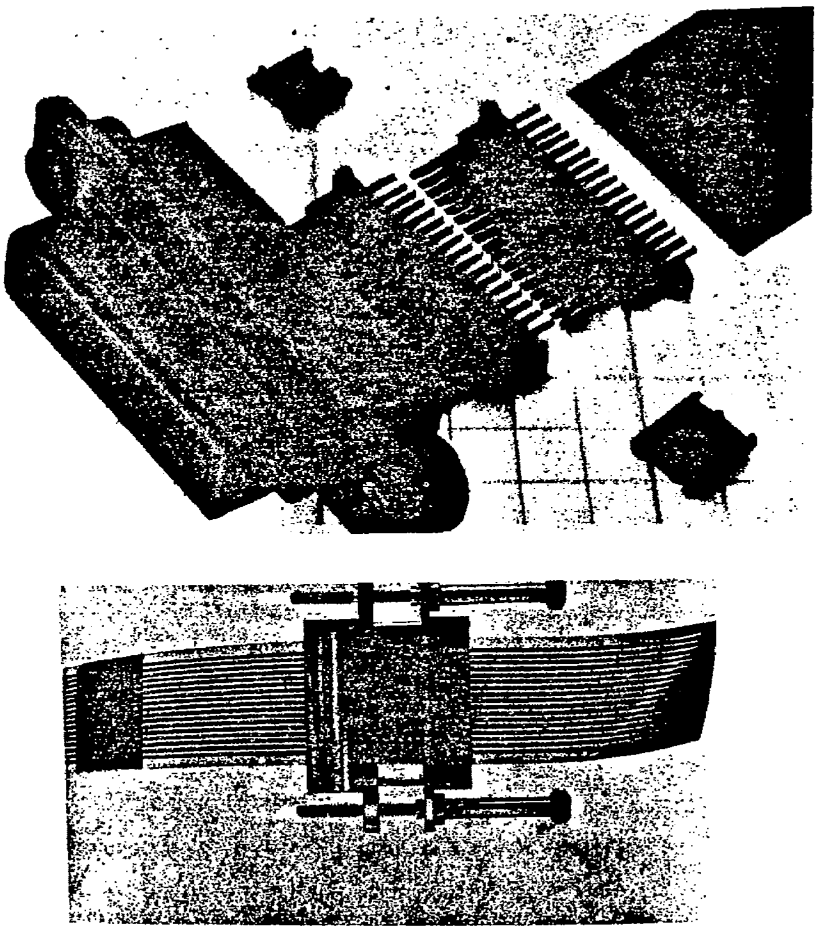


FIGURE 2-22. MMD high-density connector (Micro Dot).

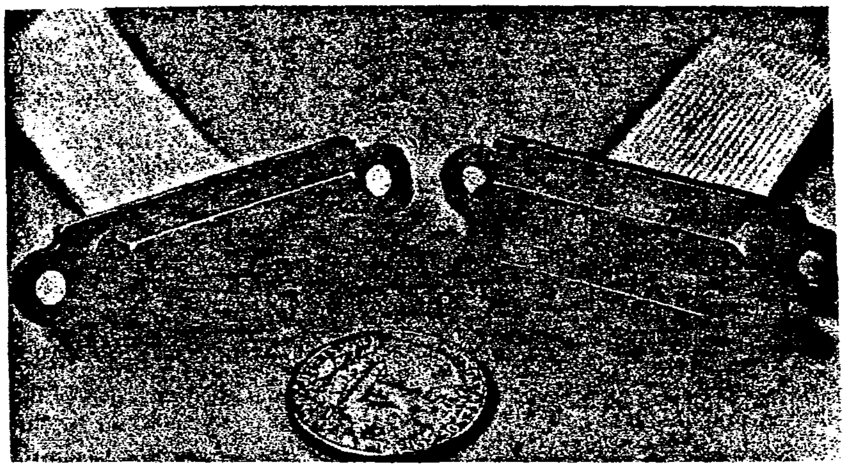


FIGURE 2-23. 50-Mil center multilayer prototype (Cannon IT&T).

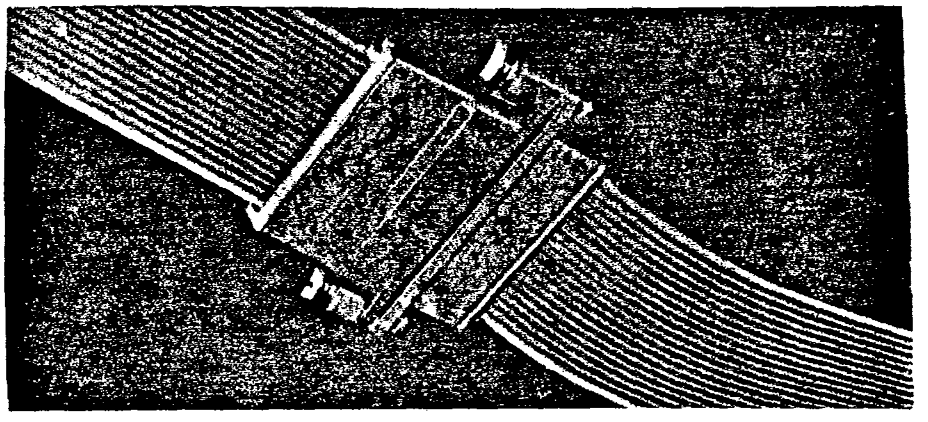


FIGURE 2-24. 218 Flex-1 series connector (Amphenol).

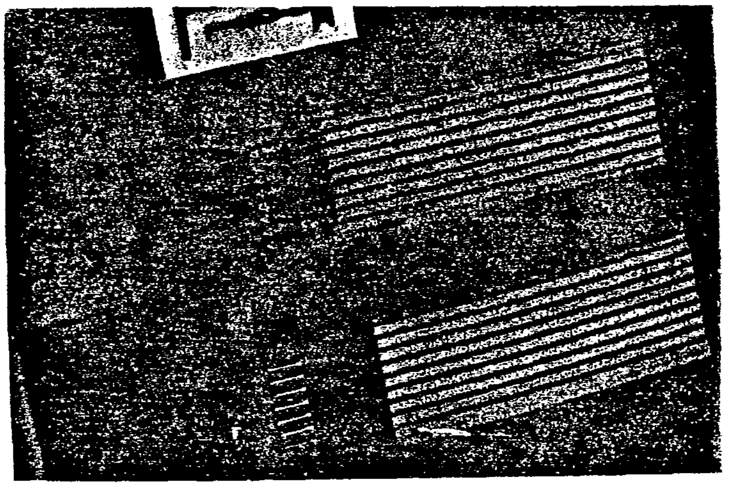


FIGURE 2-25. Crimp contact connector (Amp).

2.3.4.2 Nonenvironmental Connectors. Many different types of FCC connectors have been developed and manufactured for applications not requiring the MIL-C-55544 performance requirements. These can generally be broken down into pin-and-socket and conductor-contact systems.

2.3.4.2.1 Pin-and-Socket Contacts. Figure 2-24 shows a 218 Flex-1 series connector made by Amphenol. This connector was designed to meet the operational requirements of the IPC-FC-218 FCC commercial specification. The 218 Flex-1 connectors are available in 2- and 3-inch widths with 75-, 100-, and 150-mil contact spacing. In addition to the weldable contacts for FCC, solder eyelet contacts are available for RWC, to permit easy transition from FCC to RWC. Contact is made to the FCC by a simple welding process that melts the insulation at the junction point and welds the conductor directly to the contact.

Figure 2-25 shows a crimp-contact connector manufactured by Amp, Incorporated. This production, commercial-type FCC connector utilizes reel-fed contacts for high production termination. The stamped and formed (0.025 square) gold-plated contact can be incorporated into numerous existing Amp miniature connector designs. No cable preparation, soldering, or welding are required for this termination system.

Figure 2-26 shows a multilayer connector with Varicon[3] contacts manufactured by ELCO Corporation. Many existing, similar connector configurations can be adapted to FCC use for nonsealed, low-environment applications.

Figures 2-27 and 2-28 show completed cable assemblies manufactured by ACI, Inc. which specializes in furnishing completed FCC harness assemblies to meet the customer requirements. These are called Signalflo systems, and they are furnished for special transmission lines, memory devices, etc., with specific requirements for impedance, propagation velocity, crosstalk, capacitance, and other physical and electrical parameters. The combinations of characteristics available are limitless.

Figure 2-29 shows completed, typical FCC harness assemblies manufactured by Methode Electronics which supplies completed harness assemblies in addition to several types of rectangular connectors suitable for use with FCC. The Plyo-Duct harnesses can be furnished in many configurations of nonshielded, shielded, continuous, and PC-type circuits. In addition, Methode Electronics has a complete line of Reli-Acon PC-type connectors which can be applied to low-environmental FCC interconnecting systems.

Figures 2-30 and 2-31 show completed FCC harness assemblies manufactured by Ansley West. This company designs and manufactures many special FCC harness configurations for military high-performance systems. Figure 2-30 shows flexible, continuous shielded cable terminated to rectangular and round connectors. This is one of a large series of SINS cables made for Autonetics. Figure 2-31 shows a special gyro cable with very low torque requirements, which is used by Autonetics on the Minuteman II. Ansley West uses, almost exclusively, their Flex-Weld termination method to terminate the FCC. Welding is accomplished through the insulation to the connector contact or to an intermediate pin or wire.

2.3.4.2.2 Conductor Contacts. Figure 2-32 shows a completed harness assembly manufactured by Rogers, Inc. This company has available a line of receptacles and molded-on plug assemblies for various FCC widths. This company has developed two high-performance FCC connector lines; the nonmetal backshell connector shown, and a metal backshell version for extreme environmental conditions. The Positerm[4] system shown in Figure 2-32 is available in four sizes for 0.100-inch conductor centerline cables of approximately 0.90 through 3.30-inch widths. Two mating receptacle configurations for wire soldering and PC-board application are available. The metal backshell connector has only been developed for a 3.20-inch-wide, 100-mil center FCC. All plugs are limited to terminating one FCC.

3. Trademark of Elco Corporation.
4. Trade name of Rogers Corp.

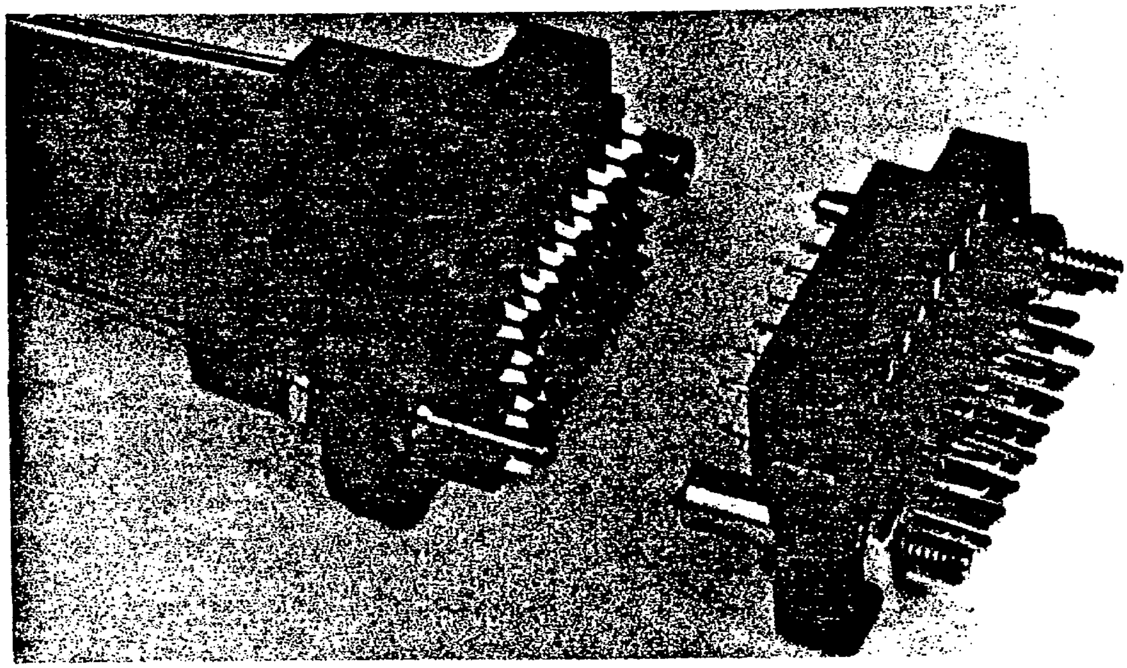


FIGURE 2-26. Multilayer connector (ELCO).

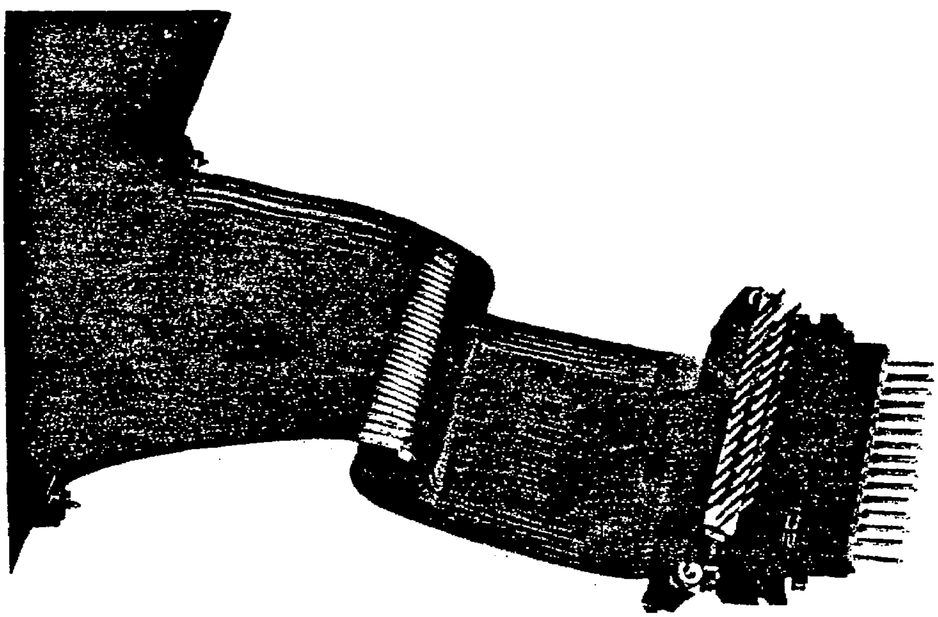


FIGURE 2-27. Retractable cable assembly (ACI).

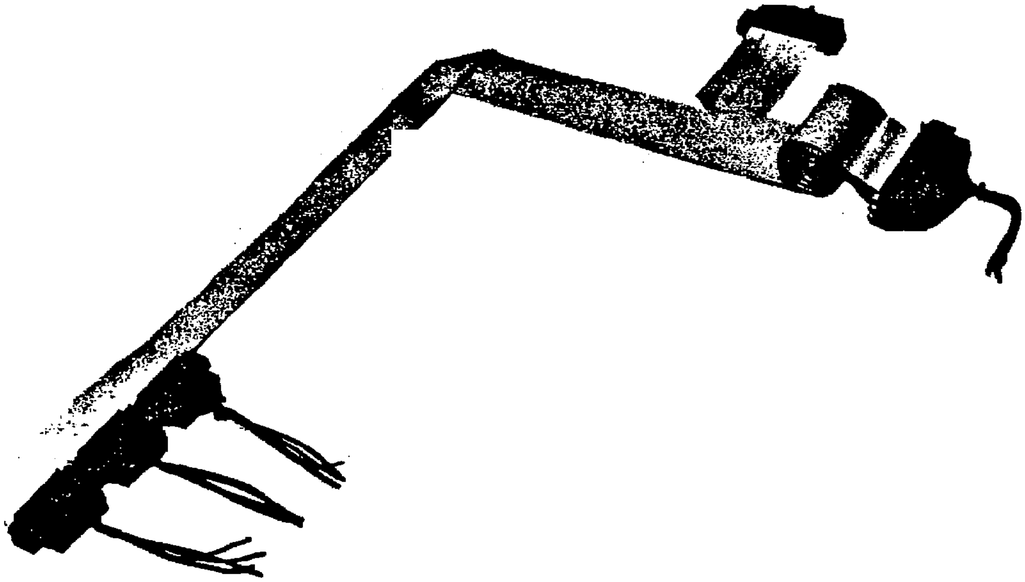


FIGURE 2-28. Harness Assembly (ACI).

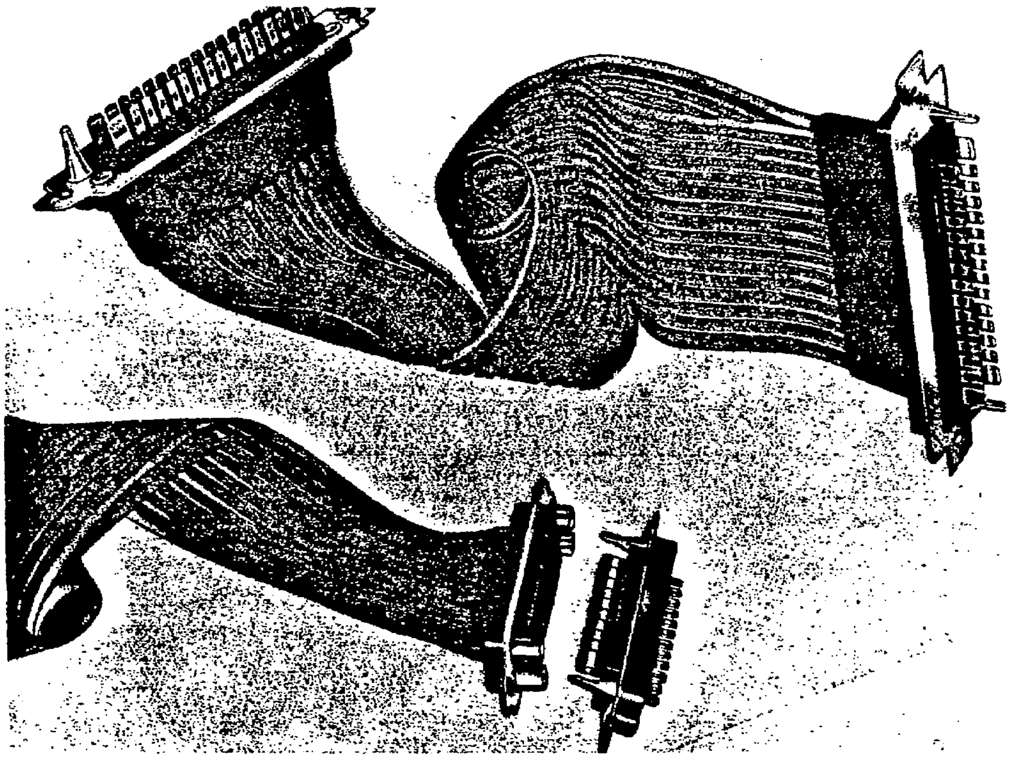


FIGURE 2-29. Harness assembly (Methode Electronics).

FIGURE 2-30. Shielded assembly (Ansley West).

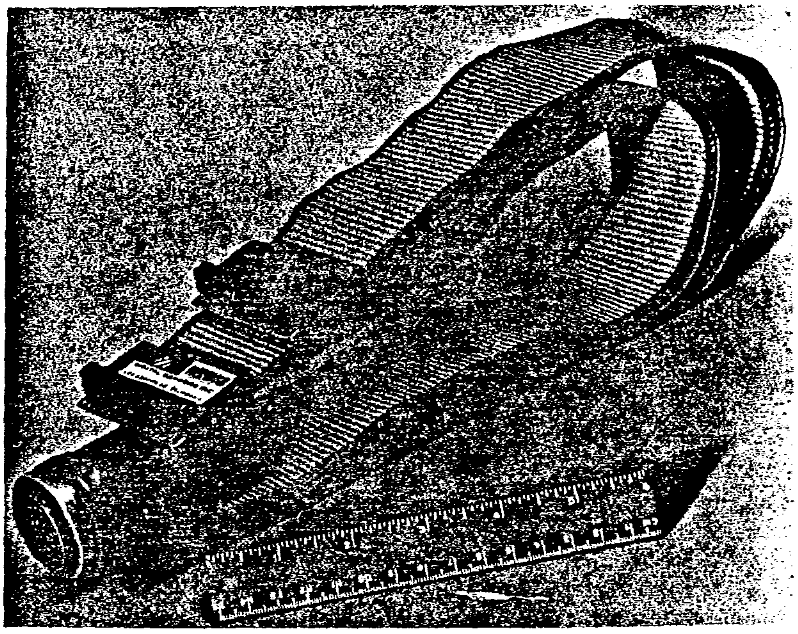


FIGURE 2-31. Gyro harness assembly (Ansley West).

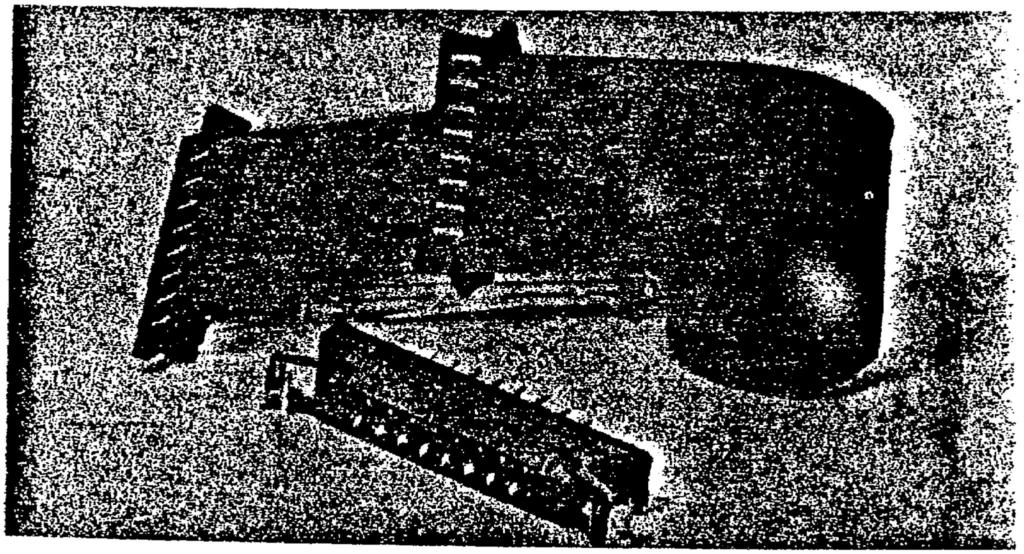


FIGURE 2-32. Harness assembly (Rogers Corp.).

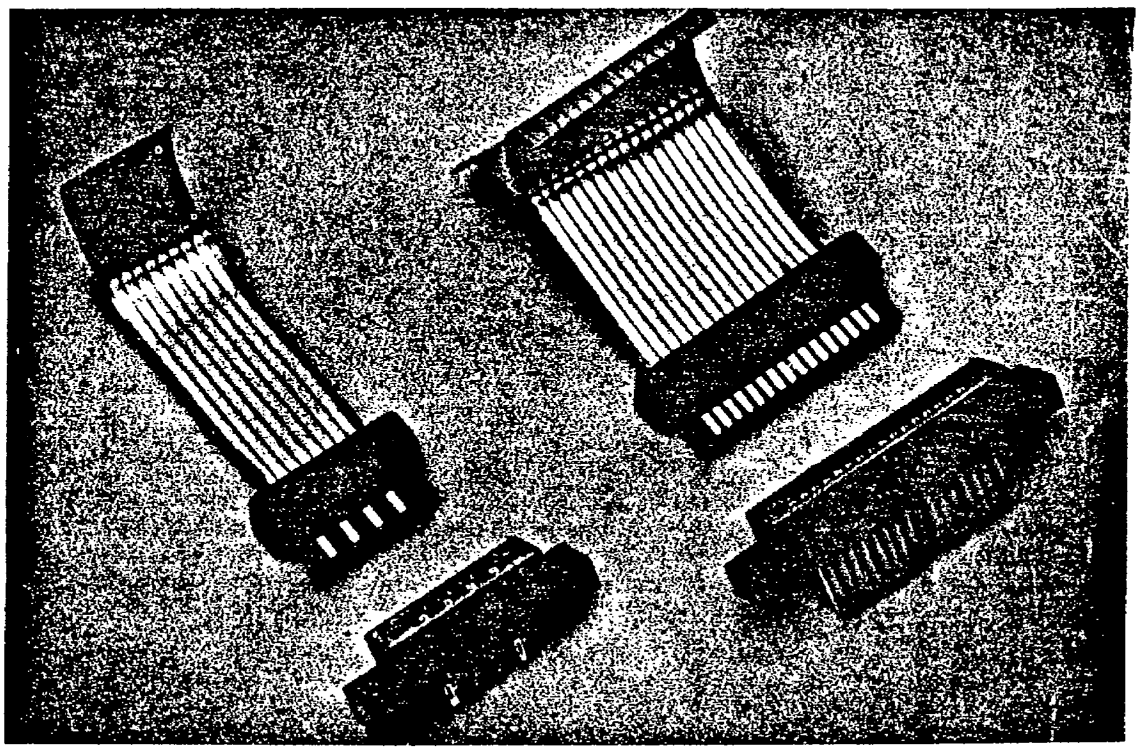


FIGURE 2-33. Harness assembly (ECS).

Figure 2-33 shows the Electronic Connective Systems (ECS) SIM/PLUG[5] FCC system. Complete harness assemblies with molded-on plugs are furnished by EGS. The 100-mil centerline connectors are presently tooled, and the design has been completed for 50-mil centerline. Both opposed and alternating contact configurations are available. The opposed arrangement permits redundant contacting for each conductor when used with a single cable. For maximum density with the opposed arrangement, two separate cables can be terminated in the single plug. The copper conductors can continue through a plug to provide parallel connections to a mating receptacle without interrupting the basic cable circuitry. The receptacle contacts are available with various detailed configurations for soldering, wire wrapping, and PC-board tab soldering.

2.4 Wire Change Devices

2.4.1 Introduction. Various wiring-change devices have been proposed and developed for FCC interconnecting systems. The philosophy, application, and hardware descriptions are given in Section IV for many different schemes. The following paragraphs define existing and prototyped hardware for accomplishing wiring changes.

2.4.2 FCC to RWC Transition. Figure 2-34 shows both a straight-and right-angle version of a round-wire plug with an adapter-bracket-supported FCC to RWC transition. As detailed in Section IV, Paragraph 4.2.1.2, NASA/MSFC has completely developed, tooled, and tested this wire-change transition device. The use of removable crimp pins in the RWC connector permits simple rework for maximum pin-assignment changes. Section VI, Paragraph 6.3.7, describes the manufacturing techniques for accomplishing the required transition.

2.4.3 PC-Board Distribution Box. Figures 2-35 and 4-11 show a PC-board distribution box developed by NASA/MSFC. Circuit changes are accomplished by introducing a short removable length of parallel-conductor PC-board on which the necessary alterations or connections are made. This unit is installed between two NASA/MSFC conductor-contact plug assemblies. Nonsymmetrical mounting holes assure proper installation registration of the distribution box.

2.4.4 Jumper-Wire Distribution Box. Figures 2-36 and 4-10 show a typical jumper-wire distribution box using NASA/MSFC FCC to RWC receptacles. The required interconnections are made by soldering insulated RWC between solder pots of the two receptacles. More than two receptacles can be used as required, and the box can be pressurized. Simple field rework can be easily accomplished.

2.4.5 Termi-Point[6] Distribution. Figure 2-37 illustrates a multiple-receptacle distribution unit mockup made by MDC under contract to NASA/MSFC. A receptacle similar to the conductor-contact FCC receptacle, except for Termi-Point posts, would be required. This unit would be capable of automatic interconnection, but could also be wired and/or reworked with simple hand tools.

2.5 Clamps

2.5.1 Introduction. The rectangular cross section of FCC precludes the use of conventional cushioned clamps used with RWC bundles. During the Saturn IV-B FCC Development Program, goals were established for clamp designs, and various type clamps were developed and installed on the mockup fixture.

2.5.2 Design Goals. Design goals for clamps to be used with FCC interconnecting harnesses are listed as follows:

a. Simple and lightweight

b. Utilize captivated hardware (no loose parts)

5. Trade name of ECS.
6. Trade name of AMP Incorporated.

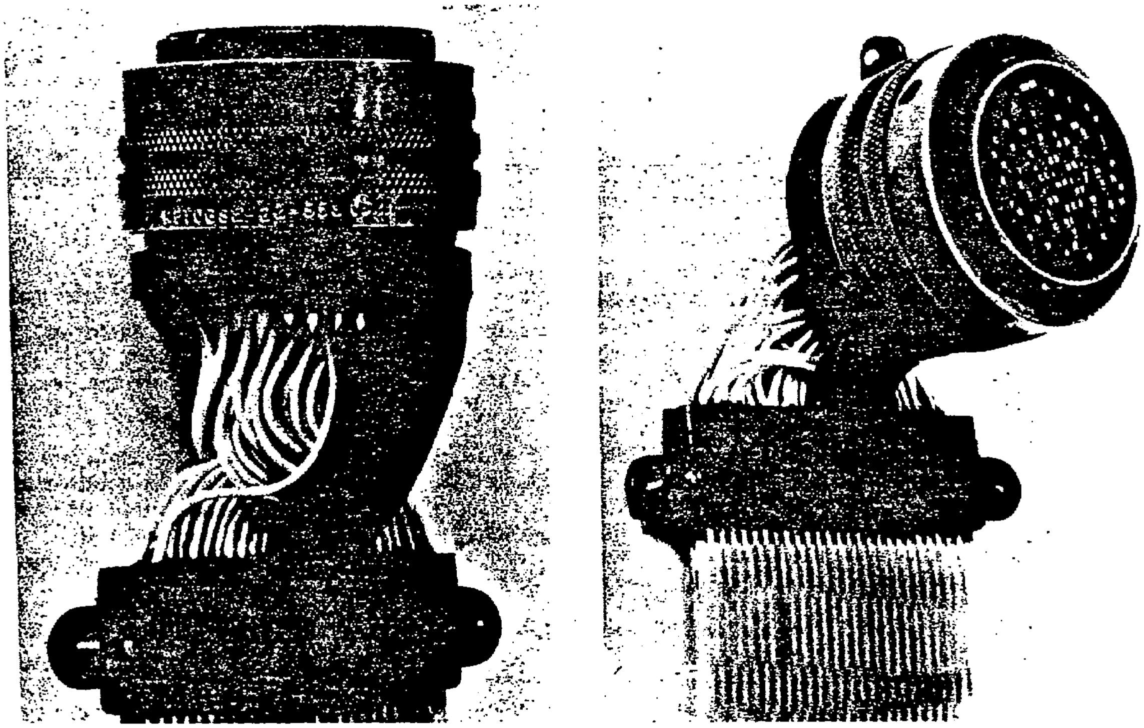


FIGURE 2-34. FCC to RWC transition.

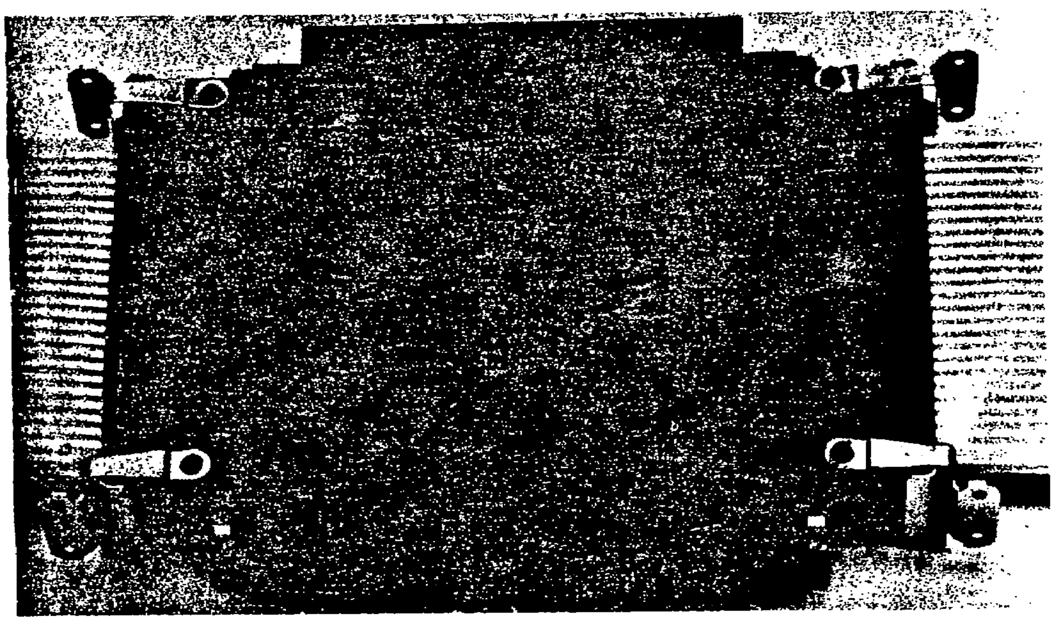


FIGURE 2-35. PC-board distribution box.

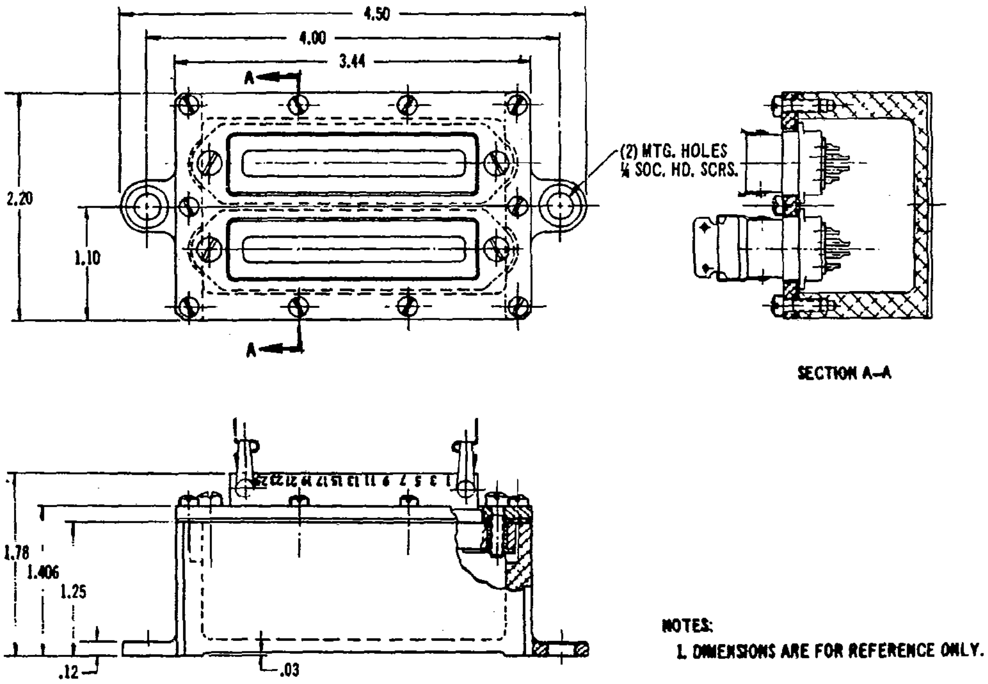


FIGURE 2-36. Jumper wire distribution box.

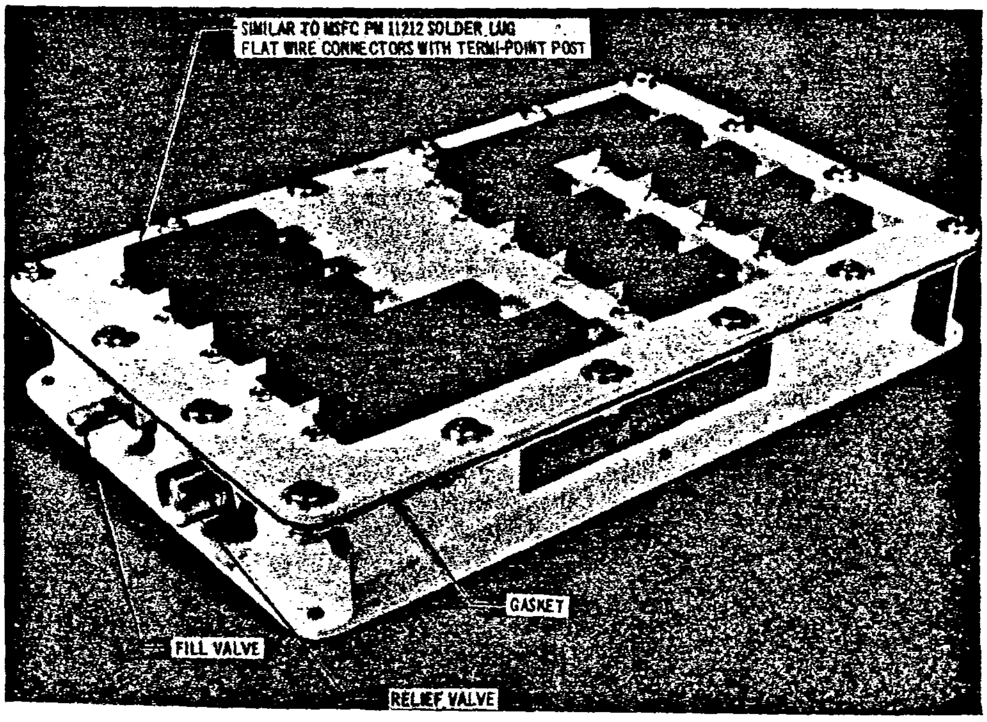


FIGURE 2-37. Termi-point distributor.

c. Require minimum mounting cutouts and hardware in supports or structure.

d. Modular in construction to accommodate the different FCC widths with the same clamp design.

e. Contain no sharp protrusions.

f. Be capable of installing in blind or poor-access areas.

2.5.3 Clamps for Severe Environmental Conditions. Several clamp types have been developed which are suitable for the handling, temperatures, and vibrations normally encountered in airborne applications. These are described in the following paragraphs.

2.5.3.1 Nonmetal Clamps for 100°C. Figures 2-38, 2-39, and 2-40 show lap clamps. These clamps utilize a Velero hook-and-pile material to securely hold the FCC bundles. The multiple clamps permit the minimum centerline spacing between adjacent bundles. The grommet prevents the tearout of the nylon material when exposed to loads over an extended time period. The Velero material and the nylon plunger fasteners are available from the Hartwell Corporation.

Figure 2-41 shows a lap-type clamp and support suitable for installation on curved surfaces.

Figure 2-42 shows a tubular cushioned clamp developed by NASA/MSFC which utilizes nylon fasteners. Figure 2-45 shows a similar clamp which uses conventional attaching screws in lieu of the nylon fasteners.

2.5.3.2 Metal Noncushioned Clamps for 200°C. Figure 2-43 shows a simple C-section aluminum clamp with captivated attaching screws. Tests conducted by NASA/MSFC on this type clamp indicate that maximum screw torque can be applied to a polyimide (Kapton) FCC over an extended time period without mechanical or electrical degradation of the FCC.

Figure 2-44 shows a tubular metal clamp for FCC right-angle routing and support. Sheet-metal spacers, similar to the one shown on Figure 2-45, are installed under the tubes for properly securing the FCC metal bracket.

2.5.3.3 Metal-Cushioned Clamps for 200°C. Figure 2-47 shows a metal-cushioned clamp with Expando grip fasteners. This clamp requires only a round mounting hole in the support brackets, and is installed and removed by rotating the fastener a quarter turn. The fasteners are available from the Adjustable Bushing Company, North Hollywood, California.

Figure 2-48 shows a double-grip cushioned clamp which provides added resistance to cable slippage. Figure 2-49 shows two simple-cushioned C-channel clamps used to accomodate two adjacent right-angle folds for nonshielded FCC.

2.5.4 Clamps for Noncritical Application. Figure 2-50 shows two plastic clamps and fasteners utilizing existing, commercially available hardware. These are the simplest and lowest cost of all clamps presented.

2.5.5 Shop-Aid Clamp Support. Figure 2-51 shows a shop-aid cable support. It permits all FCC harnesses to be temporarily routed and assembled on the deliverable end item. These clamps are then replaced by flight-type clamps prior to the final installation.

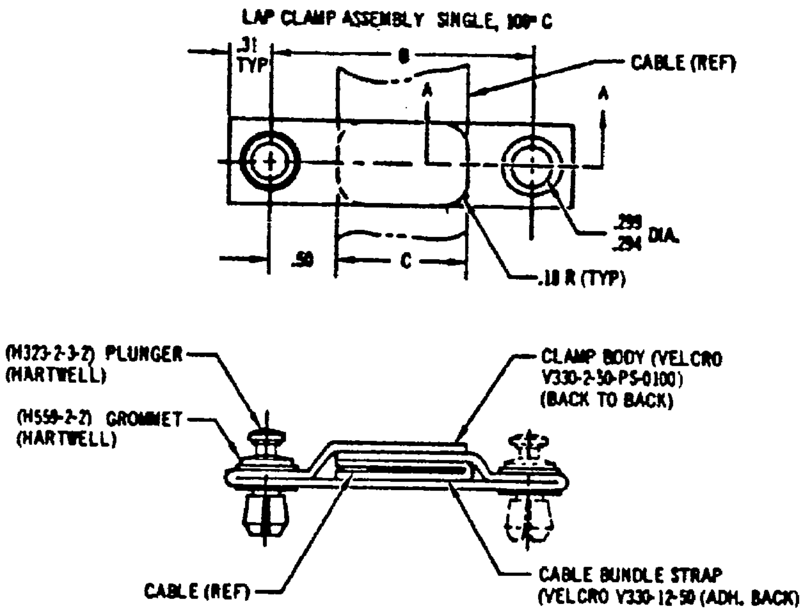
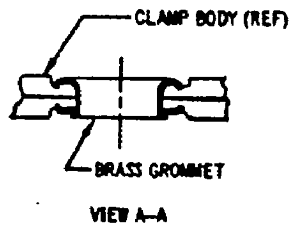


TABLE I			
CLAMP ASSY TYPE	CABLE WIDTH IN INCHES	B DIM.	LAP DIM. C
I	½" - 1"	2"	1"
II	1¼" - 2"	3"	2"
III	2¼" - 3"	4"	3"



GENERAL NOTES:

1. PROVIDE $\frac{.314}{.312}$ DIA. MOUNTING HOLE FOR INSTALLATION OF CLAMP ASSEMBLY.
2. CLAMP ASSEMBLY CONSISTS OF CLAMP BODY, CABLE BUNDLE STRAP, TWO (2) BRASS GROMMETS, TWO (2) PLUNGERS, AND TWO (2) GROMMETS.

FIGURE 2-38. Lap clamp assembly, single, 100° C.

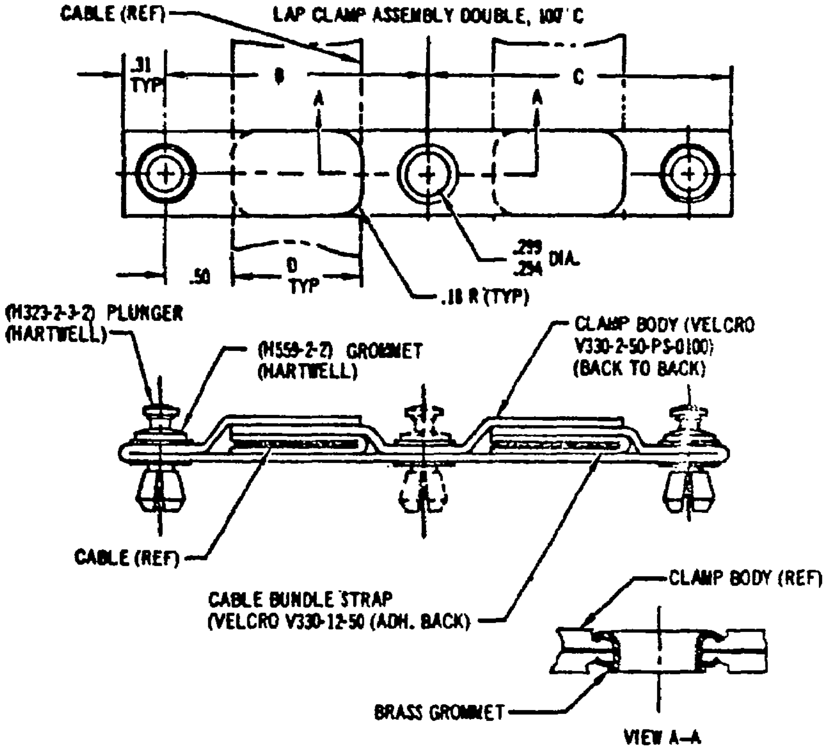


TABLE I				
CLAMP ASSY TYPE	CABLE WIDTH IN INCHES	B DIM.	C DIM.	LAP DIM. C
I	½" - 1"	2"	2"	1"
II	1½" - 2"	3"	3"	2"
III	2½" - 3"	4"	4"	3"

GENERAL NOTES:

1. PROVIDE $\begin{smallmatrix}.314\\.312\end{smallmatrix}$ DIA. MOUNTING HOLE FOR INSTALLATION OF CLAMP ASSEMBLY.
2. CLAMP ASSEMBLY CONSISTS OF CLAMP BODY, TWO (2) CABLE BUNDLE STRAPS, THREE (3) BRASS GROMMETS, THREE (3) PLUNGERS, AND THREE (3) GROMMETS.

FIGURE 2-39. Lap clamp assembly, double, 100° C.

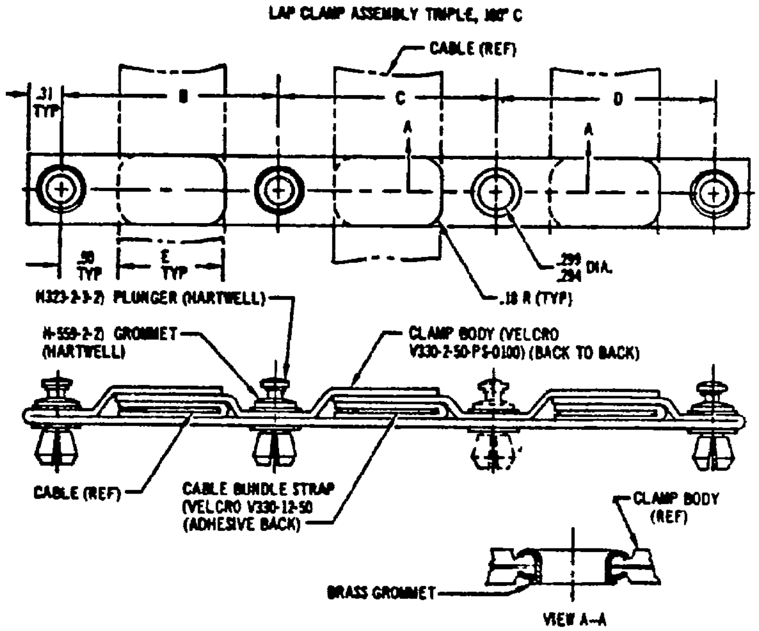


TABLE I

CLAMP ASSY TYPE	CABLE WIDTH IN INCHES	B DIM.	C DIM.	D DIM.	LAP DIM. E
I	¼" - 1"	2"	2"	2"	1"
II	1¼" - 2"	3"	3"	3"	2"
III	2¼" - 3"	4"	4"	4"	3"

GENERAL NOTES:

1. PROVIDE $\frac{.314}{.312}$ DIA. MOUNTING HOLE FOR INSTALLATION FOR CLAMP ASSEMBLY.
2. CLAMP ASSEMBLY CONSISTS OF CLAMP BODY, THREE (3) CABLE BUNDLE STRAPS, FOUR (4) BRASS GROMMETS, FOUR (4) PLUNGERS, AND FOUR (4) GROMMETS.

FIGURE 2-40. Lap clamp assembly, triple, 100° C.

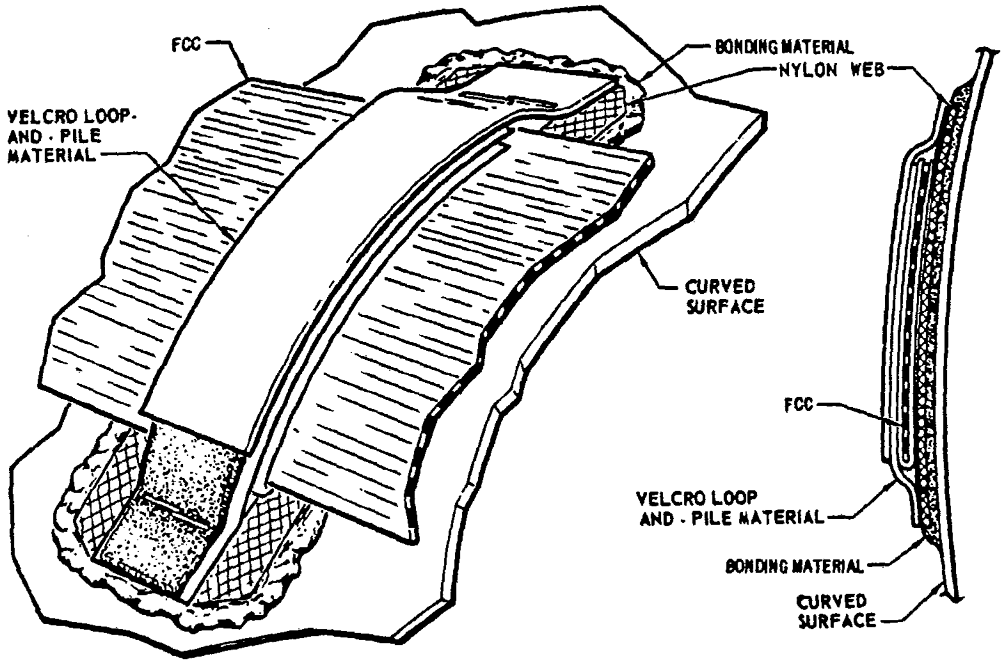


FIGURE 2-41. Lap clamps and support, curved surface, 100° C.

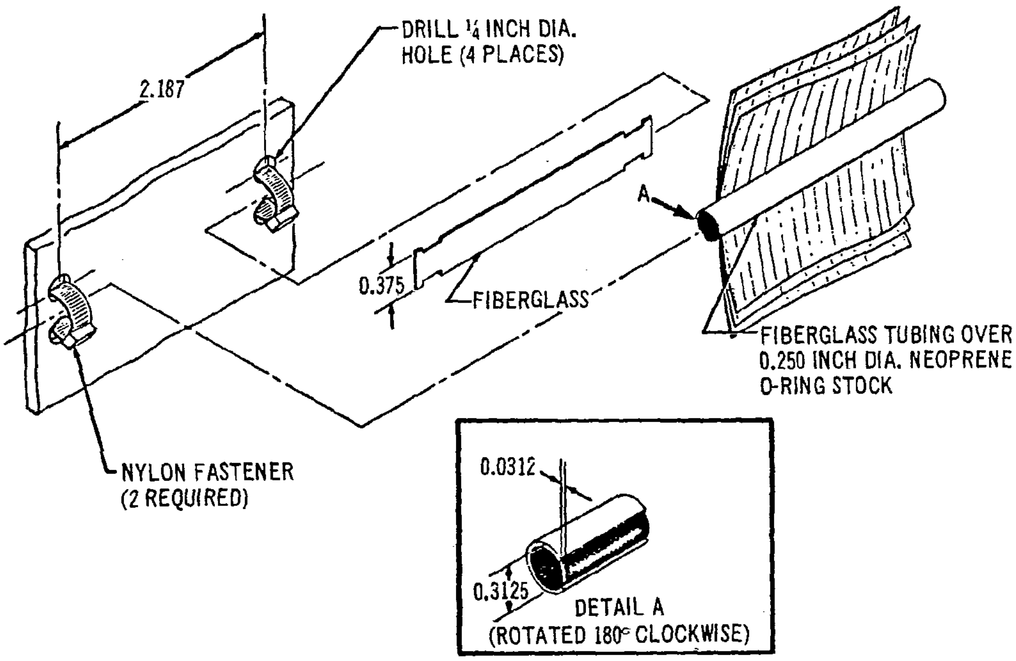


FIGURE 2-42. Tubular clamps with nylon fasteners, 100° C.

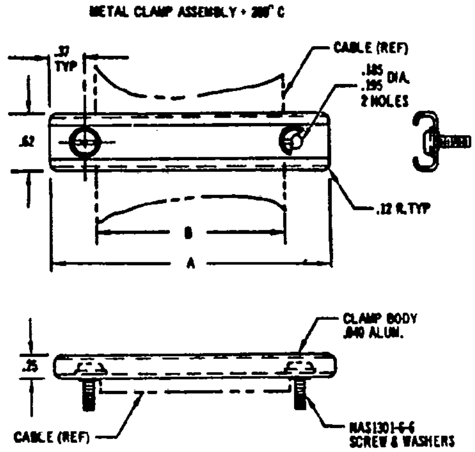


TABLE I			
CLAMP ASSY TYPE	CABLE WIDTH IN INCHES	A DIM.	B DIM.
I	1/2" - 1"	2"	1"
II	1 1/2" - 2"	3"	2"
III	2 1/2" - 3"	4"	3"

GENERAL NOTES
1. CLAMP ASSEMBLY CONSISTS OF CLAMP BODY, TWO (2) SCREWS, TWO (2) WASHERS. TWO (2) RETAINERS.

FIGURE 2-43. Metal noncushioned clamps, 200° C.

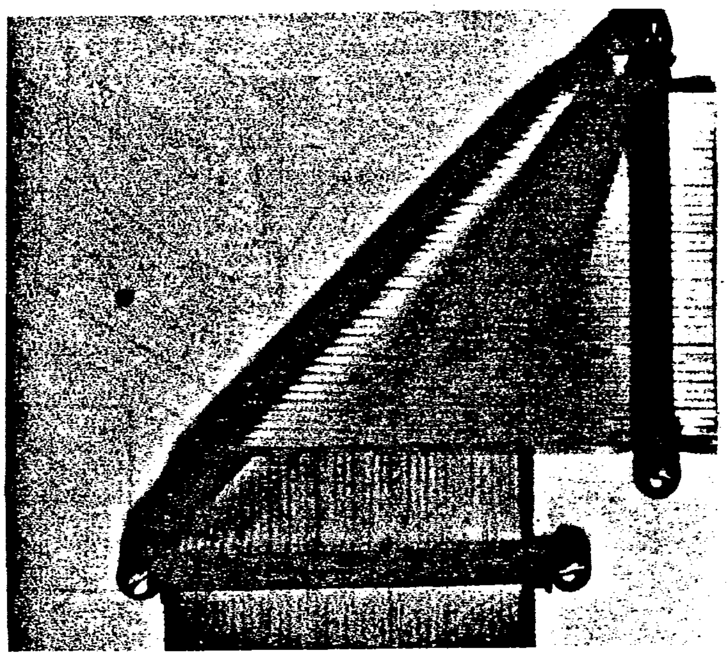


FIGURE 2-44. Metal noncushioned clamp, right-angle tubular, 200° C.

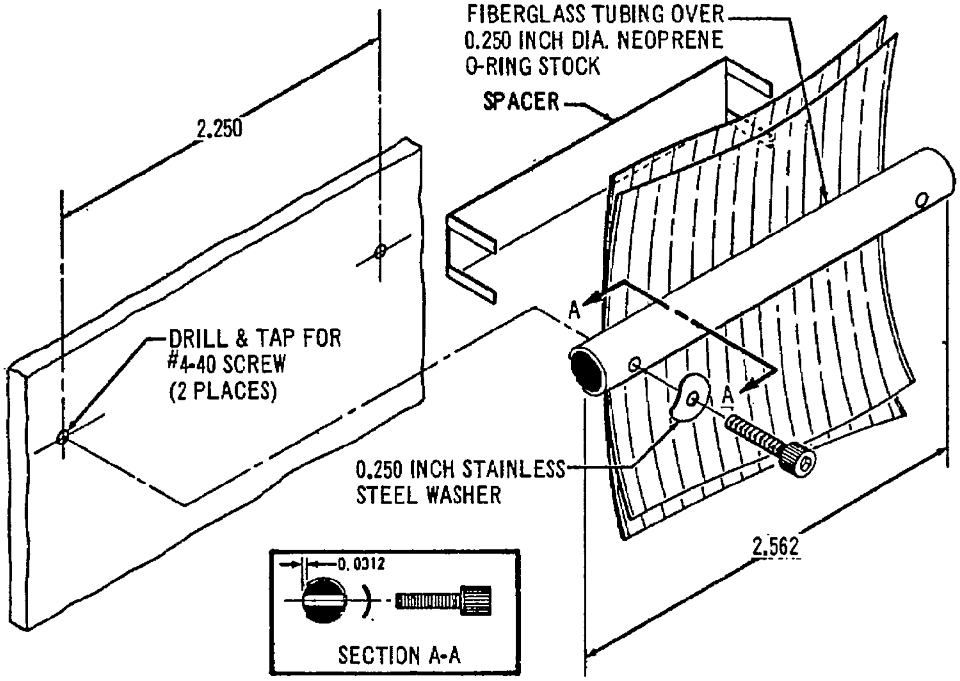


FIGURE 2-45. Tubular clamps with screw fasteners, 100° C.

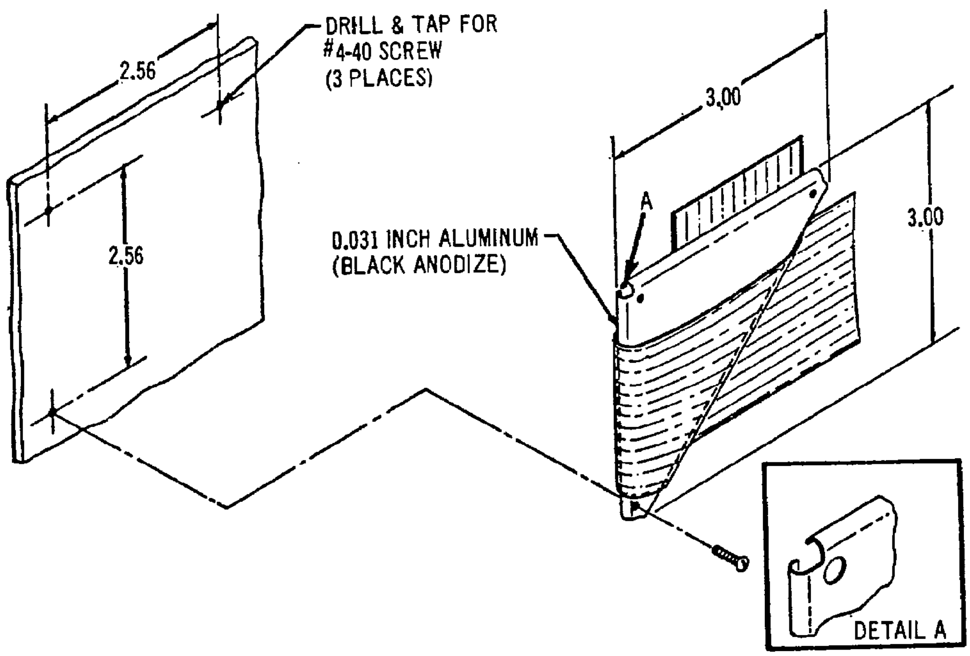


FIGURE 2-46. Metal noncushioned clamp, right-angle sheet metal, 200° C.

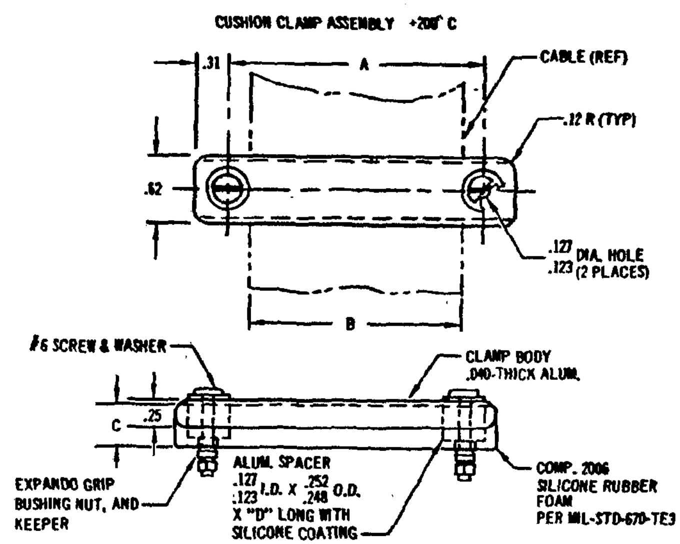


TABLE I					
CLAMP ASSY TYPE	CABLE WIDTH IN INCHES	A DIM.	B DIM.	C DIM.	D DIM.
I	½" - 1"	1.38	1"	.50	.30
IA	½" - 1"	1.38	1"	.60	.40
II	1½" - 2"	2.38	2"	.50	.30
IIA	1½" - 2"	2.38	2"	.60	.40
III	2½" - 3"	3.38	3"	.50	.30
IIIA	2½" - 3"	3.38	3"	.60	.40

GENERAL NOTES:

1. PROVIDE $\frac{.317}{.312}$ DIA. MTG. HOLE FOR INSTALLATION OF CLAMP ASSEMBLY.
2. ALL CUSHIONS TO BE INSTALLED TO CLAMPS USING RTV-731 CEMENT.
3. CLAMP ASSEMBLY CONSISTS OF CLAMP BODY, SILICONE RUBBER CUSHION, TWO (2) NO. 6 SCREWS, TWO (2) WASHERS, TWO (2) EXPANDO GRIP BUSHINGS, NUTS, AND KEEPERS, TWO (2) SPACERS.

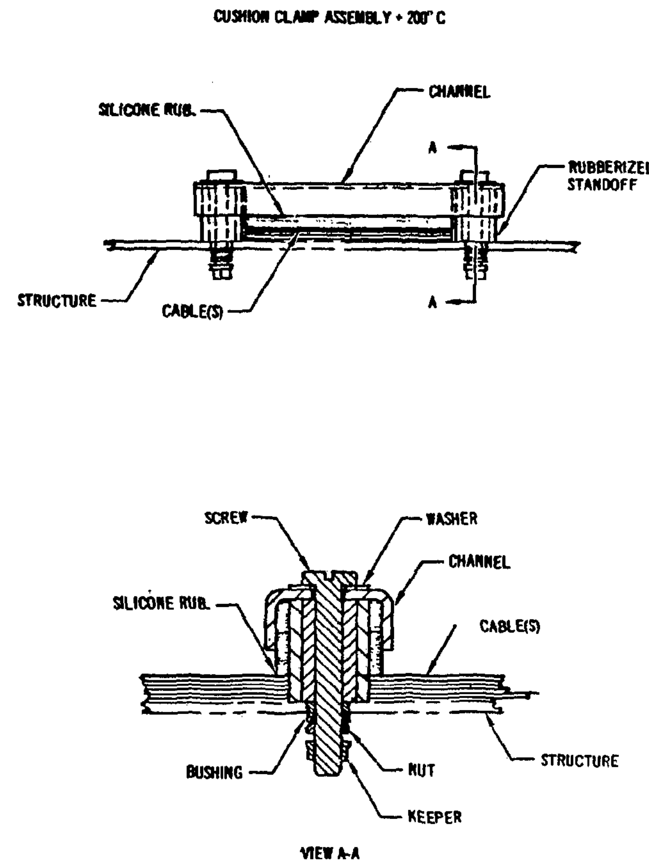


FIGURE 2-47. Metal-cushioned clamp, 200° C.

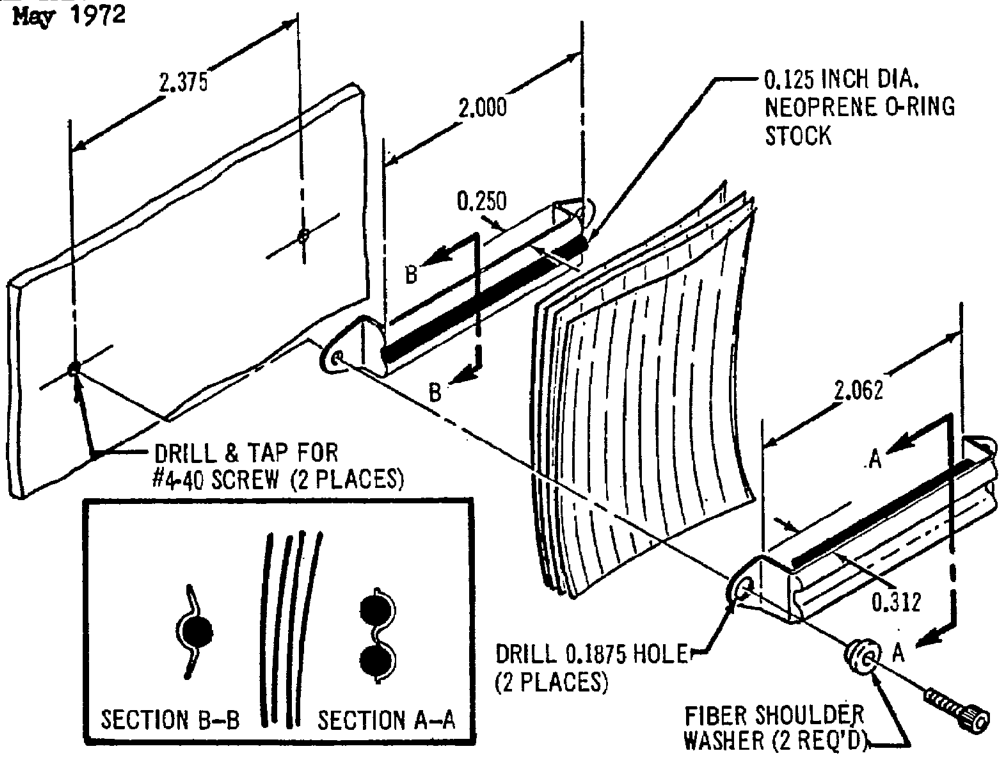


FIGURE 2-48. Metal-cushioned clamp, double grip, 200° C.

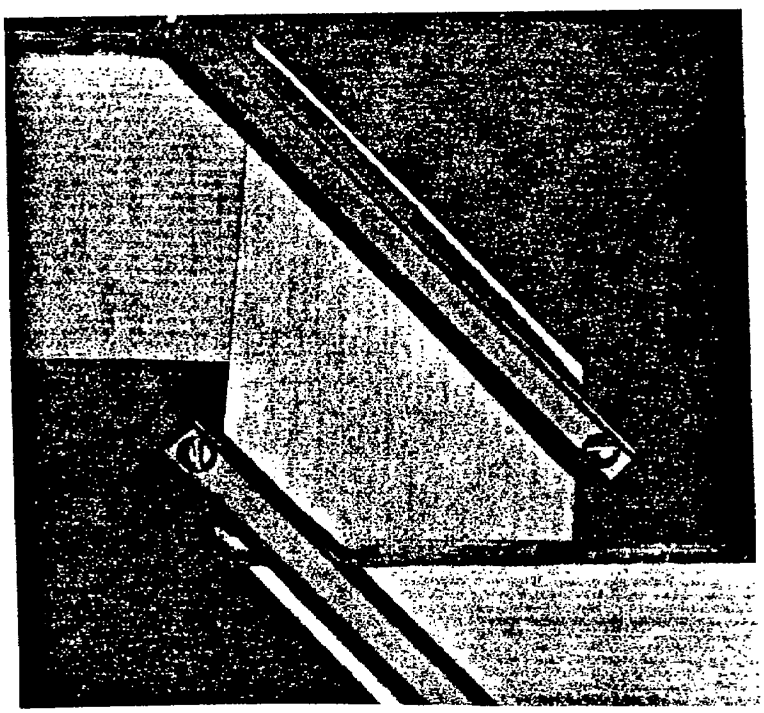


FIGURE 2-49. Metal-cushioned clamps for angle fold, 200°C.

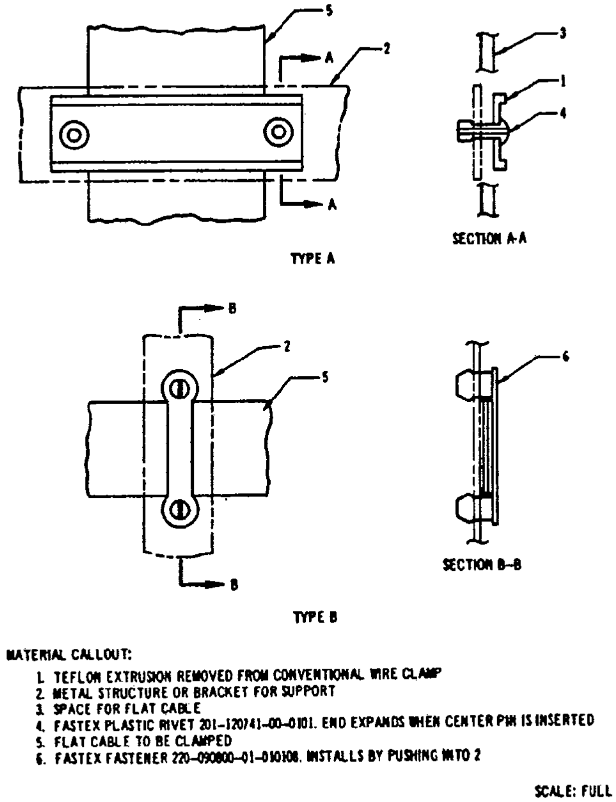


FIGURE 2-50. Plastic clamps and fasteners.

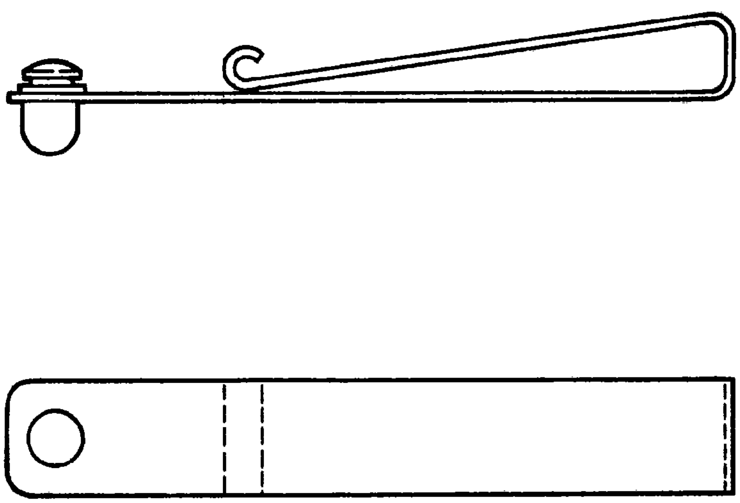


FIGURE 2-51. Shop aid cable support.

2.6 Supports

2.6.1 Introduction. The use of FCC, with the resultant fewer numbers of simpler wire harness runs, reduces the quantity and complexity of the required support system. The philosophy, promoted throughout this report, of considering the FCC interconnection harnesses as system components and including them into the initial design and development encourages careful thought and consideration for a simple, lightweight, efficient support system. Section III and IV contain additional information on FCC supports.

2.6.2 Use of Existing Structure. Every attempt should be made to support the FCC bundles directly to existing structure (Figures 1-1 and 1-2). This practice assures the rigidity, minimum weight, fewest protrusions, and most uniform installation to the structure ground plane. Structure sections of Z's, L's, C's, hats, etc., generally contain rigid, flat surfaces that are ideally suited for FCC bundle support. It is necessary only to drill the required mounting holes for the FCC clamps to be used. In many cases the FCC can be bonded directly to existing structures, thus eliminating even the drilling of mounting holes. Very often, inverted channels and other basic-structure cross-sections provide a high degree of mechanical protection in addition to the support medium.

2.6.3 Added Supports. Added supports may be used if necessary to complete the support system for the FCC bundle runs and clamps.

Stress considerations often prohibit the addition of modular mounting holes in basic structure. However, simple, lightweight sections can be riveted directly to the structure sections to provide the desired mounting brackets (Fig. 2-52).

FCC support sections were developed and installed on the Saturn IV-B development mockup. Figure 6-48 shows typical sections used. The modular mounting-hole pattern shown permits installation of the supports prior to final development. The number, size, and exact installation locations of the FCC clamps can be selected as required without change to the support system. Subsequent changes in production or in the field can also be accommodated with no drilling, riveting, etc., on the end item.

For airborne applications, the support sections will generally be aluminum with the proper finish in accordance with the program requirements. However, for thermal isolation, fiberglass and other nonmetals can be used. The use of high-performance adhesives permits these sections, as well as metal support sections, to be bonded directly to basic structures to eliminate any possibility of degrading the existing structure with attaching mounting holes.

2.7 Adhesives and Tapes

Numerous adhesives and tapes have been evaluated for use with FCC systems. A brief description is given in the following paragraphs.

2.7.1 Adhesives. The recent development of FCC for use in space vehicles has created a demand for more practical and effective methods of securing the cabling to space vehicle surfaces. To meet this demand, adhesive systems have been investigated to eliminate the need for most of the tie-downs, clamps, and other mechanical securing devices generally used in conventional cable installations.

A desirable adhesive system is a pressure-sensitive type which cures at room temperature. The adhesive may be a two-part system which is mixed and brushed on, or it may be a solvent-activated type.

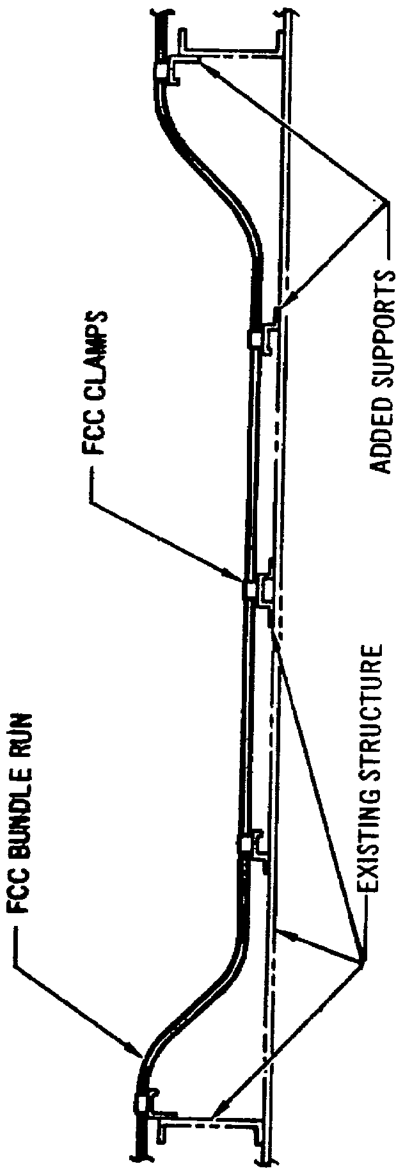


FIGURE 2-52. Typical FCC support installations.

Extensive tests have been conducted by NASA/MSFC with Minnesota Mining and Manufacturing Company's liquid-type EC-1099 adhesive for bonding polyester (Mylar) and polyimide (Kapton) cables to a liquid oxygen tank to test the ability of the adhesive to withstand the severe temperature changes (-160°C to 30°C) over several months without delamination. The bond strength increased with age.

Polyester to polyester or to aluminum joints, bonded with 3M's adhesive EC-1099 or Fasson Products Corporation's pressure-sensitive-type adhesive S-277, passed rigid mechanical and environmental test requirements imposed upon the joint to simulate conditions encountered in space flight. Dow Corning's Silastic 140 passed all environmental tests to which it was subjected, but did not have the desired initial peel and creep strengths.

Adhesives will not adhere to Teflon unless the surface has been treated to make it bondable. Tetra-Etch, prepared by W. L. Gore and Associates, Inc., is either poured on the surface or the cable is dipped into the etchant. All types of adhesives bond well to the carbonaceous film which the etchant forms on the Teflon. It is recommended to follow the manufacturer's etching procedures.

Table 2-4 shows some of the various adhesives and their comparative bonding strength. The bond is tested for creep strength by applying small loads. To determine tear strength, the 1-inch-wide cable is pulled 90 degrees from the surface of the substrate at the speed of 30 centimeters per minute. The force needed to cause tearing is the tear strength per inch width.

TABLE 2-4. TYPICAL ADHESIVES FOR FLAT-CABLE INSTALLATION

Designation	EC1099	Silastic 140	S-277
Mfg Source	3M	Dow Corning	Fasson
Type	Nitrophenolic	Silicon	Polyester
Condition	Liquid	Paste	Film
Application	Brush	Trowel	Hand
Material Bonded	Mylar, H-film	Mylar	Mylar, H-film
Temp. Range (°C)	-160 to +120	-160 to +100	-25 to +100
Cure Temp	Room Temp	Room Temp	Room Temp
Cure Time (hr)	24	24	24
Peel Strength	15 lb/in	12 lb/in	10 lb/in

Good results have been obtained by the use of a nitrophenolic resin for mounting polyimide cable to aluminum.

A polyimide/FEP cable bonded to an aluminum sheet 0.0625 by 6.0 by 48.0 inches was exposed to a weathering test at the southside (sunny side) of NASA/MSFC Laboratory building starting in August 1963. The cables delaminated after 10 months, but the insulation layer, cemented with EC-1099 and Fasson S-277 adhesives to the aluminum substrate, remained in place more than 20 months.

Another test was performed with a polyester (Mylar) cable using the same adhesives and substrate. The bond between the substrate and the cable is in good shape after over 5 years of exposure to the weather. The temperature ranged from -10°C to +50°C, and the humidity varied from dry weather to rain.

Other bonding tests were made at cryogenic temperatures by cementing flat cables to a painted liquid oxygen (LOX) tank. The cables were polyester (Mylar) and polyimide (Kapton), each 10 feet long, and EC-1090 was used to bond the cables to the tank. This test was continued over several months. The LOX tank was filled every Monday and emptied during the week while rocket engines under test were using LOX. Temperature of the tank skin ranged from -160°C to +30°C. Neither icing nor changes in cable length, because of expansion and contraction, broke the bond. These tests indicate the practicality of adhesive bonding.

3M EC-2216 epoxy adhesive has been used successfully for mockup applications, but has not been subjected to extensive physical testing.

2.7.2 Tapes. Permacel EE6379 Kapton adhesive tape has been used in a mockup application, but has not been subjected to extensive physical testing. This material performed satisfactorily at ambient temperatures over a 2-year period. A word of caution is in order regarding the use of pressure-sensitive adhesive tapes. The entended application should be analyzed for possible peel and creep loads, since the pressure-sensitive tape has very low resistance to these loads.

SECTION III. DESIGN APPLICATION

3.1 Introduction

3.1.1 Purpose. The purpose of this section is to provide the necessary information for the consideration and implementation of the FCC system for electrical network interconnections.

The advantages, limitations, various design considerations, methods of implementation, special considerations, and mechanized design are included.

This section provides pertinent information for personnel responsible for selection and design of the interconnecting harness system to be used on a given program. The many advantages to be gained by FCC must be weighed against its limitations or restrictions early in the program, and an intelligent decision made on the type and extent of FCC system to be employed.

3.1.2 Comparison of FCC to RWC Systems. RWC interconnecting network systems have been used successfully for many years. Although higher-density connectors, thinner and better cable insulations, and high-strength alloy conductors are being used, the basic RWC harnesses generally still require individual conductor handling, identification, and termination. The individual conductors and insulation are subjected to potential concentrated strain and abrasion. The RWC system for interconnecting networks is generally limited to the size of conductors that can be used by mechanical and handling requirements.

The FCC systems, with conductors laminated between high-performance lamination sheets, can provide very small gages for minimum weight and space with maximum reliability and minimum cost. These are important factors which will influence the extensive use of FCC systems in the future.

3.1.2.1 Advantages of FCC System. Previous studies and system testing have indicated that up to 75 percent of the existing shielded cable on RWC systems can be replaced by nonshielded FCC by controlling the conductor registration in the harness runs. This is a major advantage of the FCC systems; however, in the comparisons that follow, this factor has not been included. Therefore, the actual advantages will be even greater than indicated. Also, all comparisons are made on equivalent conductor cross-section areas. In practice, the large surface areas of the FCC permit higher current densities (See Paragraph 3.2.3.1.3).

3.1.2.1.1 Weight Comparison. From previous studies, the weights for FCC supports and clamps are considerably less than those used with RWC. This saving results primarily from cable stacking and from simplification of clamping and supports for FCC.

The weight comparison for electrical connectors is dependent upon the connector system selected. In general, the FCC conductor-contact connector system, developed by NASA/MSFC, provides appreciable weight savings over the current, miniature, round connectors. These savings are realized primarily from the conductor-contact plug; however, it can be generalized that the weight of an FCC connector system will be equal to or less than the weight of an equivalent RWC connector system.

The cable, itself, provides the major weight savings for FCC system, especially in the smaller conductor cross-sections.

Figure 3-1 shows actual weight comparisons of three types of RWC with varying wall thicknesses and types of insulation, and FCC H/FEP standard and high-density cable per MIL-C-55543. The conductor area in square mils is plotted against weight in pounds per 1000 conductor feet to provide actual weight comparisons.

It can be concluded that appreciable weight savings can be achieved by the use of the FCC system and that the savings are greatest when the conductor cross-sections are minimized. Savings for shielded FCC are even greater than those for nonshielded FCC.

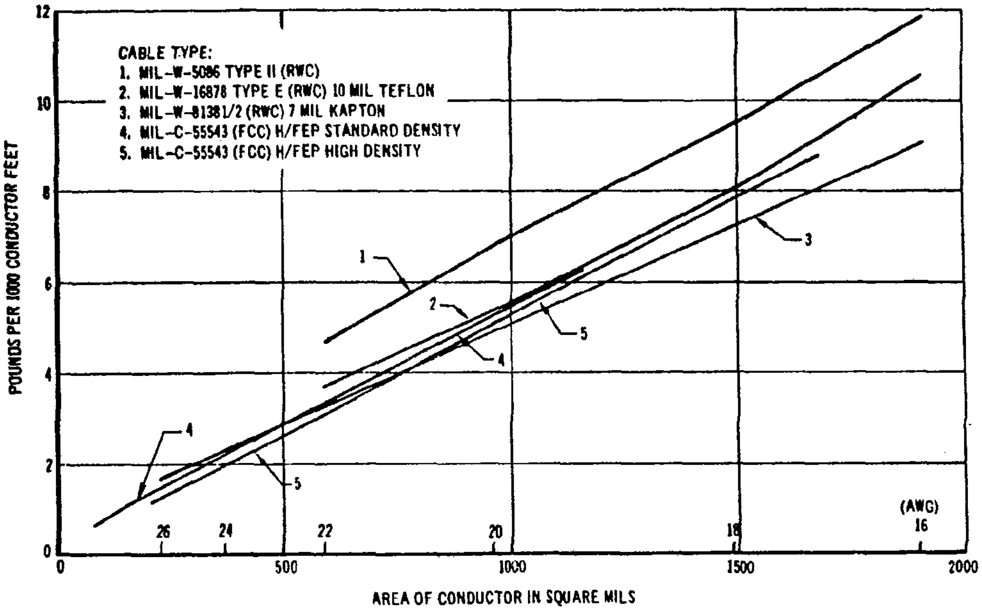


FIGURE 3-1. Nonshielded cable weight comparison.

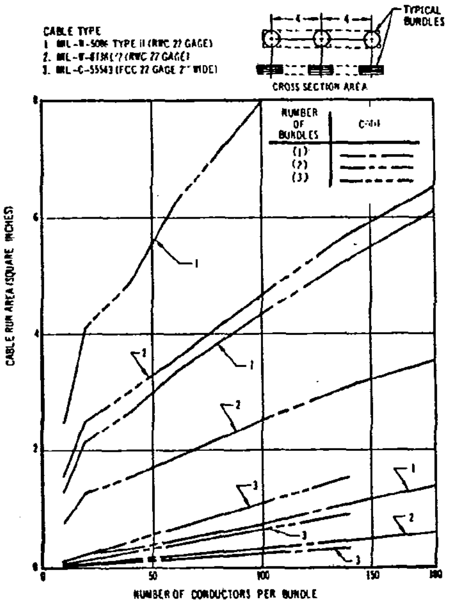


FIGURE 3-2. Nonshielded cable space comparison.

3.1.2.1.2 Space Comparison. Space comparisons have been made for various bundle run configurations and for the panel space required on electronic units for the installation of connectors.

Space saving for the FCC cable is inherent in its geometric cross-section and in the positive control of the locations of each conductor in the bundle runs which permits the use of fewer bundle runs.

Figure 3-2 shows actual comparisons of the bundle run areas required for one, two, and three bundles for two types of RWC and H/FEP FCC. It can be seen that the space saving is minimum for a single bundle and increases rapidly with the number of bundles. The space savings shown are particularly advantageous in tunnel and other congested areas where a minimum height cross-sectioned area is available for harness runs.

Appreciable connector mounting and handling area savings are achieved by the FCC connector system (Figs. 1-5 and 1-6).

It can be concluded that the FCC system offers major space savings in bundle runs and in panel mounting and handling areas.

3.1.2.1.3 Cost. To arrive at realistic cost comparisons, the cost of materials (including cable, connectors, supports, etc.) design, development, harness fabrication, and installation must be considered. Table 3-1 lists the cost comparison between FCC and RWC systems. The basis for many of the cost figures were taken from a study which included the development, fabrication, and installation of over 100 FCC harnesses of the MSFC conductor-contact system. Because of the many variables involved, certain general assumptions and conclusions have been made as follows:

a. To realize the cost savings indicated, FCC must be applied early in the program. Studies pointed out the additional costs of redesign, including those for design, development, and requalification.

b. The major cost saving for the FCC system is the recurring harness fabrication cost which is reduced 80 percent. This saving is realized by handling, identifying, and terminating all conductors in each plug layer, simultaneously.

c. The cost of the connectors will be approximately equal if the pin-and-socket-type FCC connector is used. The MSFC conductor-contact FCC connector will provide a cost saving of approximately 35 percent for a mated pair.

d. The cost saving of FCC increases as the conductor cross-sections decreases.

e. The cost of supports and clamps for the FCC system will generally be substantially less because of the simplicity of installations and reduction of parts.

Figure 1-7 gives cost comparisons for a 2-inch-wide H/FEP FCC cable and Kapton-insulated alloy conductor RWC, per MIL-W-81381/2. An FCC predicted cost of $1.50 per linear foot for nonshielded and $3.00 for shielded cable was used. The cost of the RWC is based upon CY 1968 prices quoted for 25,000 linear foot lengths. The advantage trend for FCC in the smaller conductor cross section is maintained.

In general, it can be stated that substantial cost savings can be realized with the FCC system. The actual savings will depend upon the program requirements and the application techniques employed.

TABLE 3-1. COST COMPARISON — FCC VERSUS RWC SYSTEMS

Item	Subitem of Major Item (%)	FCC Cost Saving (%)	
		Subitem	Major Item
Engineering			-5
System	25	-10	
Harness Layout	25	-10	
Production Drawings	25	0	
Schematics, etc.	25	0	
Development			20
Materials			28
Cable	40	0	
Connectors	40	35	
Clamps	5	50	
Supports	15	75	
Harness Fabrication			80
Harness Installation			40

Notes:

1. Percentages listed above are average and can vary from program to program.

2. Subitem percentages have been listed from typical space system programs.

3. Cost savings for all major items except engineering have been influenced heavily by the Reference 1-1 study; however, cost comparison reports by other major contractors verify these percentages.

4. To establish actual program percent or dollar savings would require the establishment of dollar costs for each of the major items listed above.

5. The recurring harness fabrication cost saving of 80 percent is realistic for all programs properly utilizing FCC systems, and will contribute heavily to its future use.

3.1.2.1.4 System Performance. System performance, through the use of FCC interconnecting harnesses, can be greatly improved. The FCC configurations can be selected to provide the electrical characteristics actually required by the system. Past routine selection of twisted, shielded, and other special RWC configurations has resulted in expensive, overly designed, and overweight systems requiring excessive space for installation. The positive placement control of each conductor circuit in its cable and in the bundle runs assures predictable performance plus repeatability from unit to unit.

3.1.2.1.5 Others. Other advantages of FCC include:

a. Increased mechanical strength provided by high-performance, laminated insulation layers or sheets.

b. Permits identification, termination, and handling of cable by layers, rather than individual conductors.

c. Provides many special application possibilities as explained in Paragraph 3.2.8.

3.1.2.2 Limitations in Use of FCC System. It is very important that the personnel responsible for the program application of FCC understand the current status of the system being considered, and the inherent characteristics that differ from the RWC system that has been used routinely for such a long time.

3.1.2.2.1 Hardware Availability. In the past, FCC and FCC connectors, qualified to military specifications acceptable to government and prime contractor agencies, were not available. Now, triservice coordinated military specifications, MIL-C-55543 for nonshielded FCC and MIL-C-55544 for environmental shielded and nonshielded FCC connectors, are available. It is planned to release a military specification for shielded FCC cable in the near future. These specifications will provide the prime contractors and vendors with the guiding requirements for the development and qualification of FCC systems which can be used for general application on future programs.

Many existing programs have used FCC systems utilizing cable to NASA/MSFC, NAS, or company specifications with existing connectors used as is, or modified as required. The applications, which have been used so successfully, should be understood and considered for all future programs prior to the availability of a complete line of cable and connectors qualified to the military specifications.

Extensive evaluation and qualification tests to the requirements of MSFC-SPEC-220A have been successfully performed by and for NASA/MSFC on various FCC configurations. Qualification tests per MSFC-SPEC-219 have been successfully performed by two independent agencies on the NASA/MSFC conductor-contact connector system. Extensive FCC evaluation testing has been performed per NAS729 by USAEC of Ft. Monmouth, N.J. Since the performance requirements of MIL-C-55543 and MIL-C-55544 are essentially in accordance with the above listed specifications, it is anticipated that little difficulty will be encountered in qualification to the new specifications.

A complete line of military specification NASA/MSFC conductor-contact connectors, utilizing molded and premolded plugs, has been tooled and is currently available, with contacts on 75-mil centers. Additional effort is required for other centerline spacings, final production tooling, and formal qualification. One size single-layer pin-and-socket, shielded-type, military specification connector with 100-mil spacing has been developed and is being evaluation tested. Additional connector sizes and center spacings are required with qualification.

Studies have indicated all other hardware required for general FCC application is available, with the exception of a suitable production, high-reliability, distribution-unit system. The requirements for these units will be discussed in Paragraph 3.2.5 and design concepts will be covered in Section IV.

3.1.2.2.2 Harness Electrical Flexibility. The current RWC system permits random registration of conductors to connectors. Pin-assignment changes on connectors with removable crimp contacts can be readily made after initial connector assembly. Soldered and potted connectors are readily adaptable to pin-assignment design changes accomplished on new harness fabrication. The flexibility of the RWC system has resulted in the licensing, by all phases of engineering, of their right to avoid final harness pin assignments until very late in the development of the prototype or first article unit. The black-box designer was permitted to make wiring and pin-assignment changes, the system designer could change the systems' interconnections, and the harness designer made the final pin-assignment changes late in the development stages. This flexibility was provided at hidden costs which were more or less taken for granted. First, all major harness-run drawings required many engineering changes; 50 or more is common for todays complicated space systems. These engineering changes required costly planning and manufacturing changes. Second, this system provides random conductor registration with no assurance of electrical repeatability from unit to unit.

The FCC systems using the military specification connectors cannot make individual pin-assignment changes at the connectors on the FCC side. Although cable segments can be reversed and relocated, and pin-assignment-change devices can be incorporated into initial design, or added later as required, the harness pin-assignment flexibility is limited without distributors. The FCC system with distributors assures minimum harness drawing changes, permits registration control for all conductors, and provides the maximum interconnecting wiring network flexibility.

3.1.2.2.3 Terminating with Round Connectors. The termination of FCC to round connectors will be required when mating to existing or black boxes having round connectors, or when round connectors are used to provide pin-assignment flexibility. Several systems have been developed for this termination. The first shown in Figure 3-3 provides pin assignment changes, and the second shown in Figure 3-4 essentially has predetermined pin assignments. One method of manufacturing the Figure 3-3 transition is covered in Section VI. All methods add additional circuit joints and reduce the major harness cost saving afforded by layer termination to the connectors. The Figure 3-4 method should be used only for very special applications.

3.1.2.2.4 Multiple-Plane Bending. FCC permits very small bend radius and efficient multiplane bending and routing as described in Paragraph 3.2.6. However, the planar nature of FCC could present problems in some special routing requirements. An example would be of routing through conduit with bends in multiple planes.

3.1.2.2.5 Familiarization and Training

3.1.2.2.5.1 Design. New design philosophy, application techniques, and drawing preparation are required for the successful application of the FCC system. It is the primary purpose of Section III to present information for the design and application of the FCC system to electrical interconnecting networks.

3.1.2.2.5.2 Manufacturing. Manufacturing facilities producing and installing FCC systems must establish the required capability (including equipment), facility space, procedures, and trained personnel. It is the primary purpose of Section VI to detail these requirements for a typical FCC system.

3.1.2.2.5.3 Quality Control. It is important to establish the proper quality control on new production technologies. Section VII gives an extensive quality control treatise on receiving inspection for incoming cable and connectors, and for subsequent manufacturing processes for cable assembly and installation of FCC systems.

3.1.3 Conclusions. It can be concluded that the FCC system offers many advantages for future application of electrical interconnecting networks. A thorough understanding of the advantages which can be achieved, and the effort which must be expended, is necessary before FCC application can be intelligently considered. The information contained in Section III should be thoroughly reviewed, prior to proceeding with FCC application.

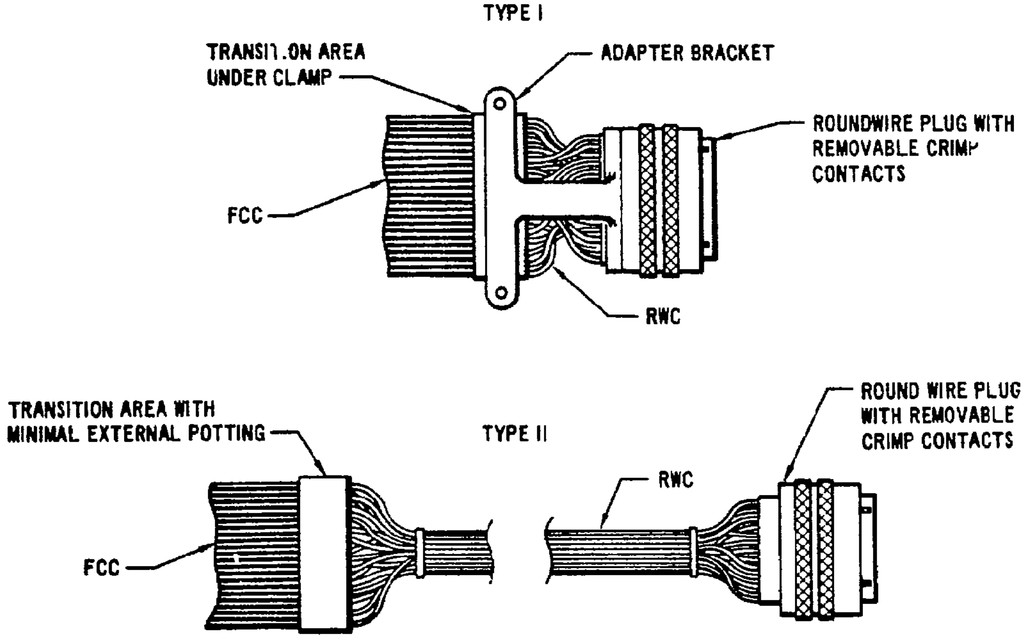


FIGURE 3-3. FCC to round connectors - with pin-assignment changes.

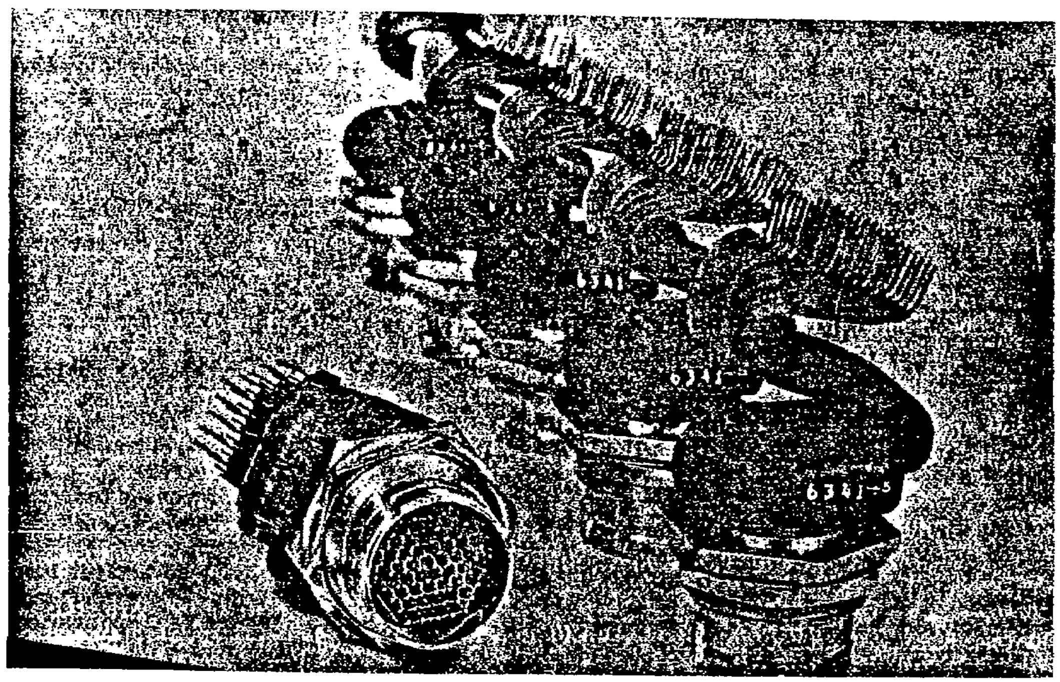


FIGURE 3-4. Flat to round connectors - without pin-assignment changes (Ansley West).

3.2 FCC Application

3.2.1 Program Considerations. Certain questions must be asked, and considerations given early in the program to determine the feasibility of utilizing the FCC system for electrical interconnecting networks.

3.2.1.1 Program Requirements. How important are weight and space savings? What are the schedule requirements? Will the program electronic units be newly designed, or will existing units or those common with other programs be utilized? What quantity of program end items will be required? What are the conductivity and special wiring characteristic requirements?

3.2.1.2 Approval for Use. Does the customer procuring document require, encourage, or permit the use of the FCC system? With the FCC and FCC connector triservice military specification issuances, MIL-C-55543 and MIL-C-55544, this customer approval is easier to obtain. If the program can benefit substantially by using FCC, then a request for approval, listing the program advantages, should be acceptable.

3.2.1.3 Company Capability. What is the company current FCC capability in design, manufacturing, and quality control? Does the magnitude of the current program or future proposed programs warrant establishing the capability if it does not exist? If a major contractor expects to remain active and successful in future programs, he would do well to review Figure 1-7 and Table 1-1 before answering this question.

3.2.1.4 Preliminary Selection of FCC system. After proper consideration is given to those items listed above, an early program decision should be made on the areas for FCC application consideration.

3.2.2 Network System Requirements. With the decision made to use FCC on the program, the various system requirements should be analyzed and defined to establish a basis for the design requirements.

3.2.2.1 System Definition. All electronic system requirements should be established that include a definition of the number and type of subsystems, their performance requirements, and their mutual interactions.

3.2.2.2 Electrical Interface Requirements. Electrical interfaces between end items and associated equipment (umbilicals, flight disconnects, stage joining, etc.) must be established for the number and type of circuits, the interfacing connectors, and for their physical location. To obtain the maximum advantages from FCC interconnecting networks, it is highly desirable to utilize FCC interface connectors in locations best suited for FCC routing and support.

3.2.2.3 Environmental Requirements. The system environmental requirements should be compared with those of the proposed FCC system procurement specifications. In general, these specifications cover very rigid environmental requirements. The geometry and inherent characteristics of FCC make it adaptable to meeting high-vibration, flexing cleanliness, and other requirements. However, special requirements, such as hermetically sealed connectors, cryogenic temperatures, extremely high temperatures, and exposure to nuclear radiation, should be considered.

3.2.3 Design Considerations. The design of FCC interconnecting harnesses requires careful consideration of the electrical characteristics of FCC plus the design and implementation of the selected system.

3.2.3.1 FCC Electrical Characteristics

3.2.3.1.1 Introduction. The FCC electrical characteristics useful to the designer are discussed in the following paragraphs. Some characteristics, such as resistance and current-carrying capability, can be used directly by the designer to select the required conductor cross-sections. Other characteristics can be used for more complicated considerations in determining the FCC component compatibility in meeting the overall requirements for proper system functions.

TABLE 3-2. FCC CABLE SELECTION CHART-CONDUCTOR SIZE AND RESISTANCE

Centerline Spacing (in.)	Conductor Configuration	Conductor Size (in) Width (in.)	Conductor Size (in) Thickness (in.)	Equiv AWG Size[a]	Square Mils	Nominal Resistance Ohms per 1000 ft at 20°C	Resistance Tolerance in Ohms (±)
0.050	Standard	0.025	0.003	30	75	140	15.0
			0.004	29	100	98	7.8
			0.005	28	125	76	4.9
	High Density	0.040	0.003	28	120	87	5.8
			0.004	27	160	61	3.1
			0.005	26	200	47	1.9
0.075	Standard	0.040	0.003	28	120	87	5.8
			0.004	27	160	61	3.1
			0.005	26	200	47	1.9
	High Density	0.065	0.003	26	195	53	2.2
			0.004	25	260	38	1.2
			0.005	24	325	29	0.72
0.100	Standard	0.065	0.004	25	260	38	1.2
			0.005	24	325	29	0.84
			0.006	23	390	24	0.50
	High Density	0.090	0.004	24	360	27	0.59
			0.005	23	450	21	0.38
			0.006	22	540	17	0.25
0.150	Standard	0.115	0.004	22	460	21	0.36
			0.005	22	575	16	0.22
			0.006	21	690	13	0.16
	High Density	0.140	0.004	22	560	18	0.25
			0.005	21	700	14	0.15
			0.006	20	840	11	0.11

Note: Only the cable configurations shown in MIL-C-55543 are shown.
For resistance tolerance explanation see Paragraph 3.2.3.1.2.

a. Shown graphically on Figure 3-5.

3.2.3.1.2 Resistance. The resistance of an electrical conductor is a function of its material, cross-section, temperature, and length.

The nominal resistances in ohms per 1000 feet, for copper conductors for the various MIL-C-55543 conductor cross-sections, are given in Table 3-2. Figure 3-5 shows various FCC cross sections for equivalent AWG sizes 20 through 30.

The tolerances for the conductor width and the thickness of conductors provide a ± tolerance to the nominal cross-section. Using the dimensional tolerances listed in MIL-C-55543, the last column of Table 3-2 lists the resistance tolerances for the various conductor configurations.

The resistance change with temperature change is a function of the temperature coefficient of the conductor material which is, in this case, annealed copper. Conversions must be made in determining resistance for conductors at temperature other than 20°C. This may be done using the formula

$$R_T = R_{20^\circ C}\left[1 + \alpha_T (T - 20^\circ)\right]$$

where

R_T = resistance at a revised temperature T

R_{20° = resistance at a temperature of 20°C

T = revised temperature (°C)

α_T = temperature coefficient of resistivity as a function of T, as given by Knowlton.

The resistance temperature correction factors $[1 + \alpha_T (T - 20^\circ)]$ are given in Figure 3-6. Multiplying the resistance values listed in Table 3-2 by the correction factors given in Figure 3-6 will give the resistance at temperatures other than 20°C.

3.2.3.1.3 Current-Carrying Capacity. The current-carrying capacity of conductors in a cable is primarily a function of the temperature rise that can be tolerated in the cable. This, in turn, is dependent on the density of power dissipation from ohmic losses in the conductor, which result from current levels and conductor resistance. Temperature rise is also dependent on the medium for conducting heat away from the cable, and on the cross-sectional shape of the cable. This shape determines the amount of surface area on the outside of the cable for heat dissipation.

The geometry of FCC lends itself uniquely to effective surface-heat dissipation. The cross-sectional surface of an FCC is significantly greater than the surface of an RWC bundle, when both have the same aggregate of cross-sectional conductor area (Fig. 3-7).

The net effect of the surface difference allows a greater current-carrying capacity for FCC. This fact is demonstrated by a NASA study in comparative data of a 2-inch-wide cable of 25 0.004- by 0.040-inch conductors (27-gage equivalent), and a 25-wire bundle of 26- or 28-gage round wires. See Figures 3-8 and 3-9 for the data for both air and vacuum surroundings.

Additional data are available for FCC, for both single cables, and for 3- and 10-stacked cables of 0.004- by 0.040-inch conductors with 0.075-inch centerline spacing, both vacuum and air. These data are illustrated in Figures 3-10 and 3-11, as maximum allowable current for a stated maximum temperature rise in the hottest conductor of the cable(s).

To apply these data to FCC of other conductor configurations, use the following correction formula:

$$I \text{ (new cable)} = K_C \cdot I \text{ (0.004 x 0.040 x 0.075 centerline spacing)},$$

where

I (new cable) = allowable current for each conductor of the new cable

I (0.004 x 0.040 x 0.075 centerline spacing) = allowable current as given in Figures 3-10 or 3-11 for air or vacuum as appropriate.

K_C = configuration factor as tabulated in Table 3-3.

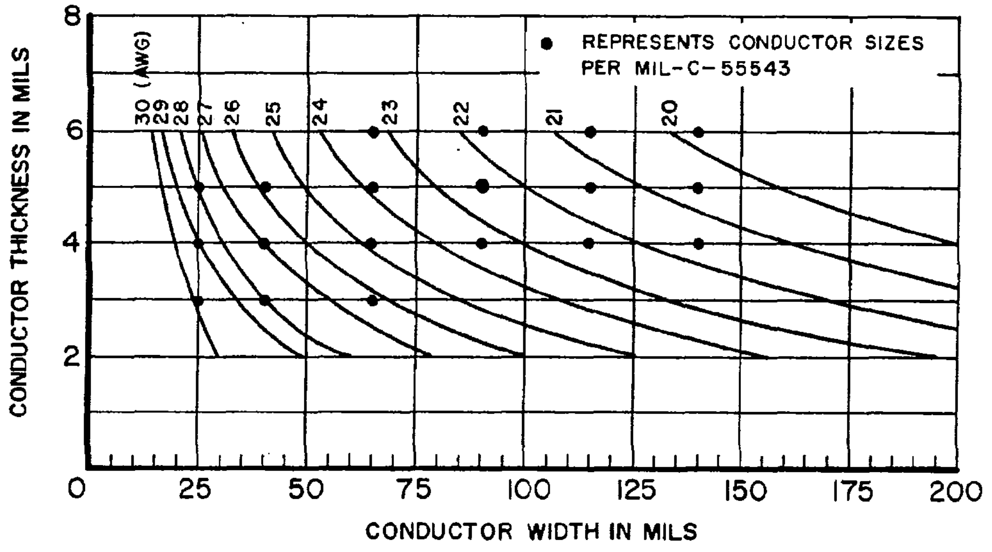


FIGURE 3-5. FCC cross-sections - equivalent AWG 20 through 30.

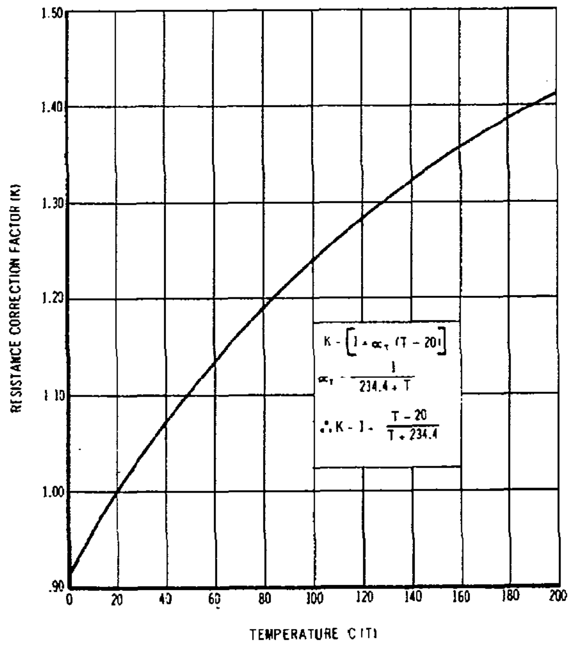


FIGURE 3-6. Resistance correction factor.

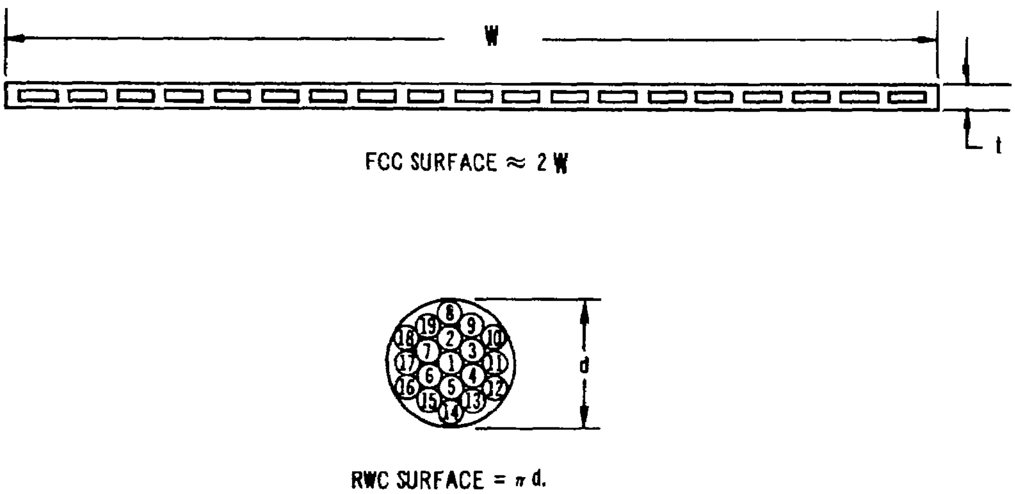


FIGURE 3-7. Surface cross-section comparison - FCC to RWC.

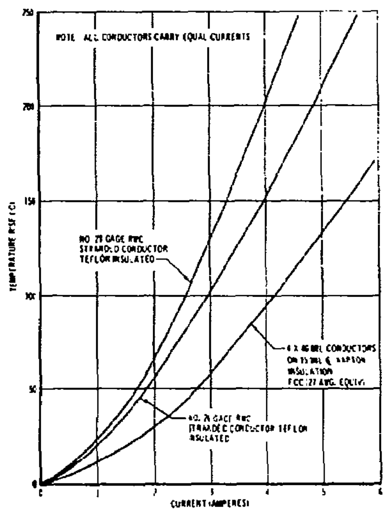


FIGURE 3-8. Current versus temperature rise in hottest conductor in air (25 conductors).

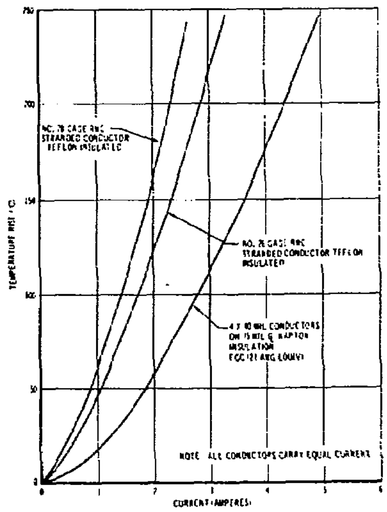


FIGURE 3-9. Current versus temperature rise in hottest conductor in vacuum (25 conductors).

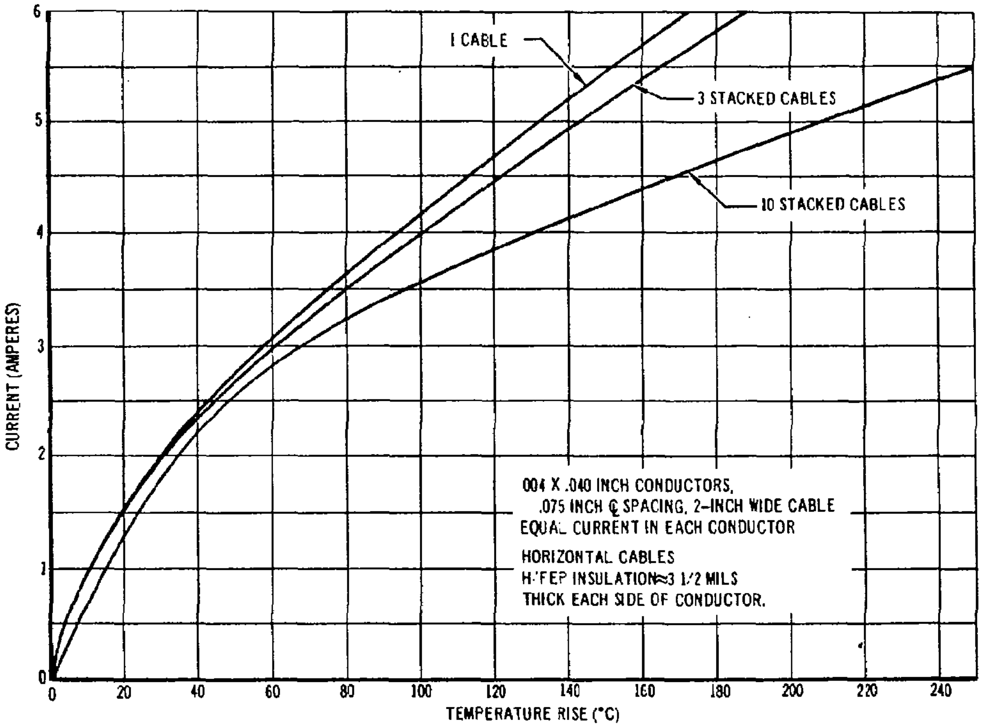


FIGURE 3-10. Maximum current versus temperature rise in hottest conductor in air.

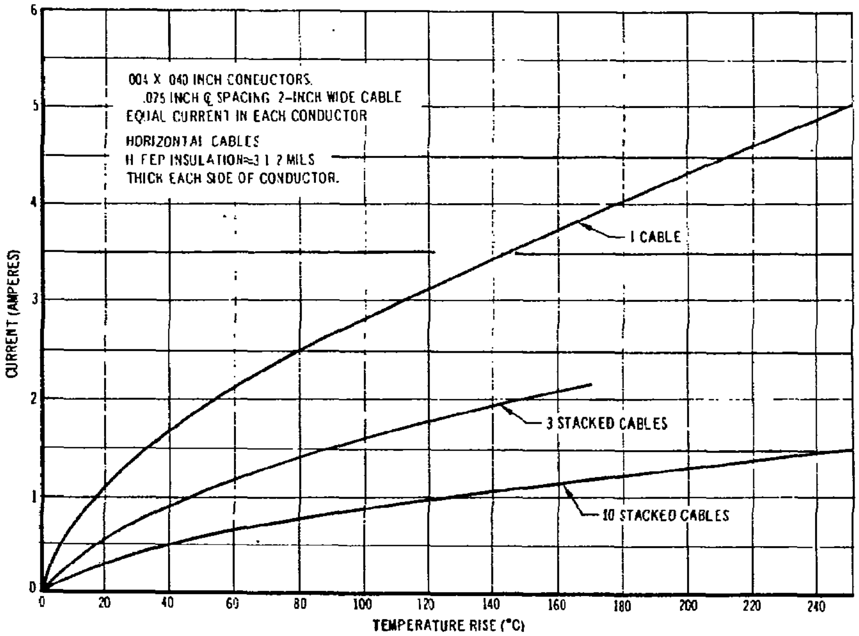


FIGURE 3-11. Maximum current versus temperature rise in hottest conductor in vacuum.

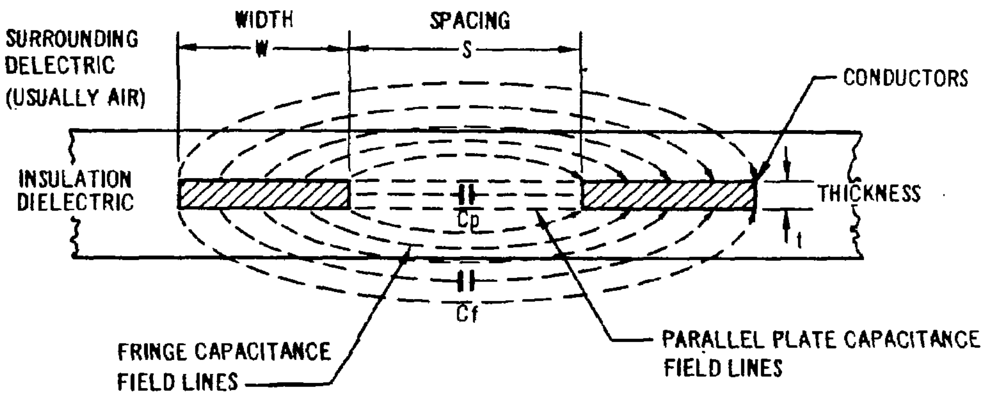


FIGURE 3-12. Distributed capacitance between conductors.

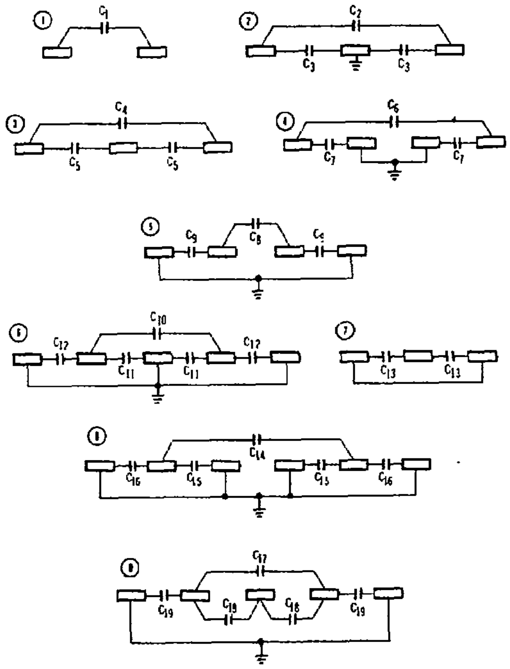


FIGURE 3-13. Inner conductor capacitance configurations for unshielded flat cable.

This formula and Table 3-3 correction factors are based on the assumption that the maximum conductor temperature for the same type and thickness of FCC insulation is dependent on the I^2R losses of the conductors per unit of cable width and length; therefore, FCC cables with equal I^2R losses per unit width and length will have equal maximum conductor temperatures.

3.2.3.1.4 Capacitance Data. Capacitance per unit length between conductors is a function of the cross-sectional geometry of the cable, the dielectric material, the shielding configuration, and the mounting technique. Capacitance between adjacent conductors consists of parallel plate capacitance and fringing capacitance. Parallel plate capacitance is usually small relative to the total capacitance, except when the conductors are very closely spaced.

For an unshielded cable, the fringing field extends into the air outside the insulation (Fig. 3-12). Calculation of exact capacitance values is difficult, since the capacitance depends on thickness and dielectric constant of the insulation, dielectric constant of the surrounding medium (usually air), widths and thicknesses of the conductors, spacing of the conductors, presence of nearby grounds, and operating frequency of the circuit. One approach which can be used to approximate distributed capacitance is to establish a "composite dielectric" value which falls between that of the insulation material and the air.

Tables 3-4 and 3-5 provide standard flat-cable capacitance values for those configurations shown in Figure 3-13. These tables were compiled by using calculated values and all available experimental data. It should be pointed out to the designer that manufacturing tolerances for insulation thickness, conductor spacing, and dielectric material play an important part in the capacitance values. The range of values found in Tables 3-4 and 3-5 are the values which should be anticipated by the designer because of manufacturing tolerances and variations in measuring techniques. These tables are for isolated conductors not influenced by ground planes or close conductors. Table 3-6 shows calculated capacitance values for stacked FCC conductors.

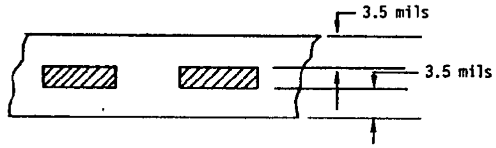
The use of electrical shields permits reduction of capacitive cross-coupling and minimization of conducted and radiated electro-magnetic interference. The flat-cable geometry lends itself to effective shielding. Use of a grounded shield, bonded to one or two sides of a cable, lowers the direct conductor-to-conductor capacitance. Suitable shielding and grounding arrangements can be used to reduce the direct capacitance in various configurations of FCC. For example, the capacitance of approximately 6.5 pf/ft for C_1 of Figure 3-13 for an unshielded cable with conductors 4 by 40 mils spaced on 75 mil centers and ϵ equal to 2.9 (Table 3-5) can be reduced to approximately 0.051 pf/ft by adding a double shield as shown in Configuration 1 of Figure 3-14. Shielding material may be foil, wire mesh, or, in some cases, vacuum-deposited aluminum, copper, or silver. The foil used may be solid, perforated, wrinkled, or expanded. For the double-shielded cable, the field is contained within the shields, with a minimal field, if any, ever extending beyond the shield. Table 3-7 provides shielded flat-cable capacitance values for those configurations shown in Figure 3-14. These tables were compiled by using calculated values and all available experimental data. The range of values found in Table 3-7 are values which the designer should anticipate because of manufacturing tolerances and variations in measuring techniques. The tolerances used for compiling Table 3-7 were: ±0.5 mil on the distance between the surface of conductor and the shield (this variation assumed to occur on either side of conductor simultaneously for analysis); ±2.0 mils on the conductor width; ±0.4 mil on conductor thickness; and ±2.0 mils on conductor separation for high-density cable; and ±5.0 mils on conductor separation for standard cable. From a magnitude standpoint, the distance between the conductor and shield had the greatest impact. Since the conductor and shield are relatively large area plates closely spaced, small changes in distance result in sizeable variations of capacitance; for example, it would be expected that the capacitance C_2 (Fig. 3-14) for a 40- by 4-mil cable would go from 186 to 286 pF/ft to 163 to 360 pF/ft if the conductor-to-shield tolerance were increased to ±1.0 mil with all other tolerances remaining the same.

For cables other than the standard cables listed in Table 3-7, the conductor-to-shield capacitance can be determined by using the curves in Figures 3-15 through 3-19 [3-1]. If the geometry of the cable is known, C_{pp} is obtained from Figures 3-15 through 3-18. The total fringe capacitance, which is four times C_f, is obtained from Figure 3-19. The sum of C_{pp} and $4C'_F$ is equal to the total conductor-to-shield capacitance. The capacitance between adjacent conductors can be expected to decrease to approximately 1/45 to 1/150 of the equivalent value for an unshielded cable.

TABLE 3-3. CONFIGURATION CORRECTION FACTORS FOR CURRENT RATINGS

Cable Configuration (in.)			Configuration Correction Factor K_C
Centerline Spacing	Width	Thickness	
0.050	0.025	0.003	0.56
0.050	0.025	0.004	0.64
0.050	0.040	0.003	0.71
0.050	0.040	0.004	0.82
0.050	0.040	0.005	0.91
0.075	0.040	0.003	0.87
0.075	0.040	0.004	1.00
0.075	0.040	0.005	1.12
0.075	0.065	0.003	1.10
0.075	0.065	0.004	1.27
0.075	0.065	0.005	1.42
0.100	0.065	0.004	1.47
0.100	0.065	0.005	1.65
0.100	0.065	0.006	1.80
0.100	0.090	0.004	1.73
0.100	0.090	0.005	1.94
0.100	0.090	0.006	2.12
0.150	0.115	0.004	2.36
0.150	0.115	0.005	2.68
0.150	0.115	0.006	2.72
0.150	0.140	0.004	2.65
0.150	0.140	0.005	2.96
0.150	0.140	0.006	3.24

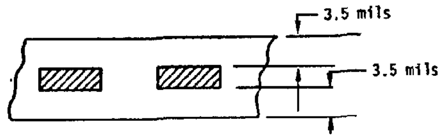
TABLE 3-4. CAPACITANCE VALUES IN pF/ft FOR MYLAR INSULATED FLAT CABLE ($\epsilon = 2.5$) (SEE FIGURE 3-13 FOR CAPACITANCE SYMBOL DESIGNATION)



Note: 4 X 40 mil conductors, spaced on 75 mil center-line spacings. See Figure 3-13 for C_1 - C_{19} measurement.

Centerline Spacing (in.)	Conductor Separation (in.)	Conductor Width (in.)	Conductor Thickness (in.)	C_1, C_3, C_5	C_2	C_4	C_6	C_7	C_8	C_9	C_{10}	$C_{11}, C_{12}, C_{13}, C_{15}, C_{16}$	C_{14}	C_{17}	C_{18}	C_{19}
0.050	0.025	0.025 (Std)	0.003	5.3- 7.6	1.2-1.7	3.3-4.8	0.7-1.1	5.7- 8.2	4.3- 6.1	7.4-10.7	0.5-0.8	10.6-15.2	0.2-0.4	2.7-4.0	5.1- 7.6	6.7-10.0
			0.004	5.4- 7.7	1.2-1.8	3.4-4.9	0.8-1.1	5.8- 8.3	4.3- 6.2	7.6-10.8	0.5-0.8	10.8-15.4	0.2-0.4	2.8-4.0	5.3- 7.6	7.0-10.0
0.050	0.010	0.040 (Hi Den)	0.003	9.5-12.3	1.4-1.8	5.5-7.1	0.9-1.1	10.2-13.2	7.6- 9.8	13.3-17.2	0.6-0.8	19.0-24.5	0.3-0.5	3.9-5.0	7.4- 9.5	11.3-14.5
			0.004	9.8-12.6	1.5-1.9	5.7-7.3	0.9-1.1	10.5-13.5	7.8-10.1	13.7-17.6	0.6-0.8	19.8-25.2	0.3-0.5	4.0-5.2	7.6- 9.9	11.6-15.0
			0.005	10.1-12.9	1.5-1.9	5.8-7.5	0.9-1.2	10.8-13.8	8.1-10.3	14.1-18.0	0.6-0.8	20.2-25.8	0.3-0.5	4.1-5.3	7.8-10.0	11.9-15.4
0.075	0.035	0.040 (Std)	0.003	5.3- 7.0	1.3-1.8	3.5-4.7	0.8-1.1	5.7- 7.5	4.3- 5.6	7.4- 9.8	0.5-0.7	10.6-14.0	0.2-0.4	3.2-4.2	6.1- 8.0	8.0-10.5
			0.004	5.4- 7.1	1.3-1.8	3.6-4.8	0.8-1.1	5.8- 7.6	4.3- 5.7	7.5-10.0	0.5-0.7	10.8-14.2	0.2-0.4	3.3-4.3	6.3- 8.2	8.3-10.8
			0.005	5.4- 7.1	1.3-1.8	3.6-4.8	0.8-1.1	5.8- 7.6	4.3- 5.7	7.5-10.0	0.5-0.7	10.8-14.2	0.2-0.4	3.3-4.3	6.3- 8.2	8.3-10.8
0.075	0.010	0.065 (Hi Den)	0.003	10.0-12.7	1.5-1.9	5.8-7.4	0.9-1.1	10.7-13.6	8.0-10.2	14.0-17.8	0.6-0.8	20.0-25.3	0.3-0.5	4.1-5.2	7.8- 9.7	11.9-15.2
			0.004	10.3-13.0	1.5-2.0	6.0-7.5	0.9-1.2	11.1-14.0	8.2-10.4	14.4-18.2	0.6-0.8	20.6-26.0	0.3-0.5	4.2-5.3	8.0- 9.8	12.2-15.4
			0.005	10.6-13.3	1.6-2.0	6.1-7.7	0.9-1.2	11.4-14.2	8.5-10.6	14.8-18.6	0.6-0.8	21.2-26.5	0.3-0.5	4.3-5.5	8.2-10.4	12.5-16.0
0.100	0.035	0.065 (Std)	0.004	6.0- 7.7	1.5-1.9	4.0-5.2	0.9-1.2	6.4- 8.3	4.8- 6.2	8.4-10.8	0.6-0.8	12.0-15.4	0.3-0.5	3.6-4.6	6.8- 8.7	9.0-11.5
			0.005	6.0- 7.7	1.5-1.9	4.0-5.2	0.9-1.2	6.4- 8.3	4.8- 6.2	8.4-10.8	0.6-0.8	12.0-15.4	0.3-0.5	3.6-4.6	6.8- 8.7	9.0-11.5
			0.006	6.2- 7.9	1.6-2.0	4.2-5.3	0.9-1.2	6.6- 8.5	5.0- 6.3	8.7-11.0	0.6-0.8	12.4-15.8	0.3-0.5	3.7-4.8	7.0- 9.1	9.2-12.0
0.100	0.010	0.090 (Hi Den)	0.004	10.6-13.3	1.6-2.0	6.1-7.7	1.0-1.2	11.4-14.2	8.5-10.6	14.8-18.6	0.6-0.8	21.2-27.2	0.3-0.5	4.4-5.4	8.3-10.2	12.8-15.6
			0.005	11.0-13.7	1.7-2.1	6.4-7.9	1.0-1.2	11.8-14.7	8.8-11.0	15.4-19.2	0.7-0.9	22.0-27.4	0.3-0.6	4.5-5.6	8.5-10.6	13.0-16.2
			0.006	11.3-14.0	1.7-2.1	6.6-8.1	1.0-1.3	12.0-15.0	9.0-11.2	15.8-19.6	0.7-0.9	22.5-28.0	0.3-0.6	4.6-5.7	8.7-10.9	13.4-16.8
0.150	0.035	0.115 (Std)	0.004	6.6- 8.1	1.7-2.0	4.4-5.4	1.0-1.2	7.1- 8.7	5.3- 6.5	9.2-11.3	0.6-0.8	13.2-16.2	0.3-0.5	4.0-4.9	7.6- 9.3	10.0-12.2
			0.005	6.8- 8.3	1.7-2.1	4.6-5.6	1.0-1.2	7.3- 8.9	5.4- 6.6	9.5-11.6	0.6-0.8	13.6-16.3	0.3-0.5	4.1-5.0	7.8- 9.5	10.2-12.5
			0.006	6.9- 8.4	1.7-2.1	4.6-5.6	1.0-1.3	7.4- 9.0	5.5- 6.7	9.7-11.8	0.6-0.8	13.8-16.8	0.3-0.5	4.2-5.1	8.0- 9.7	10.5-12.8
0.150	0.010	0.140 (Hi Den)	0.004	11.2-13.7	1.7-2.1	6.5-7.9	1.0-1.2	12.0-14.7	9.0-11.0	15.6-19.2	0.7-0.9	22.4-27.4	0.3-0.5	4.6-5.6	8.7-10.6	13.4-16.2
			0.005	11.5-14.0	1.7-2.1	6.6-8.1	1.1-1.3	12.3-15.0	9.2-11.2	16.0-19.6	0.7-0.9	23.0-28.0	0.3-0.6	4.7-5.7	8.9-10.8	13.6-16.6
			0.006	11.8-14.3	1.8-2.1	6.9-8.3	1.1-1.3	12.6-15.4	9.5-11.4	16.5-20.0	0.7-0.9	23.5-28.5	0.3-0.6	4.8-5.9	9.1-11.2	14.0-17.1

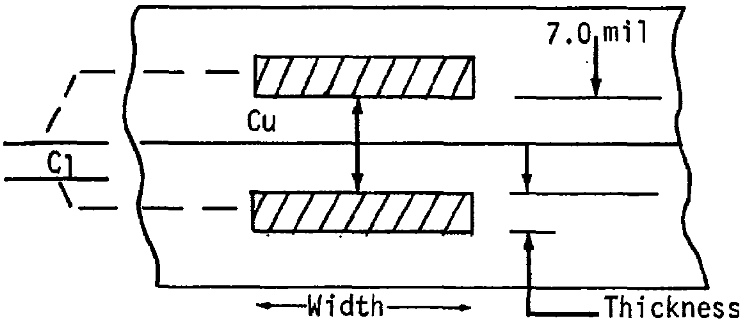
TABLE 3-5. CAPACITANCE VALUES IN pF/ft FOR H-FILM/FEP INSULATED FLAT CABLE (ϵ = 2.9-3.1)
(SEE FIGURE 3-13 FOR CAPACITANCE SYMBOL DESIGNATION)



Note: 4 X 40 mil conductors, spaced on 75 mil center-line spacings. See Figure 3-13 for C_1 - C_{19} measurement locations.

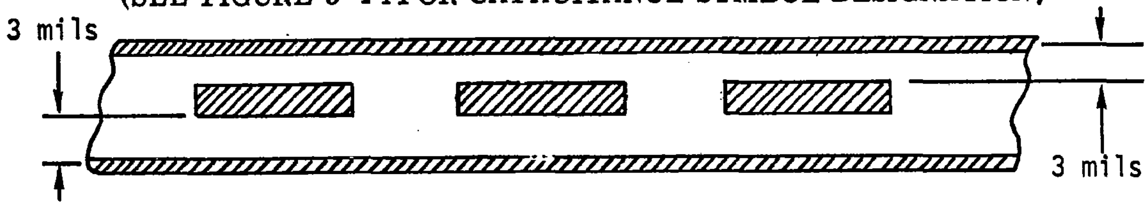
Centerline Spacing (in.)	Conductor Separation (in.)	Conductor Width (in.)	Conductor Thickness (in.)	C_1, C_3, C_5	C_2	C_4	C_6	C_7	C_8	C_9	C_{10}	$C_{11}, C_{12}, C_{13}, C_{15}, C_{16}$	C_{14}	C_{17}	C_{18}	C_{19}
0.050	0.025	0.025 (Std)	0.003	5.7- 8.1	1.3-1.9	3.6-5.1	0.8-1.1	6.1- 8.7	4.6- 6.5	8.0-11.4	0.5-0.8	11.4-16.1	0.2-0.4	3.0-4.2	5.7- 8.0	7.5-10.5
			0.004	5.8- 8.2	1.3-1.9	3.7-5.2	0.8-1.1	6.2- 8.8	4.7- 6.6	8.1-11.4	0.5-0.8	11.6-16.2	0.2-0.4	3.0-4.3	5.7- 8.2	7.5-10.8
0.050	0.010	0.040 (Hi Den)	0.003	10.6-13.7	1.6-2.0	6.1-7.9	1.0-1.2	11.4-14.7	8.5-11.0	14.8-19.2	0.6-0.8	21.2-27.4	0.3-0.5	4.4-5.6	8.3-10.6	12.8-16.2
			0.004	10.9-14.0	1.6-2.1	6.3-8.1	1.0-1.3	11.7-15.0	8.8-11.2	15.1-19.6	0.7-0.9	21.7-28.0	0.3-0.6	4.5-5.7	8.5-10.8	13.0-16.8
			0.005	11.2-14.3	1.6-2.1	6.5-8.4	1.0-1.3	12.0-15.3	9.0-11.4	15.4-20.0	0.7-0.9	22.4-28.5	0.3-0.6	4.6-5.9	8.7-11.2	13.4-17.1
0.075	0.035	0.040 (Std)	0.003	5.7- 7.5	1.4-1.9	3.8-5.0	0.8-1.1	6.1- 8.1	4.6- 6.0	8.0-10.5	0.5-0.8	11.4-15.0	0.2-0.4	3.4-4.5	6.4- 8.5	8.5-11.2
			0.004	5.8- 7.6	1.5-1.9	3.9-5.1	0.8-1.1	6.2- 8.2	4.7- 6.1	8.1-10.6	0.5-0.8	11.6-15.2	0.2-0.4	3.5-4.6	6.6- 8.7	8.7-11.5
			0.005	5.8- 7.6	1.5-1.9	4.0-5.1	0.8-1.1	6.2- 8.2	4.7- 6.1	8.1-10.6	0.5-0.8	11.6-15.2	0.2-0.4	3.5-4.6	6.6- 8.7	8.7-11.5
0.075	0.010	0.065 (Hi Den)	0.003	11.1-14.1	1.6-2.1	6.4-8.2	1.0-1.3	11.9-15.2	8.9-11.2	15.5-19.6	0.6-0.8	22.2-28.1	0.3-0.5	4.6-5.8	8.7-11.0	13.3-16.8
			0.004	11.1-14.1	1.6-2.1	6.4-8.2	1.0-1.3	11.9-15.2	8.9-11.2	15.5-19.8	0.6-0.8	22.2-28.1	0.3-0.5	4.6-5.8	8.7-11.0	13.3-16.8
			0.005	11.7-14.7	1.7-2.2	6.8-8.5	1.1-1.3	12.5-15.8	9.4-11.8	16.4-20.5	0.7-0.9	23.4-29.3	0.3-0.6	4.8-6.0	9.1-11.2	14.0-17.4
0.100	0.035	0.065 (Std)	0.004	6.4- 8.1	1.6-2.0	4.3-5.4	1.0-1.2	6.9- 8.7	5.1- 6.5	9.0-11.3	0.6-0.8	12.8-16.2	0.3-0.5	3.9-4.9	7.4 9.3	9.8-12.2
			0.005	6.5- 8.2	1.6-2.1	4.3-5.5	1.0-1.2	7.0- 8.8	5.2- 6.6	9.1-11.5	0.6-0.8	13.0-16.4	0.3-0.5	3.9-4.9	7.4- 9.3	9.8-12.2
			0.006	6.6- 8.3	1.7-2.1	4.4-5.6	1.0-1.2	7.1- 8.9	5.3- 6.6	9.2-11.6	0.6-0.8	13.2-16.6	0.3-0.5	4.0-5.0	7.6- 9.5	10.0-12.5
0.100	0.010	0.090 (Hi Den)	0.004	11.6-14.5	1.7-2.2	6.7-8.4	1.0-1.3	12.4-15.6	9.3-11.6	16.2-20.3	0.7-0.9	23.2-29.0	0.4-0.6	4.7-5.9	8.9-11.2	13.6-17.1
			0.005	12.0-14.8	1.8-2.2	7.0-8.6	1.1-1.3	12.8-15.8	9.6-11.8	16.8-20.8	0.7-0.9	24.0-29.5	0.4-0.6	4.9-6.1	9.3-11.6	14.2-17.7
			0.006	12.2-15.1	1.8-2.3	7.2-8.8	1.1-1.4	13.1-16.2	9.7-12.1	17.0-21.1	0.7-0.9	24.4-30.2	0.4-0.6	5.0-6.2	9.5-11.8	14.5-18.0
0.150	0.035	0.115 (Std)	0.004	7.1- 9.2	1.8-2.3	4.8-6.2	1.1-1.4	7.6- 9.9	5.7- 7.3	9.9-12.8	0.7-0.9	14.2-18.4	0.3-0.5	4.2-5.5	8.0-10.4	10.5-13.8
			0.005	7.2- 9.3	1.8-2.3	4.8-6.2	1.1-1.4	7.7-10.0	5.8- 7.4	10.1-13.0	0.7-0.9	14.4-18.6	0.3-0.5	4.3-5.6	8.2-10.6	10.7-14.0
			0.006	7.3- 9.4	1.8-2.4	4.9-6.3	1.1-1.4	7.8-10.1	5.8- 7.5	10.2-13.2	0.7-0.9	14.6-18.8	0.3-0.5	4.4-5.7	8.4-10.8	11.0-14.2
0.150	0.010	0.140 (Hi Den)	0.004	12.1-14.9	1.8-2.2	7.0-8.6	1.1-1.3	13.0-16.0	9.7-11.9	17.0-20.8	0.7-0.9	24.2-29.8	0.4-0.6	5.0-6.1	9.5-11.6	14.5-17.6
			0.005	12.4-15.2	1.9-2.3	7.2-8.8	1.1-1.4	13.3-16.3	9.9-12.2	17.4-21.2	0.7-0.9	24.8-30.4	0.4-0.6	5.1-6.2	9.7-11.8	14.8-18.0
			0.006	12.7-15.5	1.0-2.3	7.4-9.0	1.1-1.4	13.6-16.6	10.2-12.4	17.8-21.6	0.8-0.9	25.3-30.4	0.4-0.6	5.2-6.4	9.9-12.2	15.0-18.6

TABLE 3-6. CAPACITANCE VALUES FOR MYLAR ($\epsilon = 2.5$) AND H-FILM/FEP ($\epsilon = 2.9 - 3.1$) INSULATED FLAT CABLE



Conductor Width (in.)	Conductor Thickness (in.)	Mylar C_1 (pf/ft)	H-Film/FEP C_1 (pf/ft)
0.025	0.003	23.5 - 44.4	27.2 - 51.9
0.025	0.004	24.1 - 45.1	27.8 - 52.7
0.040	0.003	35.8 - 64.7	40.2 - 75.5
0.040	0.004	35.3 - 65.3	40.8 - 76.3
0.040	0.005	35.8 - 65.9	41.4 - 77.0
0.065	0.003	53.5 - 98.4	61.8 - 114.9
0.065	0.004	54.1 - 99.1	62.5 - 115.7
0.065	0.005	54.6 - 99.7	63.1 - 116.4
0.065	0.006	55.0 - 100.2	63.6 - 117.0
0.090	0.004	72.8 - 132.8	84.2 - 115.1
0.090	0.005	73.3 - 133.4	84.8 - 155.8
0.090	0.006	73.8 - 133.9	85.3 - 156.4
0.115	0.004	91.6 - 166.6	105.8 - 194.5
0.115	0.005	92.1 - 167.1	106.4 - 195.2
0.115	0.006	92.5 - 167.7	106.9 - 195.8
0.140	0.004	110.3 - 200.3	127.5 - 233.9
0.140	0.005	110.8 - 200.9	128.1 - 234.6
0.140	0.006	111.3 - 201.4	128.6 - 235.2

TABLE 3-7. CAPACITANCE VALUES IN pF FOR A DOUBLE-SHIELDED H-FILM/FEP CABLE (= 2.9-3.1)
(SEE FIGURE 3-14 FOR CAPACITANCE SYMBOL DESIGNATION)



Centerline Spacing (in.)	Conductor Separation (in.)	Conductor Width (in.)	Conductor Thickness (in.)	C_1, C_3, C_8	C_2, C_4, C_7, C_6, C_9	C_5, C_{10}
0.050	0.025 (Std)	0.025	0.003	0.04 - 0.07	116 - 192	0.03 - 0.06
			0.004	0.05 - 0.09	118 - 195	0.04 - 0.08
0.050	0.010	0.040 (Hi Den)	0.003	0.09 - 0.18	184 - 284	0.08 - 0.15
			0.004	0.13 - 0.23	186 - 286	0.11 - 0.20
			0.005	0.16 - 0.28	188 - 290	0.14 - 0.24
0.075	0.035	0.040 (Std)	0.003	0.03 - 0.05	184 - 284	0.02 - 0.04
			0.004	0.04 - 0.06	186 - 286	0.03 - 0.05
			0.005	0.05 - 0.08	188 - 290	0.04 - 0.06
0.075	0.010	0.065 (Hi Den)	0.003	0.09 - 0.18	282 - 420	0.08 - 0.15
			0.004	0.13 - 0.23	285 - 425	0.10 - 0.20
			0.005	0.16 - 0.28	286 - 426	0.14 - 0.24
0.100	0.035	0.065 (Std)	0.004	0.04 - 0.06	285 - 425	0.03 - 0.05
			0.005	0.05 - 0.08	286 - 426	0.04 - 0.07
			0.006	0.06 - 0.09	287 - 427	0.05 - 0.08
0.100	0.010	0.090 (Hi Den)	0.004	0.13 - 0.23	437 - 638	0.11 - 0.20
			0.005	0.16 - 0.28	438 - 642	0.14 - 0.24
			0.006	0.19 - 0.33	440 - 645	0.16 - 0.28
0.150	0.035	0.115 (Std)	0.004	0.04 - 0.06	632 - 920	0.03 - 0.05
			0.005	0.05 - 0.08	634 - 922	0.04 - 0.07
			0.006	0.06 - 0.09	635 - 823	0.05 - 0.08
0.150	0.010	0.140	0.004	0.13 - 0.23	780 - 1170	0.11 - 0.20
			0.005	0.16 - 0.28	782 - 1172	0.16 - 0.28
			0.006	0.19 - 0.33	782 - 1172	0.16 - 0.28

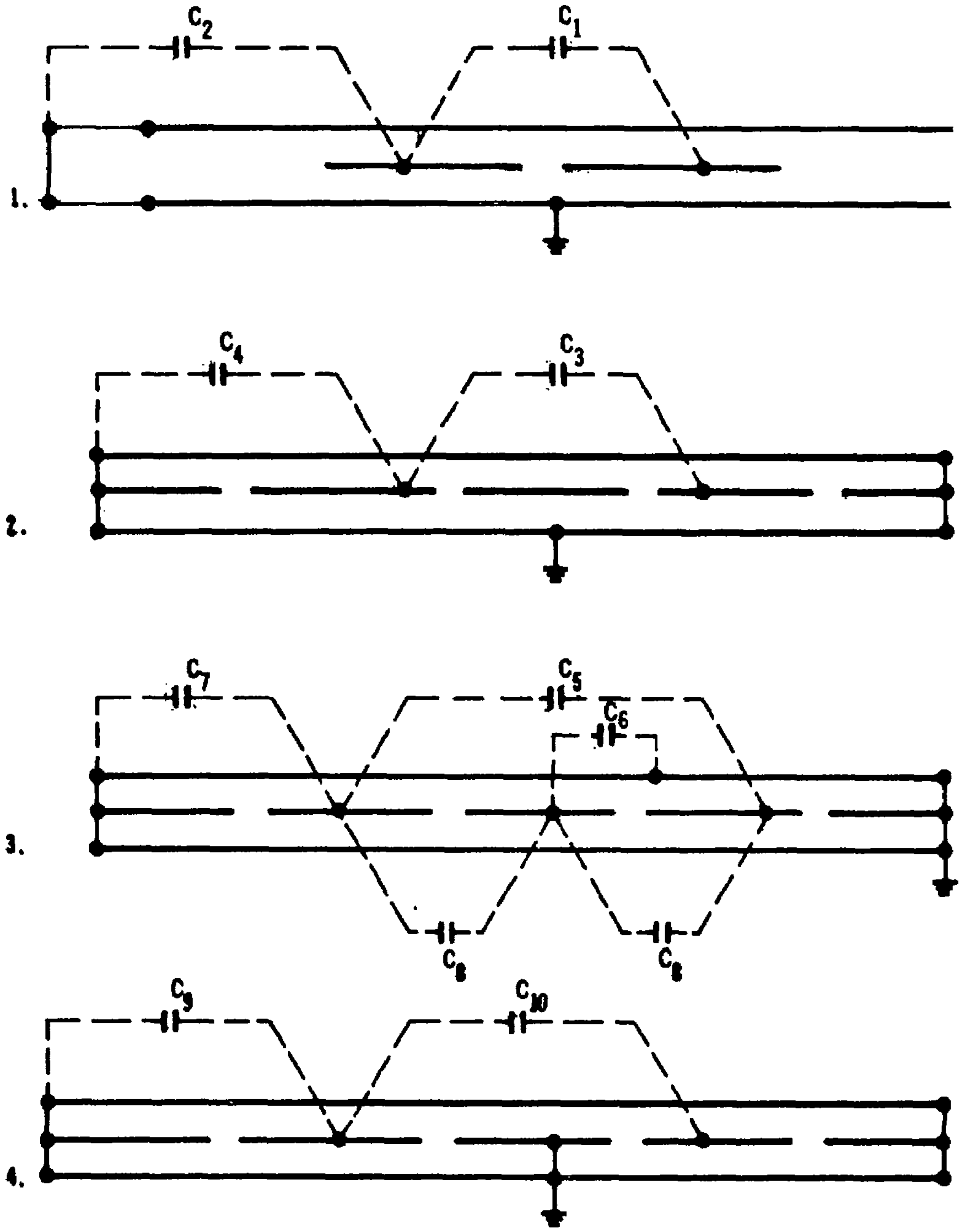


FIGURE 3-14. Double-shielded cable capacitance configurations.

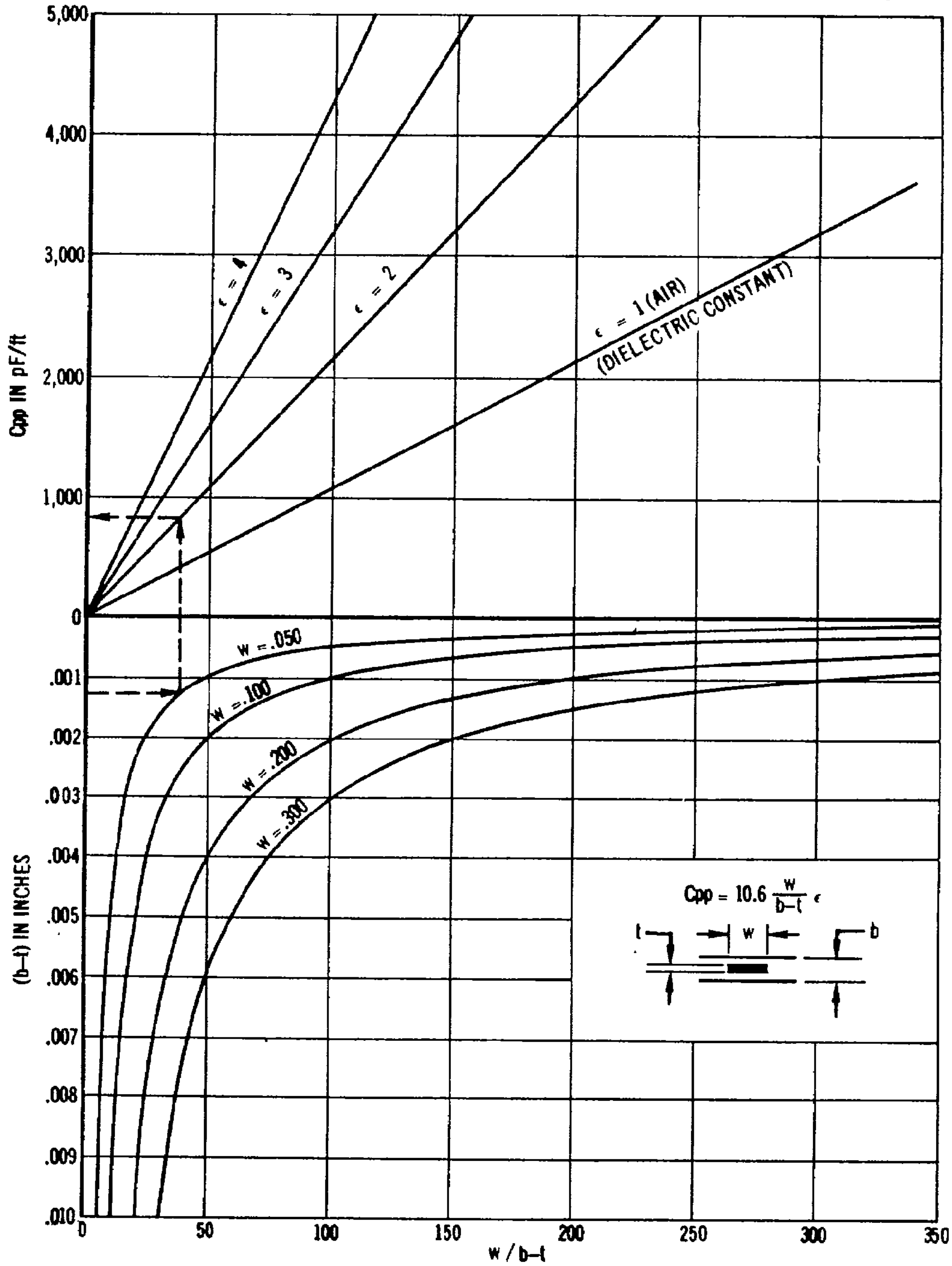


FIGURE 3-15. Conductor-to-shield capacitance for double-shielded FCC.

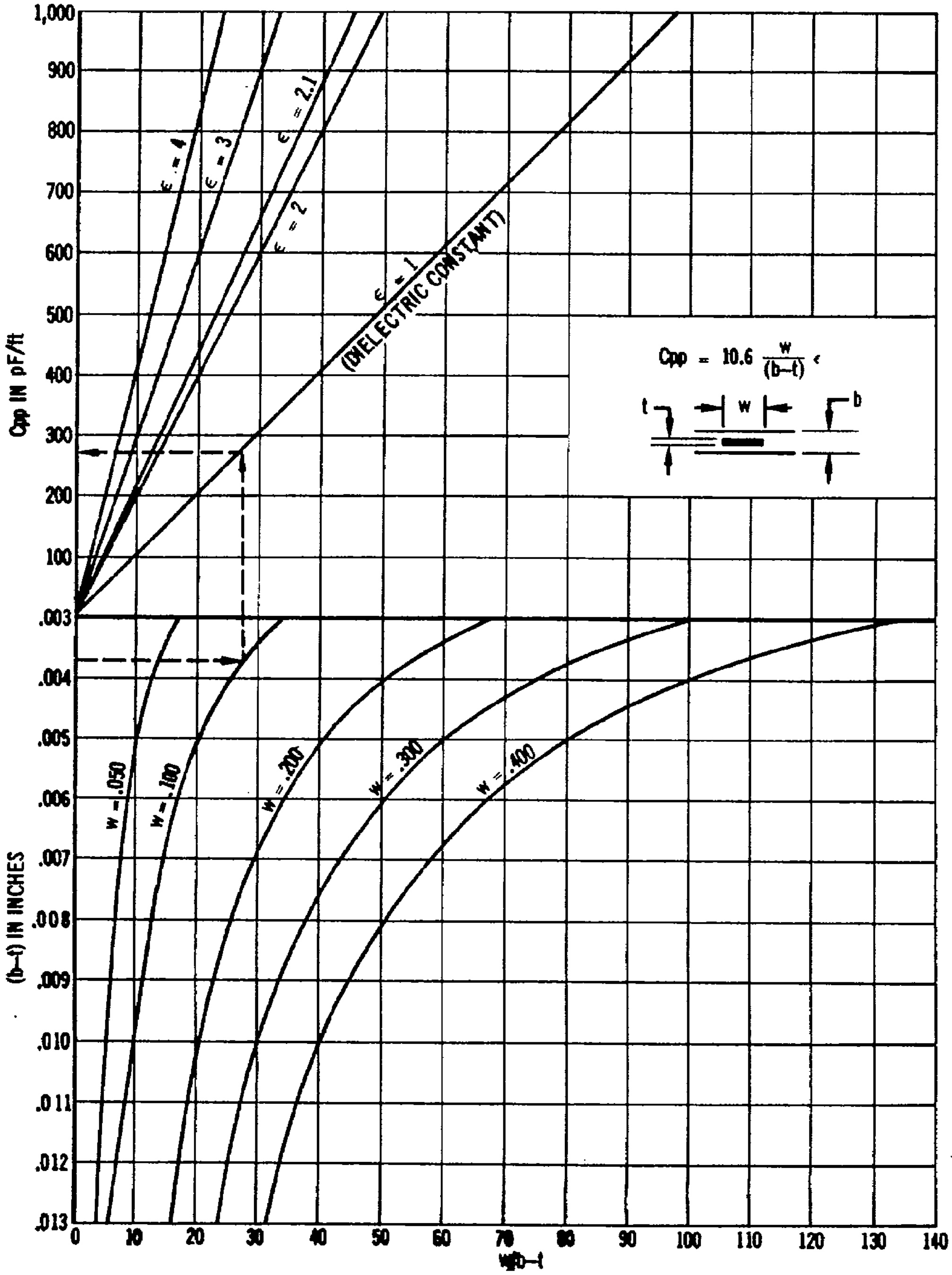


FIGURE 3-16. Conductor-to-shield capacitance for double-shielded FCC.

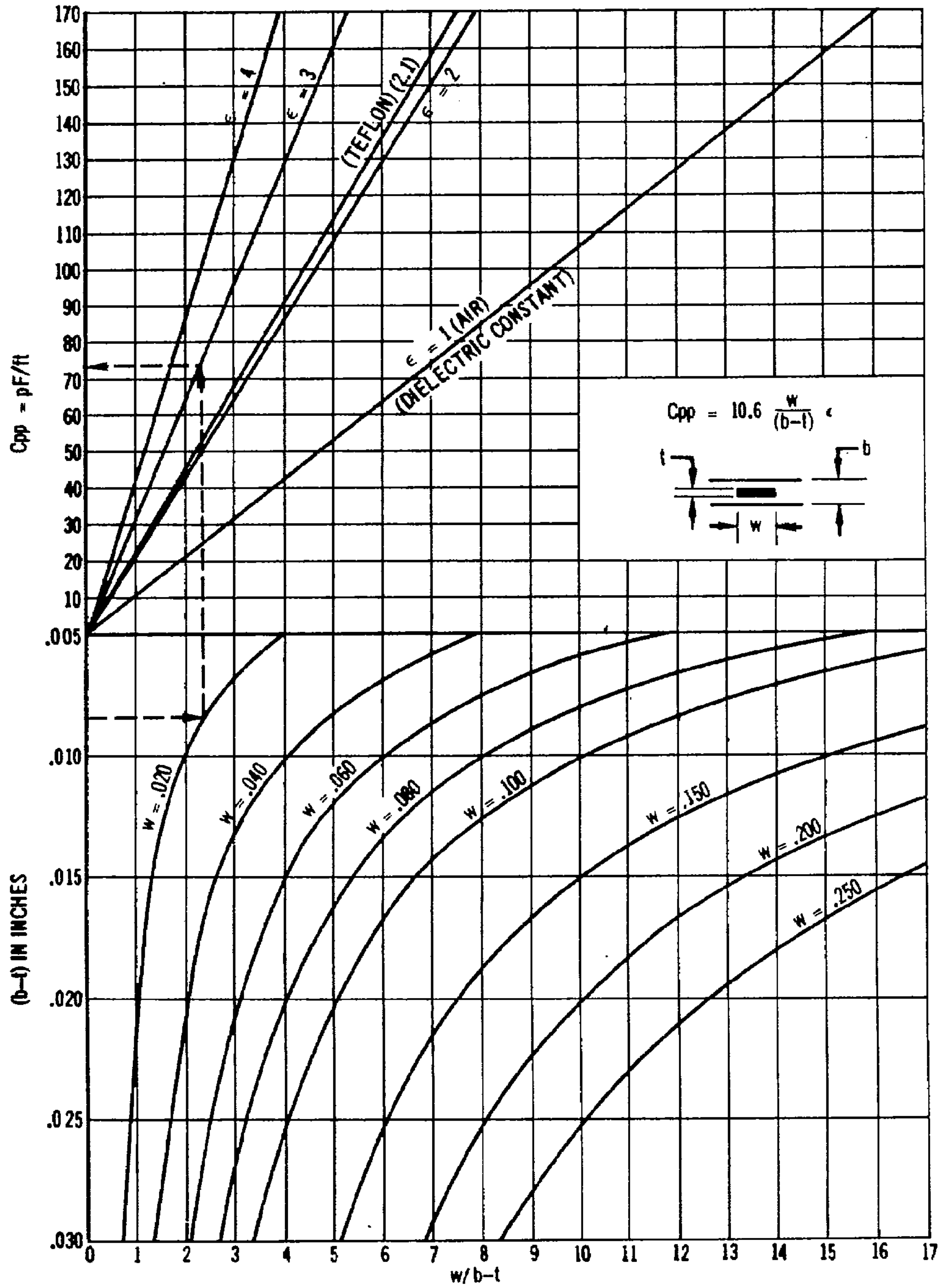


FIGURE 3-17. Conductor-to-shield capacitance for double-shielded FCC.

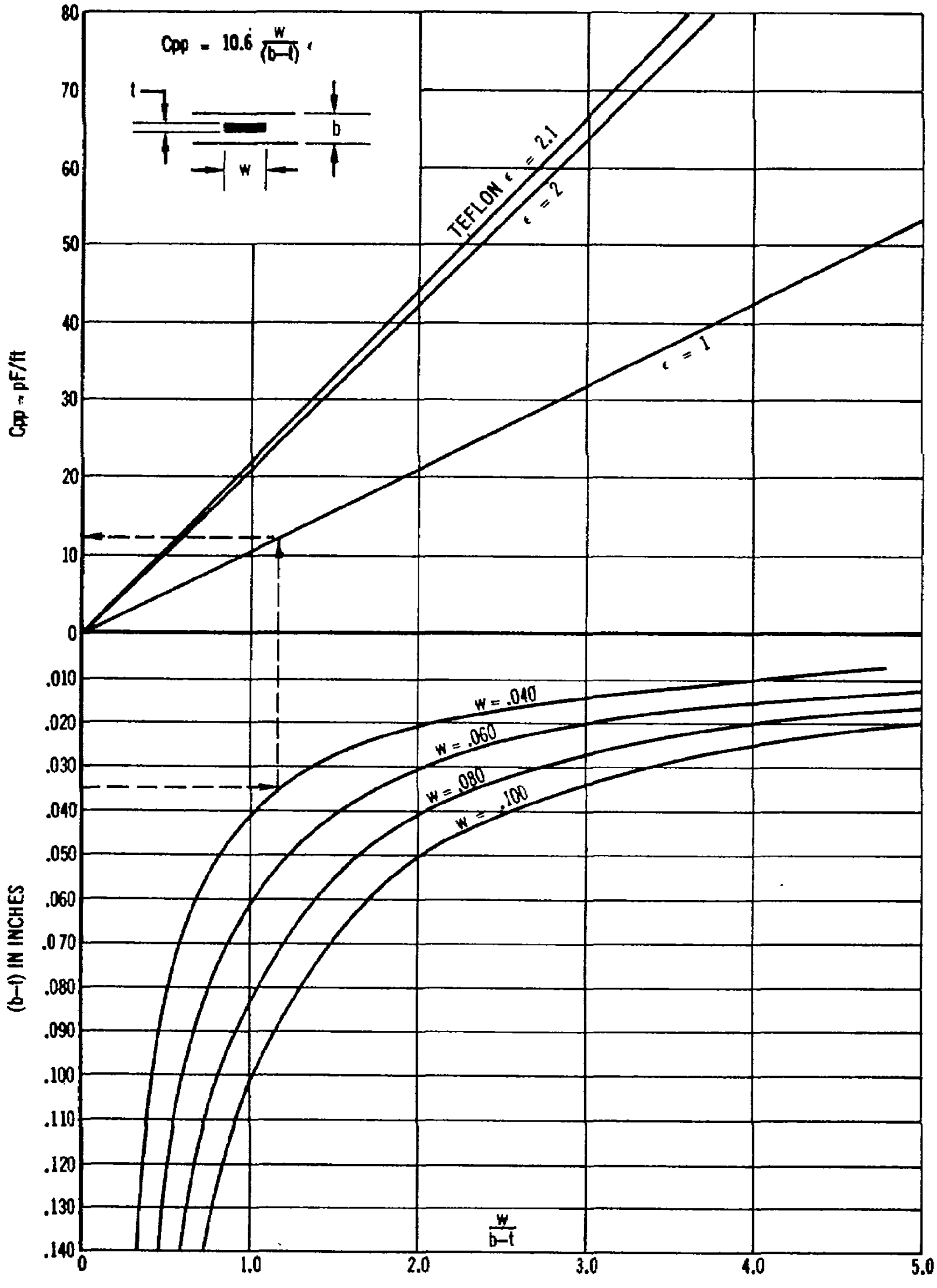


FIGURE 3-18. Conductor-to-shield capacitance for double-shielded FCC.

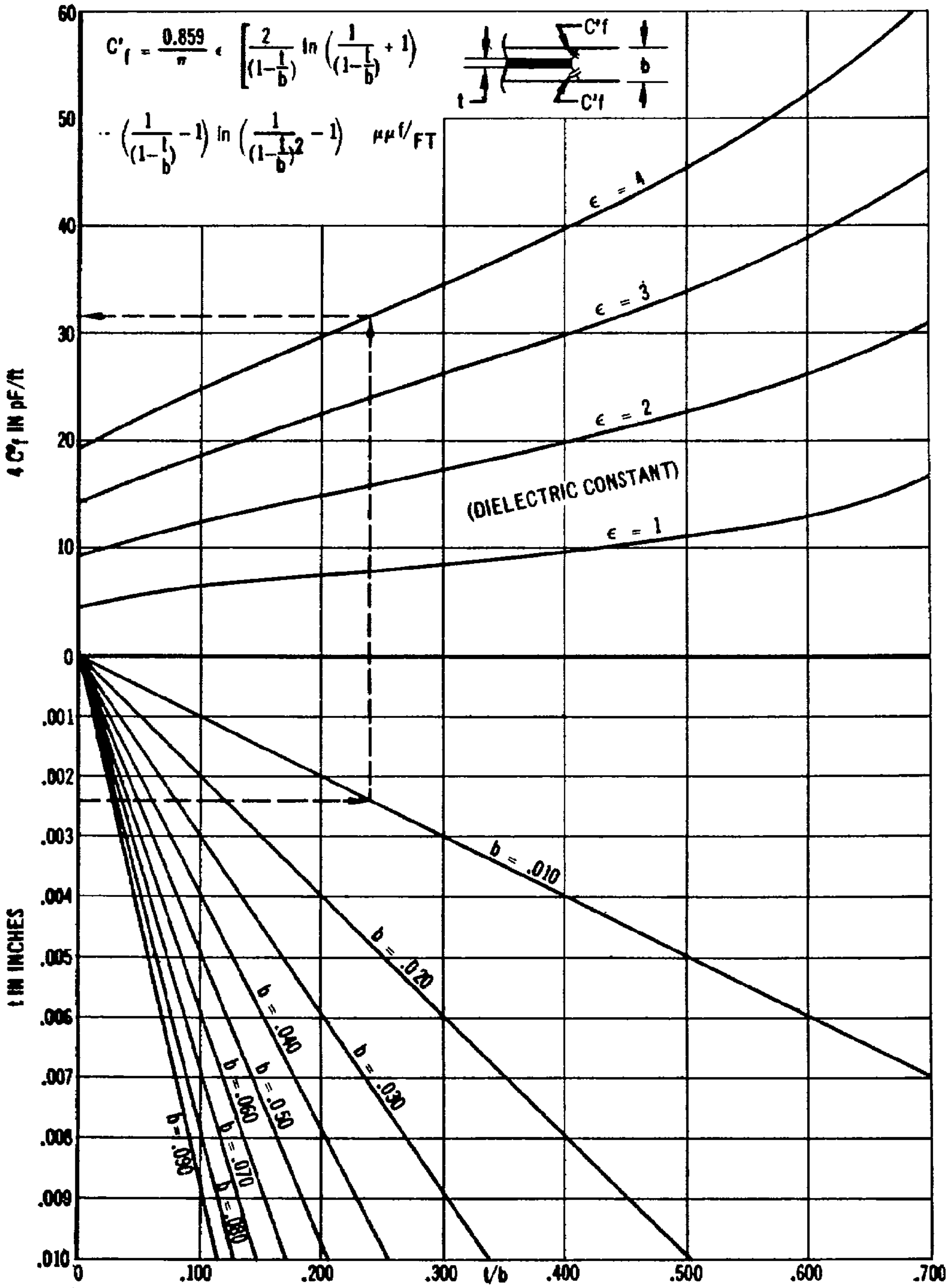


FIGURE 3-19. Conductor-to-shield fringe capacitance for double-shielded FCC.

3.2.3.1.5 Inductance Data. Any selected pair of conductors within moderately close proximity exhibits some amount of inductive coupling between the two conductors whenever current flows through one of the conductors. This can be measured as mutual inductance, M. In addition, any selected pair of differential elements (in the differential calculus sense) of a single conductor interacts inductively when a current flows through these elements. When this effect is considered over the entire conductor, it can be measured as self-inductance, L_{self}. If no magnetic materials are in the vicinity of the conductors, inductance of conductors can be calculated analytically for simple geometrical configurations. Dr. Frederich W. Grover provides formulas and tables that are applicable to FCC[1]. In the case of a straight conductor of rectangular cross-section, self-inductance is given by

$$L_{self} = 0.00200\,A \left[\ln \frac{2A}{B+C} + \frac{1}{2} - \ln E + \frac{0.2235(B+C)}{A} - \frac{0.04995(B+C)^2}{4\,L^2} \right]$$

where

L_{self} = microhenries

A = length of conductor in centimeters

B and C = width and thickness, respectively, of the conductor in centimeters

E = a correction term computed and tabulated by Grover[2]

Mutual inductance of a pair of straight, parallel conductors is given by

$$M = 0.00200\,A \left[\ln \frac{2A}{R} - 1 + \frac{R}{A} - \frac{R^2}{4A^2} \right]$$

where

M = microhenries

A = length of the conductors in centimeters

R = geometric mean distance in centimeters between all elements of the cross-section of one conductor and all elements of the cross-section of the other conductor.

Data for calculating geometric mean distances for adjacent conductors of rectangular cross sections are tabulated by Grover[3].

Calculations of self and mutual inductance have been made for adjacent parallel, straight conductors in 23 standard configurations of FCC, both on an edge-to-edge basis within a cable and on an over-and-under basis for conductors in stacked cables, with no magnetic material in close proximity. These calculations were made for cable lengths of 0.1 through 100 feet. From these calculated data, the total inductance of these pairs of conductors was computed for connection in a current-opposing circuit, as in transmission lines. This transmission line (*tl*) value of inductance is given by

$$L_{tl} = 2L_{self} - 2M$$

with all dimensions in consistent units (microhenries in our case).

The inductance, in terms of microhenries per foot, is essentially independent of length for each cable configuration for the transmission line circuit, while the ratio increases with length toward an asymptotic limit for both self and mutual inductance. This effect is shown graphically in Figure 3-20 for 0.004- by 0.040-inch conductors on 0.075-inch centerline spacing.

1. Grover, Frederich W.: Inductance Calculations: Working Formulas and Tables. Dover Publications, Inc., New York, N.Y., 1962.

2. Ibid, p. 14.

3. Ibid, p. 14.

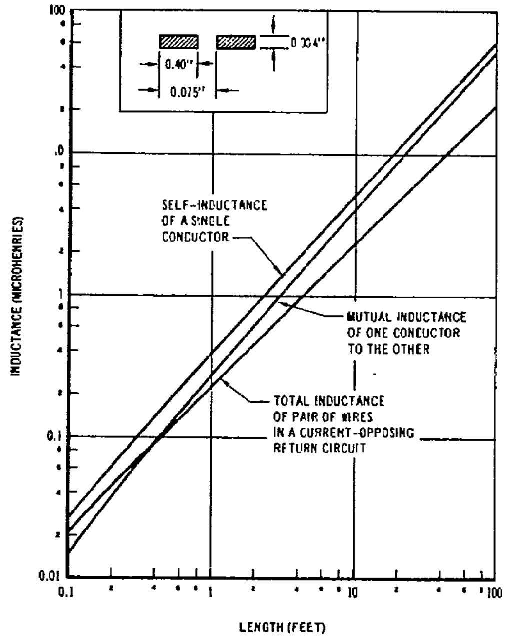


FIGURE 3-20. Components of inductance in a flat cable running in a straight line.

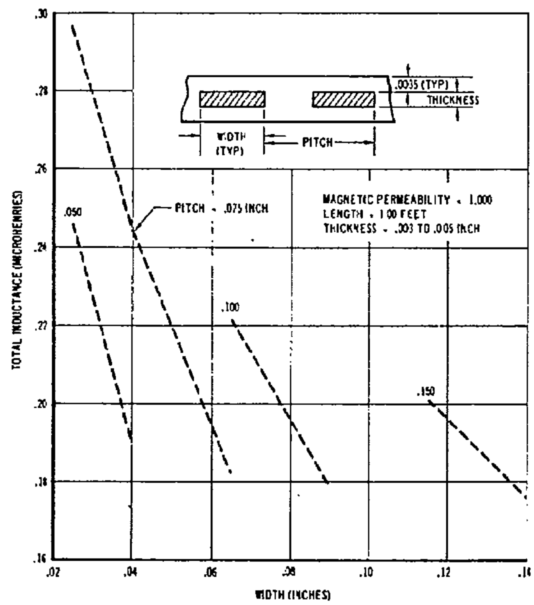


FIGURE 3-21. Total inductance of edge-to-edge conductors in a return circuit.

Because of the close coupling between parallel pairs of adjacent conductors, these pairs, when connected in a transmission-line circuit, exhibit a total inductance that is almost entirely dependent on only this coupling, and essentially independent of whether the pairs of wires travel a straight or a circuitous path between their sources and destinations. As a result, calculations of transmission-line inductance that are made for straight conductors are also valid for other-than-straight routing that can be expected in the wiring of electronic equipment. These values of inductance for 23 standard cable configurations (edge-to-edge and over-and-under) are shown in Figures 3-21 and 3-22, respectively.

The total inductance tolerance of a transmission-line pair of conductors in edge-to-edge configuration will be primarily a function of pitch or centerline spacing between the conductor and of conductor width. This can be seen from examination of Figure 3-21. As an example, for conductors of 0.040-inch width, an increase from 0.050 to 0.075 inch in pitch (an increment of 0.025 inch) results in an increase in inductance from 0.190 to 0.244 microhenry per foot (an increment of 0.054). As a result, inductance increases by approximately 0.6 percent per 1.0 percent pitch change. For a constant pitch of 0.075 inch, inductance will decrease by 0.9 percent per 1.0 percent width change. Other variation ratios may be derived from the figure.

By similar analysis, the total inductance tolerance of a transmission-line pair of conductors in over-and-under configurations is primarily a function of conductor width and of pitch between the stacked conductors. For constant width, the variation ratio for stacked cable with 0.004- by 0.065-inch conductors is approximately 1.5 percent inductance change per 1.0 percent pitch change. For constant pitch, the ratio will be approximately 1.0 percent inductance change per 1.0 percent width change.

3.2.3.1.6 Characteristic Impedance. Characteristic impedance of transmission-line pairs can be determined from capacitance, inductance, series resistance, and shunt conductance, according to

$$Z_o = \left(\frac{\sqrt{R^2 + 4\pi^2 f^2 L_{tl}^2}}{\sqrt{G^2 + 4\pi^2 f^2 C^2}} \right)^{1/2}$$

where

Z_o = characteristic impedance in ohms

R = series resistance in ohms per unit length

L_{tl} = inductance of the transmission line in henries per unit length

G = shunt conductance in ohms per unit length

C = shunt capacitance in farads per unit length

f = frequency of the applied signal.

The unit of length must obviously be consistent for all of the electrical parameters; e.g., a "per foot" basis.

It is appropriate for lower frequencies to simplify this formula by assuming that resistance and conductance components are insignificant. This is valid for FCC that are described in this report, for frequencies of a few megahertz or less. The simplified formula is

$$Z_o = \sqrt{\frac{L_{tl}}{C}}$$

The characteristic impedance of adjacent pairs of unshielded conductors for edge-to-edge conductors is plotted in Figures 3-23 and 3-24, and for over-and-under (stacked) conductors in Figures 3-25 and 3-26, using the simplified formula.

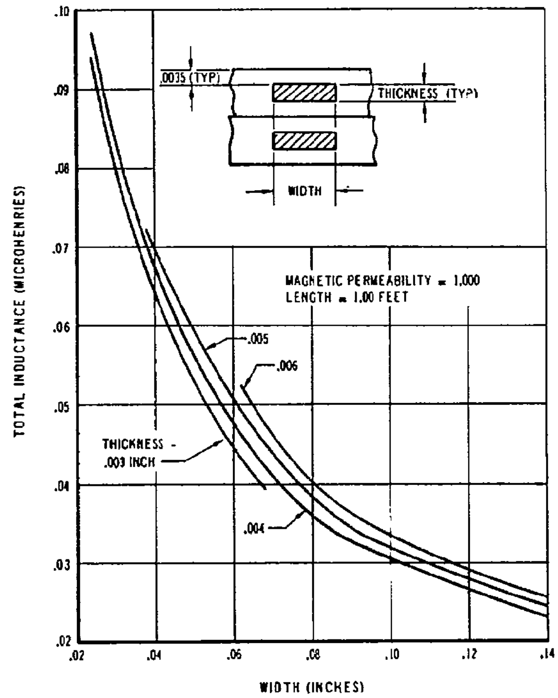


FIGURE 3-22. Total inductance of over-and-under conductors in a return circuit.

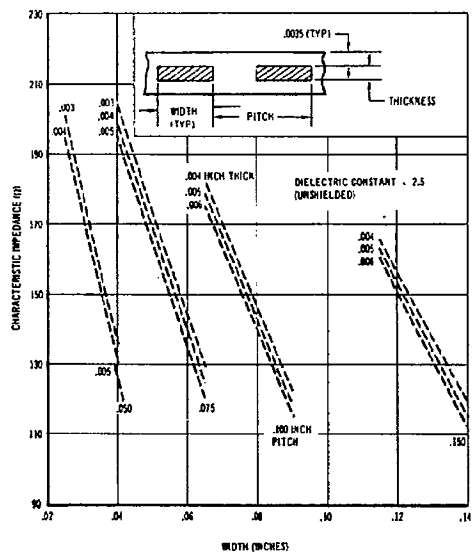


FIGURE 3-23. Characteristic impedance of edge-to-edge conductors in a transmission-line circuit, dielectric constant = 2.5.

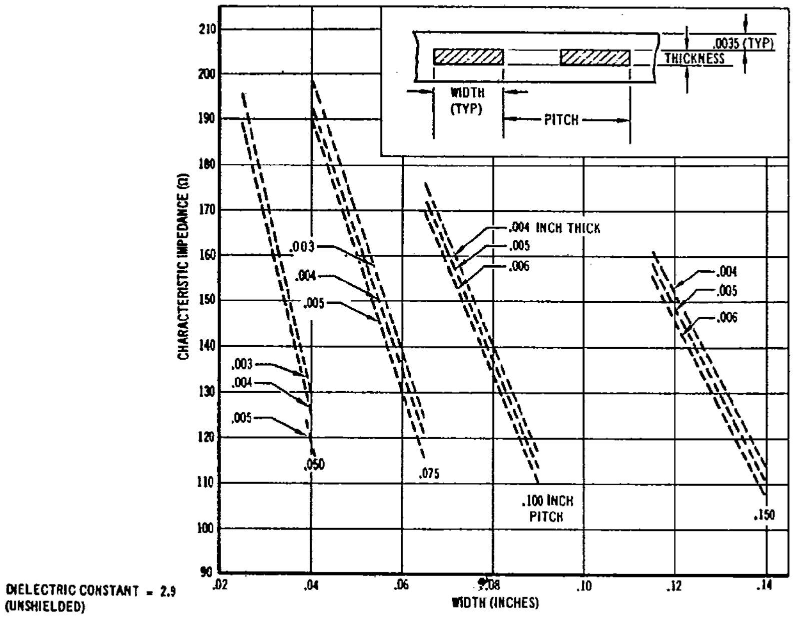


FIGURE 3-24. Characteristic impedance of edge-to-edge conductors in a transmission-line circuit, dielectric constant = 2.9.

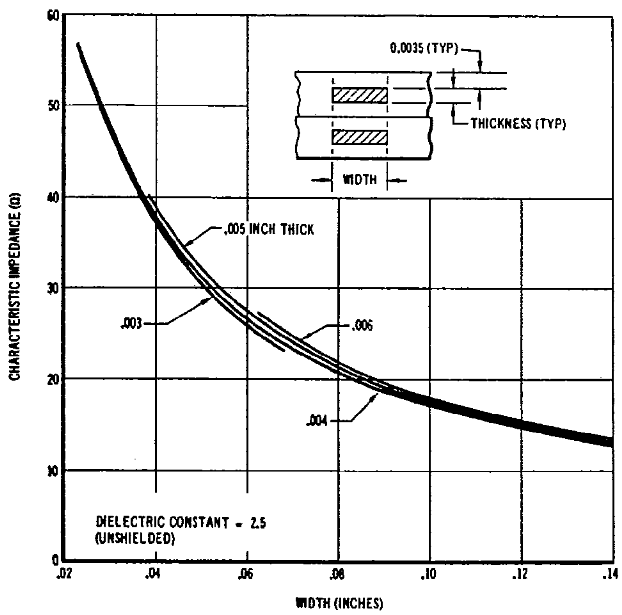


FIGURE 3-25. Characteristic impedance of over-and-under conductors in a transmission-line circuit, dielectric constant = 2.5.

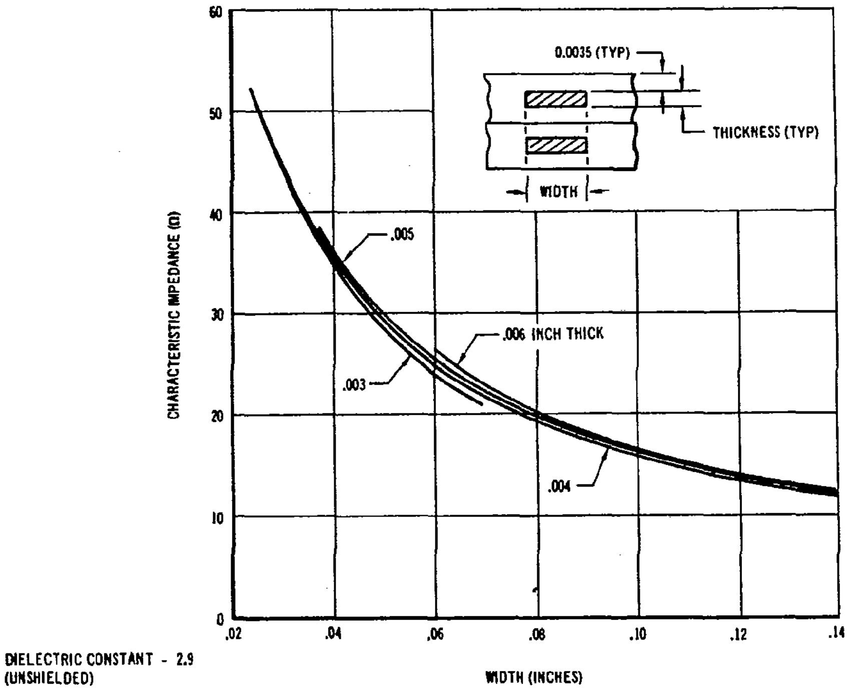


FIGURE 3-26. Characteristic impedance of over-and-under conductors in a transmission-line circuit, dielectric constant = 2. 9.

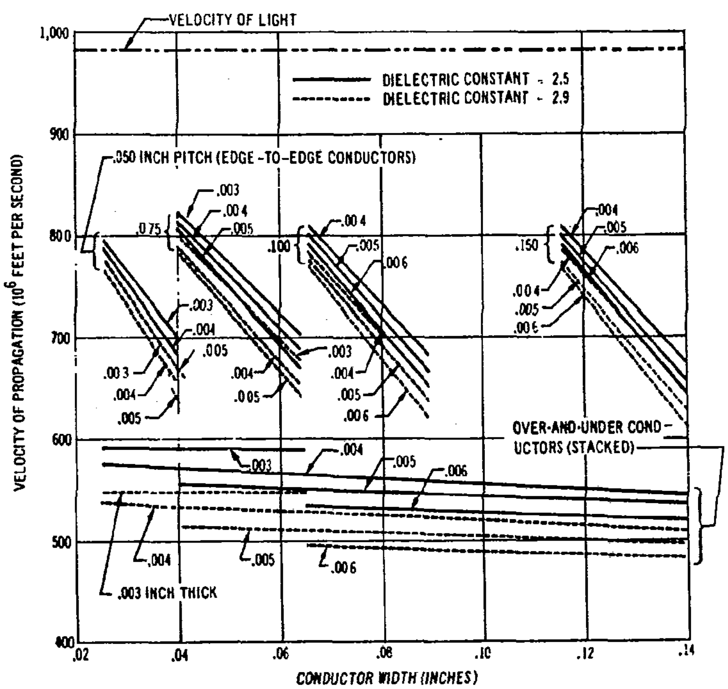


FIGURE 3-27. Velocity of propagation for conductors in a transmission-line circuit (unshielded).

3.2.3.1.7 Velocity of Propagation. Velocity of propagation of a wavefront in a transmission line is given by the formula

$$V = \frac{2\pi f}{\beta}$$

where β is the imaginary part of the complex quantity

$$\sqrt{\underline{Z} \cdot \underline{Y}}$$

where

$$\underline{Z} = R + j\,2\pi f\,L_{t\ell}$$

$$\underline{Y} = G + j\,2\pi f C$$

and where

R = series resistance in ohms per unit length

$L_{t\ell}$ = inductance of the transmission line in henries per unit length

G = shunt conductance in mhos per unit length

C = shunt capacitance in farads per unit length

f = frequency of the applied signal

The dimensions of velocity are units of length per second where the unit of length is the same as used in the electrical parameters; e.g., foot-per-second, when the electrical parameters are given in ohms per foot, farads per foot, etc.

When the resistive and conductive components of β are insignificant, say for frequencies less than a few megahertz, the formula for velocity of propagation simplifies to

$$V = \frac{1}{\sqrt{L_{t\ell}C}}$$

Velocity of propagation is plotted, using the simplified formula, in Figure 3-27 for adjacent pairs of conductors for the standard unshielded FCC configurations of this report. In this case of edge-to-edge conductors, the actual values are shown as points with straight lines drawn between the points for identification. In the case of over-and-under (stacked) conductors, the velocity values for the various thicknesses of conductor fall very close to straight lines within the range of conductor widths shown.

3.2.3.2 Electromagnetic Compatibility Considerations in Cable Design. Most of us are familiar with the slapstick comedy in which a handyman makes plumbing repairs, and water spurts from the lighting fixture when the switch is turned on. Complex electrical/electronic systems have exhibited similar tendencies under far less humorous conditions. The electrical/electronic components of any system must be mutually compatible within the system, with components in other systems of the electrical/electronic complex, and with the electromagnetic environment of the electrical/electronic installation.

A major source of electromagnetic incompatibilities, in any electrical/electronic system, is the system interconnection cabling. Most electronic units receive sufficient testing during the breadboard and prototype phases of design, so that internal spurious coupling is identified and corrected. Large systems are interconnected with cable assemblies too massive for convenient laboratory testing; therefore, most spurious system coupling problems are identified and corrected during system testing, acceptance testing, or operational usage of the hardware. The consequences of uncorrected spurious coupling occurring during a critical mission, either manned or unmanned, involving complex assemblies of nonreusable hardware, can be serious.

FCC has unique features which can be taken advantage of, in many instances, to obtain a wiring system that is superior to any cable of conventional round wires. On the other hand, the close proximity of adjacent conductors in FCC can cause more severe problems than with round-wire cable if proper and detailed attention is not paid to EMC considerations.

The ensuing paragraphs in this section discuss three major aspects of EMC design; (1) a simplified approach to optimization of conductor placement, (2) crosstalk between conductors, and (3) electric and magnetic shielding of FCC's.

The user who has not developed a sound background of experience in EMC design is strongly advised to study fundamentals of EMC, as discussed in Paragraph 3.2.10, and to consult with an EMC specialist to resolve remaining difficulties. To further emphasize this matter, an additional warning notice is given here.

WARNING

Experience has shown that certain interference and susceptibility characteristics are typical of the average electrical/electronic system, and that these characteristics can be extrapolated for use in more specialized types of systems. Because of the extremely broad spectrum of hardware involved, these characteristics are subject to wide variations and should be utilized only as a preliminary design goal until more specific hardware design and test information becomes available. As confidence in system performance increases, arbitrarily specified, initial characteristics should be superseded or refined with analyses of actual system performance.

3.2.3.2.1 Simplified Optimization of Conductor Placement. An examination of the factors influencing the actual spurious-coupling loss reveals that these factors (Tables 3-8 through 3-12), when properly chosen, can be multiplied by each other, thus providing a criticality figure ranging from an extremely severe source of interference, through a neutral condition, to an extremely sensitive susceptible circuit. By using a logarithmic scale, it becomes possible to add the transformed log values instead of engaging in a multiplication process. Avoiding multiplication provides smaller and more convenient numbers.

When the numeric values are summed, and the two alphabetic prefixes are carried through; an alphanumeric criticality figure for electromagnetic compatibility is generated for the conductor. This criticality figure identifies the function as being susceptible (S) to or a source of interference (I) that is dominantly magnetic (M) or electric-field (E) coupled, and has a magnitude removed between 20 times the numeric value (in decibels) and 20 times the difference of the numeric value less 1 (in decibels) from a neutral level.

After assigning an alphanumeric criticality figure to each function, list the functions in criticality sequence with the most-critical susceptible circuit at one end of the list and the most-critical interference source at the other end of the list. Keep conductor pairs or multiples in the same circuit adjacent to each other in the criticality sequence list. Low-impedance return or neutral conductors are partially effective as electric-field shields at low frequencies.

Within the constraints imposed on the cable segment being designed, make function assignments to conductors within the cable-segment cross-section on the basis of the function location in the criticality sequence list. Try to alternate magnetic and electric field dominant functions within the same grouping in the criticality sequence to minimize crosstalk between adjacent conductors with similar coupling characteristics.

Complete an electromagnetic compatibility analysis on several of the most-critical conductor combinations to establish a reference point for later differential analysis of the bulk of conductor combinations, and to provide a basis for the modification of the weighing factors supplied, it this becomes necessary.

Determine the distributed-parameter values of typical lengths of typical conductor combinations. Determine the ratios that exist between the various mutual capacitances, shunt capacitances, mutual inductances, series self-inductances, and other variables as the cable and cable conductor configurations are changed. Convert these ratios to equivalent decibels of change in coupling, for use as constraints for comparison with the difference in criticality figures (in decibels) of closely spaced functions assigned to conductors in accordance with the criticality sequence list.

TABLE 3-8. TERMINATION IMPEDANCE COUPLING FACTOR

Units Magnetic Coupling	Resistance/ Reactance	Reactive Component Value			
		60 Hz	400 Hz	4 kHz	50 kHz
M4	Under 10 mΩ	Above 0.3 F Under 50μH	Above 0.03 F Under 5μH	Above 3000μF Under 0.5μH	Above 300μF Under 0.05μH
M3	10 to 100 mΩ	0.03 to 0.3 F 50μH to 500μH	3000μF to 0.03 F 5μH to 50μH	300μF to 3000μF 0.5μH to 5μH	30μF to 300μF 0.05μH to 0.5μH
M2	100 mΩ to 1Ω	3000μF to 0.03 F 500μH to 5mH	300μF to 3000μF 50μH to 500μH	30μF to 300μF 5μH to 50μH	3μF to 30μF 0.5μH to 5μH
M1	1 to 10Ω	300μF to 3000μF 5mH to 50mH	30μF to 300μF 500μH to 5mH	3μF to 30μF 50μH to 500μH	0.3 F to 3μF 5μH to 50μH
M0	10 to 100Ω	30μF to 300μF 50mH to 500mH	3μF to 30μF 5mH to 50mH	0.3μF to 3μF 500μH to 5mH	0.03μF to 0.3μF 50μH to 500μH
Units Electric Coupling					
E0	100Ω to 1 kΩ	3μF to 30μF 500mH to 5H	0.3μF to 3μF 50mH to 500mH	0.03μF to 0.3μF 5mH to 50mH	0.003μF to 0.03μF 500μH to 5mH
E1	1 to 10 kΩ	0.3μF to 3μF 5H to 50H	0.03μF to 0.3μF 500mH to 5H	0.003μF to 0.03μF 50mH to 500mH	300pF to 0.003μF 5mH to 50mH
E2	10 to 100 kΩ	0.03μF to 0.3μF 50H to 500H	0.003μF to 0.03μF 5H to 50H	300pF to 0.003μF 500mH to 5H	30pF to 300pF 50mH to 500mH
E3	100 kΩ to 1 MΩ	0.003μF to 0.03μF 500H to 5000H	300pF to 0.003μF 50H to 500H	30pF to 300pF 5H to 50H	3pF to 30pF 500mH to 5H
E4	Above 1 MΩ	Under 0.003μF Above 5000H	Under 300pF Above 500H	Under 30pF Above 50H	Under 3pF Above 5H

TABLE 3-9. FREQUENCY/TIME COUPLING FACTOR

Units of Coupling	Frequency	Equivalent Pulse Width
0	Under 3 Hz	Over 100 ms
1	3 to 30 Hz	10 to 100 ms
2	30 to 300 Hz	1 to 10 ms
3	300 Hz to 3 kHz	100 μs to 1 ms
4	3 to 30 kHz	10 to 100 μs
5	30 to 300 kHz	1 to 10 μs
6	300 kHz to 3 MHz	100 ns to 1 μs
7	3 to 30 MHz	10 to 100 ns
8	30 to 300 MHz	1 to 10 ns
9	Above 300 MHz	Under 1 ns

TABLE 3-10. LENGTH COUPLING FACTOR

Units of Spurious Coupling	Unshield Length of Conductors
0	Under 1 mm
1	1 to 10 mm
2	10 to 100 mm
3	100 mm to 1 m
4	1 to 10 m
5	10 to 100 m
6	100 m to 1 km
7	1 to 10 km
8	10 to 100 km
9	Over 100 km

TABLE 3-11. AMPLITUDE SUSCEPTIBILITY/
INTERFERENCE FACTOR

Units of Susceptibility	Voltage	Current
S4	Under 10 μV	Under 0.1 μA
S3	10 to 100 μV	0.1 to 1 μA
S2	100 μV to 1 mV	1 to 10 μA
S1	1 to 10 mV	10 to 100 μA
S0	10 to 100 mV	100 μA to 1 mA
Units of Interference		
I0	100 mV to 1 V	1 to 10 mA
I1	1 to 10 V	10 to 100 mA
I2	10 to 100 V	100 mA to 1 A
I3	100 V to 1 kV	1 to 10 A
I4	Above 1 kV	Above 10 A

TABLE 3-12. RESOLUTION/ACCURACY
SUSCEPTIBILITY FACTOR

Units of Susceptibility	Resolution or Accuracy Required
S4	Better than 0.1%
S3	0.1 to 1%
S2	1 to 10%
S1	10 to 100%
S0	On-off and other bilevel functions
Units of Interference	
I2	Average value for interference

Crosstalk and shielding-effectiveness values, available in decibel units relative to unshielded cable, may also be used to evaluate the decrease in coupling achieved by the use of devices such as shielding.

Detailed design procedures are highly dependent on the specific types of cables selected for the system and on the specific assembly geometry of the mounted cabling; therefore, these procedures must be developed, refined, and expanded by the user in accordance with the general guidelines that have been previously defined.

3.2.3.2.2 Crosstalk. Crosstalk is the spurious coupling of energy from one conductor to another, both of which are located in a common electromagnetic environment, either unshielded or within a common shield. At termination impedances below the characteristic impedance of the conductor, the spurious coupling will be predominantly magnetic. At termination impedances above the characteristic impedance of the conductor, the spurious coupling will be predominantly electric. The magnitude of coupling is critically dependent on the terminating impedances, but generally becomes significant above midaudio frequencies and approaches unity coupling in the supersonic and radio-frequency spectrums.

A more detailed discussion relating to crosstalk may be found in Paragraph 3.2.10 of this handbook. Since crosstalk or spurious coupling is so highly dependent on the conductor termination characteristics and other function properties, generalizations are often misleading and individual analyses are mandatory.

Measured crosstalks between adjacent, centrally located conductors in a variety of cable configurations is shown in Figures 3-28 through 3-39.

Crosstalk can be divided into the two categories of electric and magnetic coupling.

3.2.3.2.2.1 Electric-Field Crosstalk. A classic case of electric-coupled crosstalk would exist if two adjacent, vertically stacked, unshielded conductors, 40 meters long, resulted in the assignment of the following values to Figure 3-40(A):

$R_{S,\ INT} = 1\ 000\Omega R_{L,\ INT} = 10\ 000\Omega$

$R_{S,\ SUS} = 10\ 000\Omega R_{L,\ SUS} = 100\ 000\Omega$

$C_C = 10\ 000$ PF $\qquad C_S = 1000$ pF

$V_{INT} = 10$ Vrms

$F_{INT} = 100$-kHz sine wave

$$V_{SUS} = V_{INT} \times \frac{Z_{SUS}}{XC_C + Z_{SUS}}$$

$$V_{SUS} = 10V \times \frac{1361}{1521} = 8.948 \text{ V (Fig. 3-40)}$$

In this case, a signal of 8.9 volts was generated in the susceptible circuit. Reactance values can be read from a reactance chart or calculated. Phase shift was not considered because the coupling impedance and susceptible circuit impedance were widely different values. Reasonable approximations were used for convenience because a high degree of precision was not required.

3.2.3.2.2.2 Magnetic-Field Crosstalk. A classic case of magnetic-coupled crosstalk would exist if two adjacent, vertically stacked, unshielded conductors, 40 meters long, resulted in the assignment of the following values to Figure 3-41:

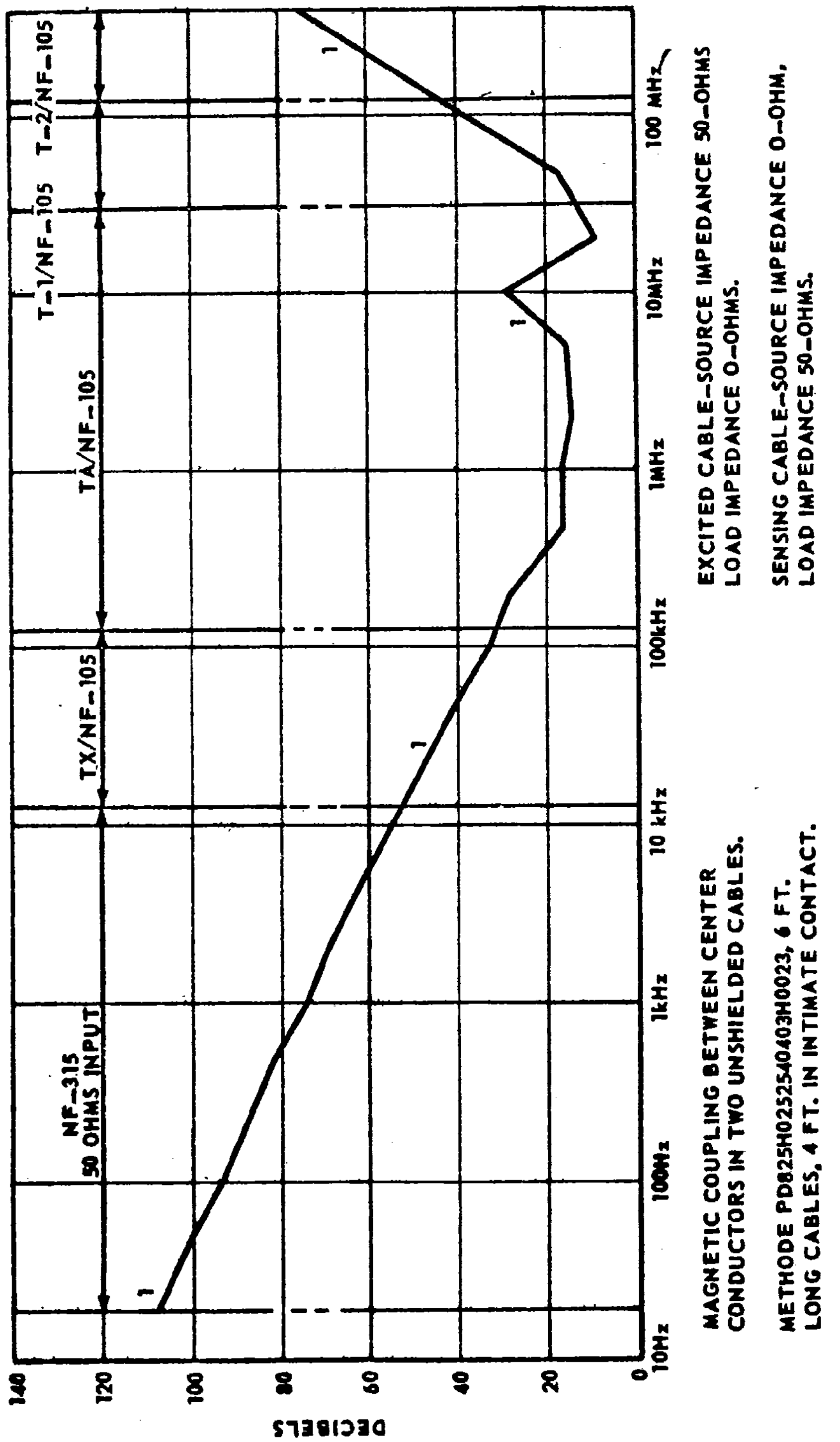
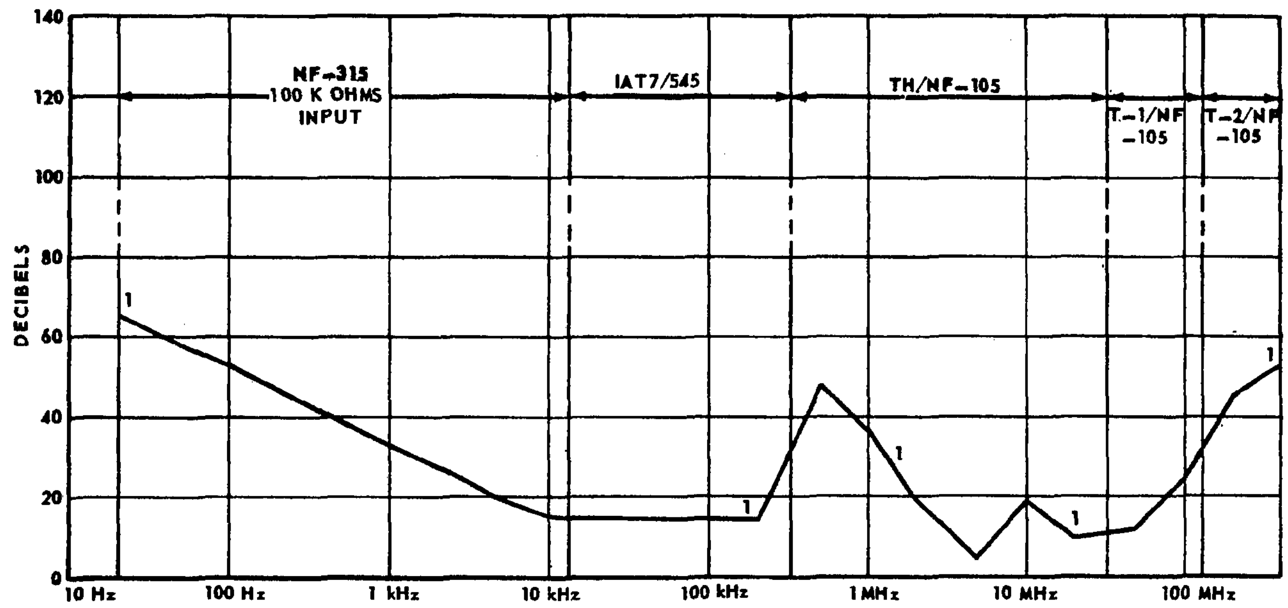


FIGURE 3-28. Magnetic crosstalk - adjacent center conductors - stacked unshielded cables.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTORS IN TWO UNSHIELDED CABLES.

METHODE PD825HC252540403H0023, 6 FT. LONG CABLES, 4 FT. IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS LOAD IMPEDANCE ∞ -OHMS.

SENSING CABLE-SOURCE IMPEDANCE ∞ -OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— UNSHIELDED CABLE MEASUREMENT

FIGURE 3-29. Electrostatic crosstalk - adjacent center conductors - stacked unshielded cables.

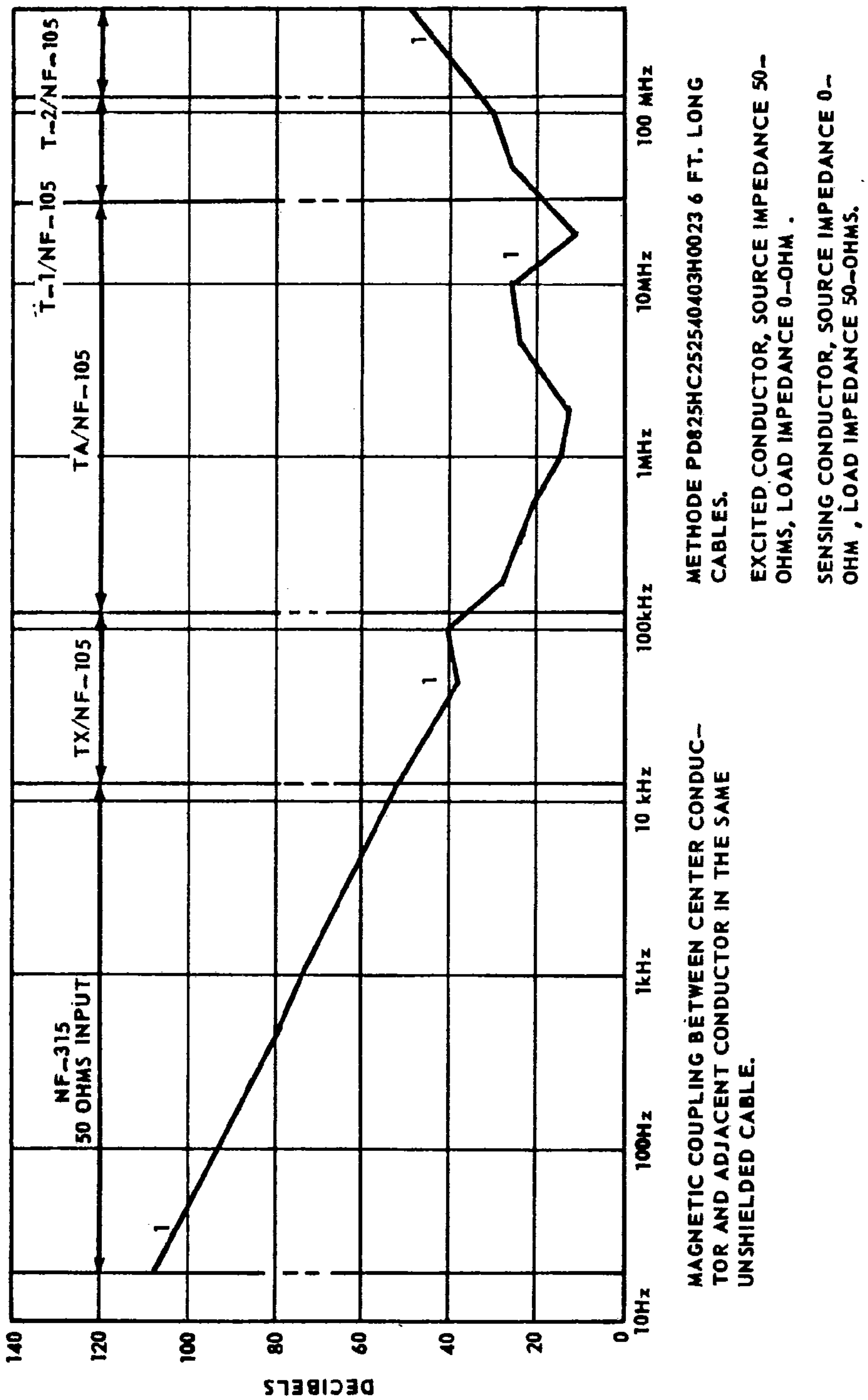
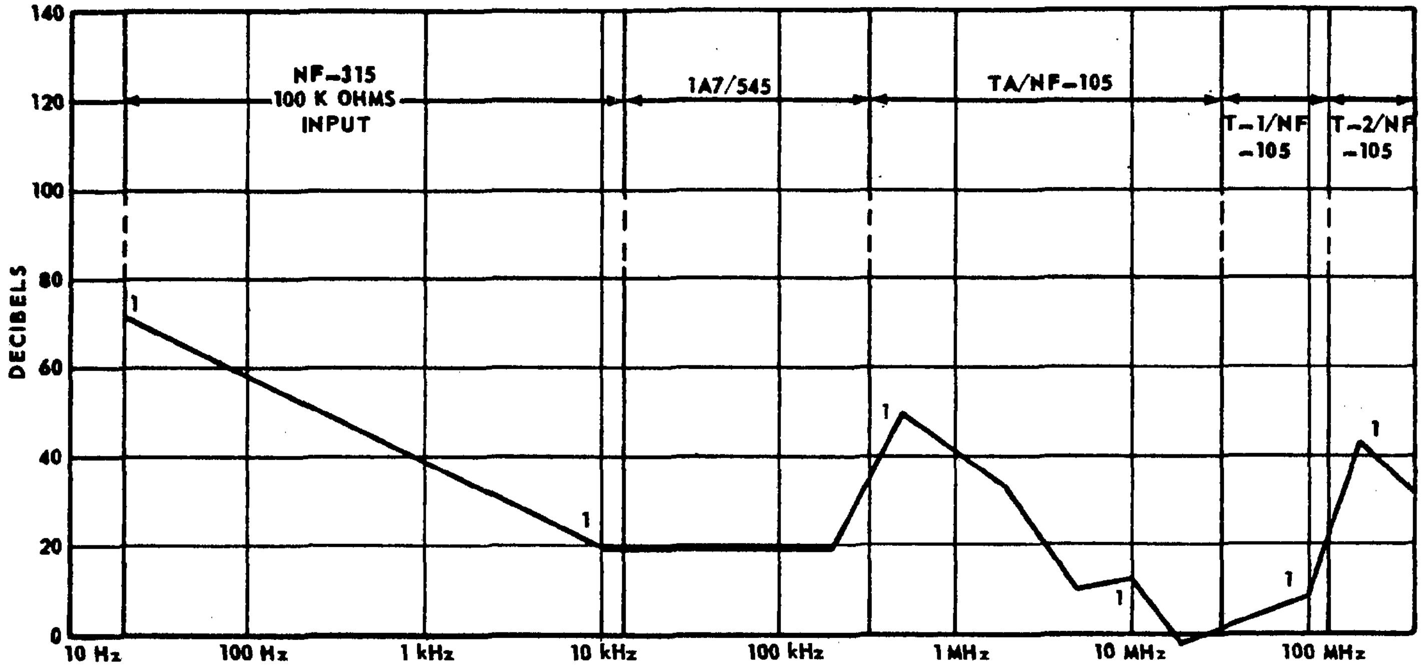


FIGURE 3-30. Magnetic crosstalk - adjacent center conductors - same unshielded cables.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTOR AND ADJACENT CONDUCTOR IN THE SAME UNSHIELDED CABLE.

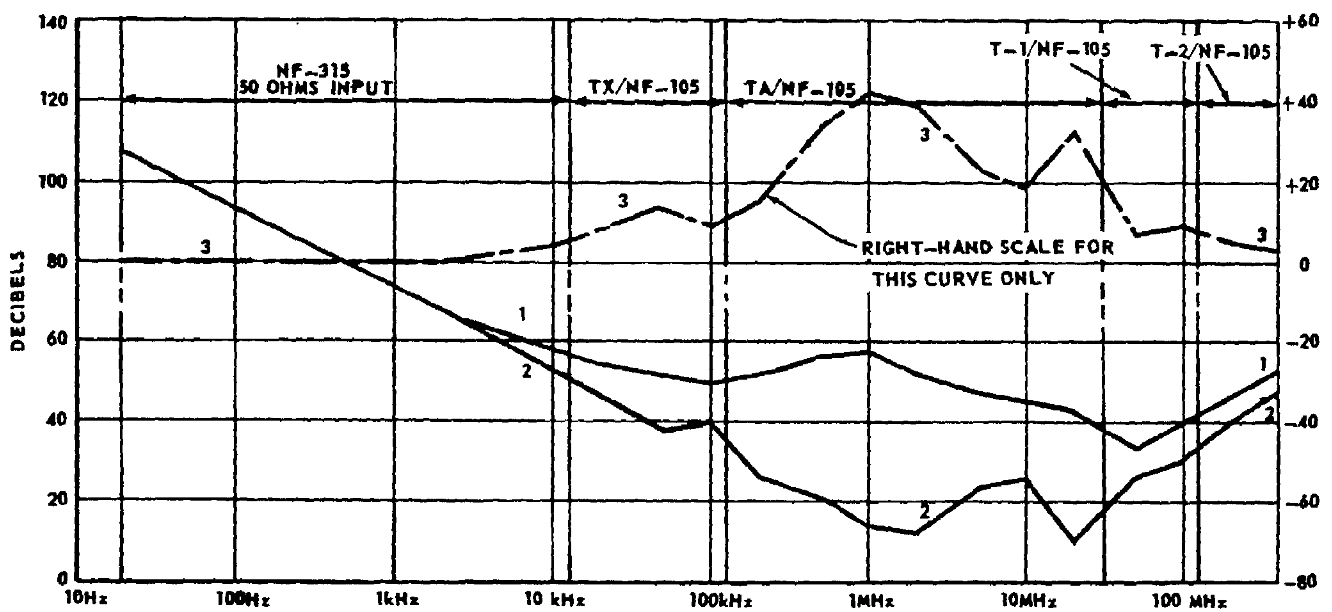
METHODE PD825HC252540403H0023 6 FT. LONG CABLES.

EXCITED CONDUCTOR, SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE ∞ OHMS.

SENSING CONDUCTOR, SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 —— UNSHIELDED CABLE MEASUREMENT

FIGURE 3-31. Electrostatic crosstalk - adjacent center conductors - same unshielded cables.



MAGNETIC COUPLING BETWEEN CENTER CONDUCTOR AND ADJACENT CONDUCTOR IN THIS SAME NASA/METHODE SPEC 220 COPPER SHIELDED CABLE WITH OPEN EDGES. CABLE LENGTH 6 FEET.

EXCITED CABLE- SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0-OHM

SENSING CABLE-SOURCE IMPEDANCE 0-OHM, LOAD IMPEDANCE 50-OHMS.

1 ——— SHIELDED CABLE MEASUREMENT

2 ——— UNSHIELDED CABLE (FIG. 3-30)

3 - - - SHIELDING EFFECTIVENESS

FIGURE 3-32. Magnetic crosstalk - adjacent center conductors - same solid copper shielded cable - open edges.

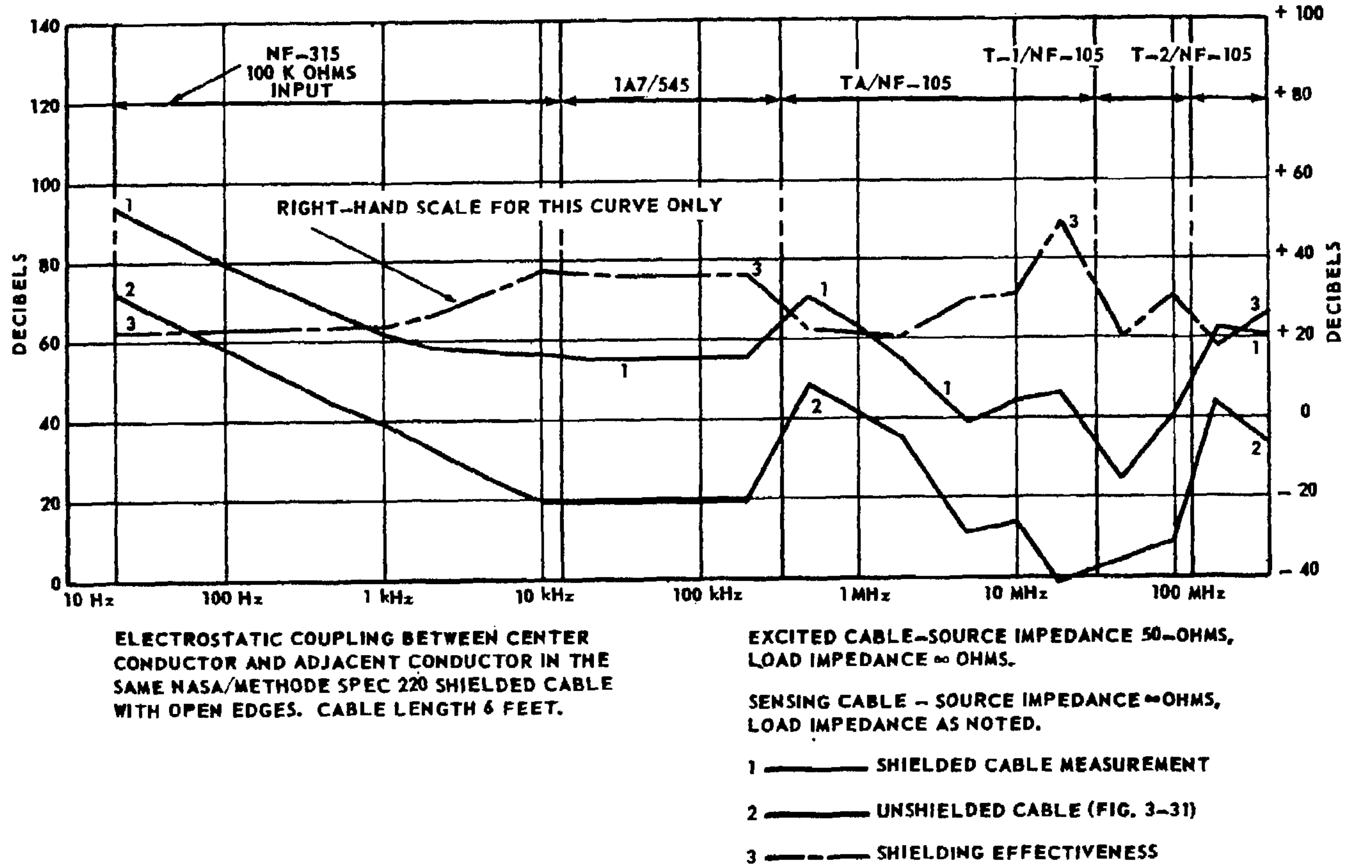


FIGURE 3-33. Electrostatic crosstalk - adjacent center conductors - same solid copper shielded cable - open edges.

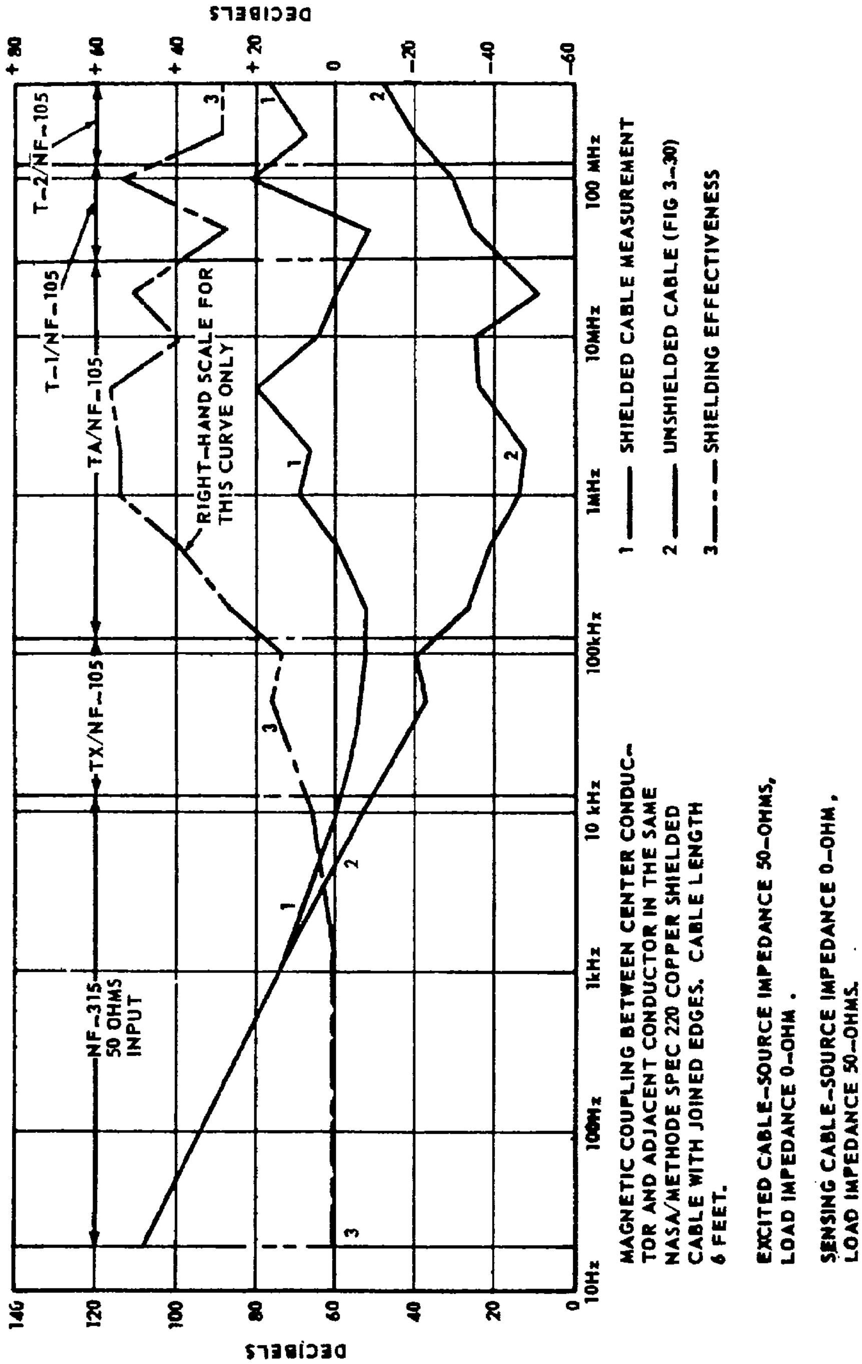
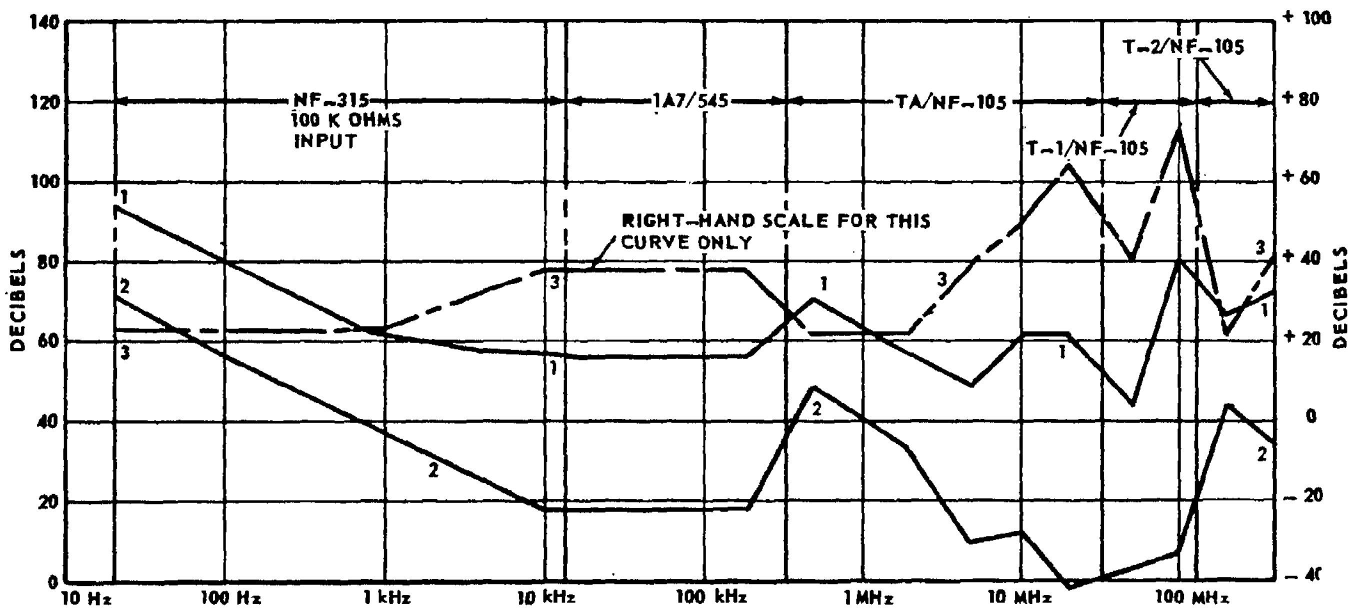


FIGURE 3-34. Magnetic crosstalk - adjacent center conductors - same solid copper shielded cable - joined edges.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTOR AND ADJACENT CONDUCTOR IN THE SAME NASA/METHODE SPEC 220 SHIELDED CABLE WITH JOINED EDGES. CABLE LENGTH 6 FEET.

EXCITED CABLE–SOURCE IMPEDANCE 50–OHMS, LOAD IMPEDANCE ∞ OHMS.

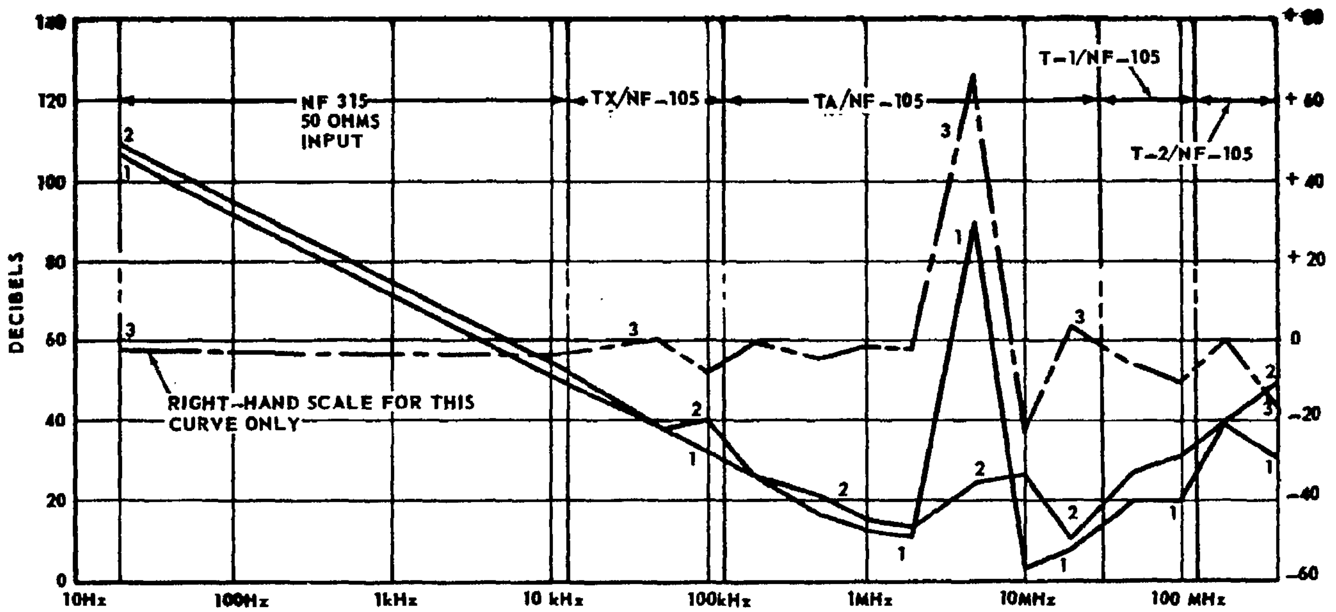
SENSING CABLE – SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— SHIELDED CABLE MEASUREMENT

2 ——— UNSHIELDED CABLE (FIG 3–31)

3 – – – SHIELDING EFFECTIVENESS

FIGURE 3-35. Electrostatic crosstalk - adjacent center conductors - same solid copper shielded cable - joined edges.



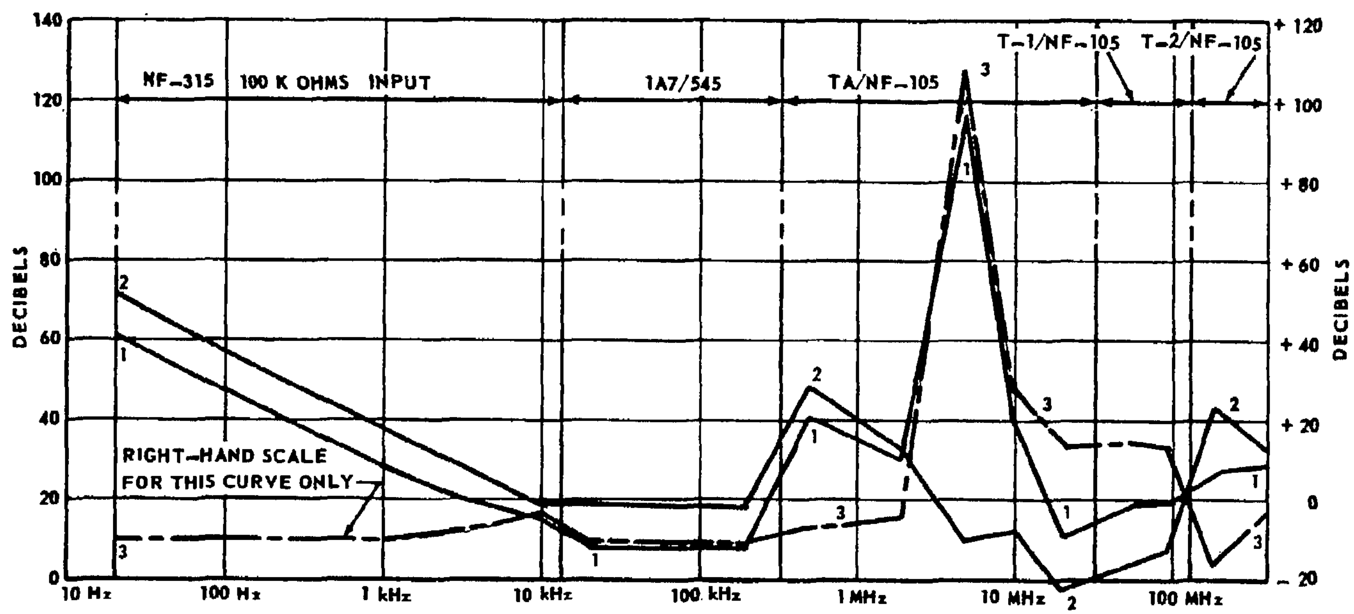
MAGNETIC COUPLING BETWEEN ONE CONDUCTOR OF A SUPRENANT 25-R04538 (300) JA 10 (15) SHIELDED TWISTED PAIR ROUND WIRE CABLE AND THE SECOND CONDUCTOR IN THE SAME CABLE. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CONDUCTOR - SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0-OHM.

SENSING CONDUCTOR - SOURCE IMPEDANCE 0-OHM, LOAD IMPEDANCE 50-OHMS.

1 ———— SHIELDED CABLE MEASUREMENT
2 ———— UNSHIELDED CABLE (FIG 3-30)
3 — — — SHIELDING EFFECTIVENESS

FIGURE 3-36. Magnetic crosstalk - adjacent conductors - same woven copper shielded RWC.



ELECTROSTATIC COUPLING BETWEEN ONE CONDUCTOR OF A SUPRENANT 25-HC4538 (300) JA 10 (15) SHIELDED TWISTED PAIR ROUND WIRE CABLE AND THE SECOND CONDUCTOR IN THE SAME CABLE. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CONDUCTOR - SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE OHMS.

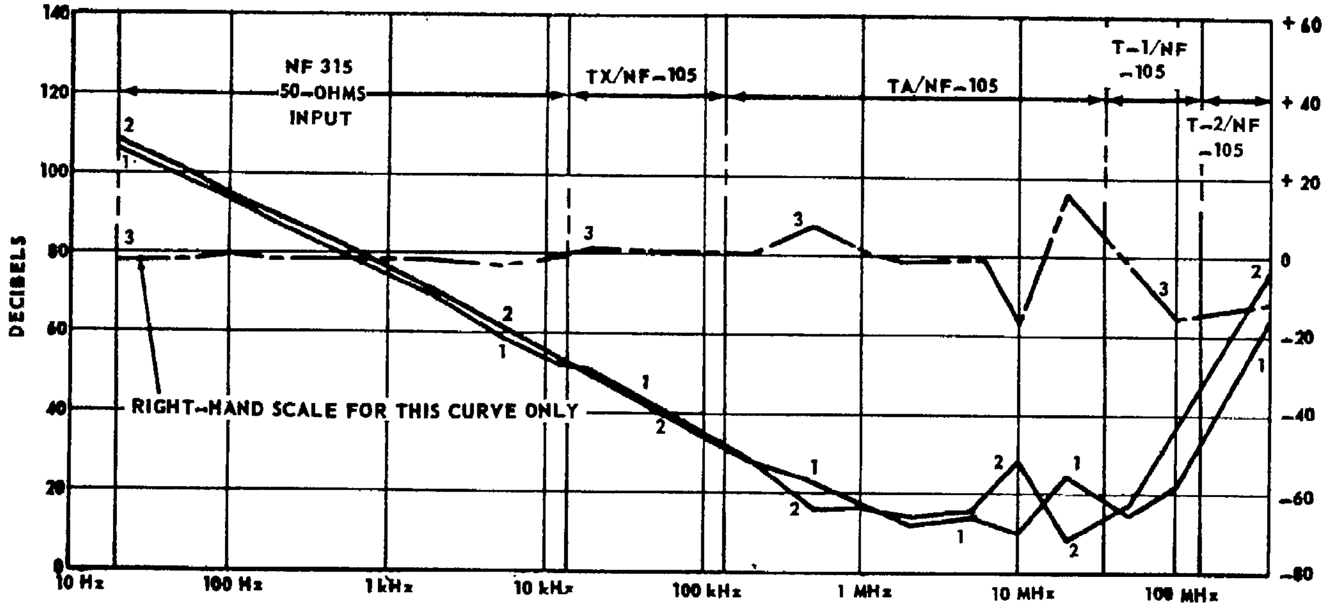
SENSING CONDUCTOR - SOURCE IMPEDANCE OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 —— SHIELDED CABLE MEASUREMENT

2 —— UNSHIELDED CABLE (FIG 3-31)

3 - - - SHIELDING EFFECTIVENESS

FIGURE 3-37. Electrostatic crosstalk - adjacent conductors - same woven copper shielded RWC.



MAGNETIC COUPLING BETWEEN CENTER CONDUCTORS IN TWO UNSHIELDED METHODE PD825HC-2525C40403H0023 CABLES SEPARATED BY 0.1875 INCHES OF FIBERGLASS BOARD. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0-OHM

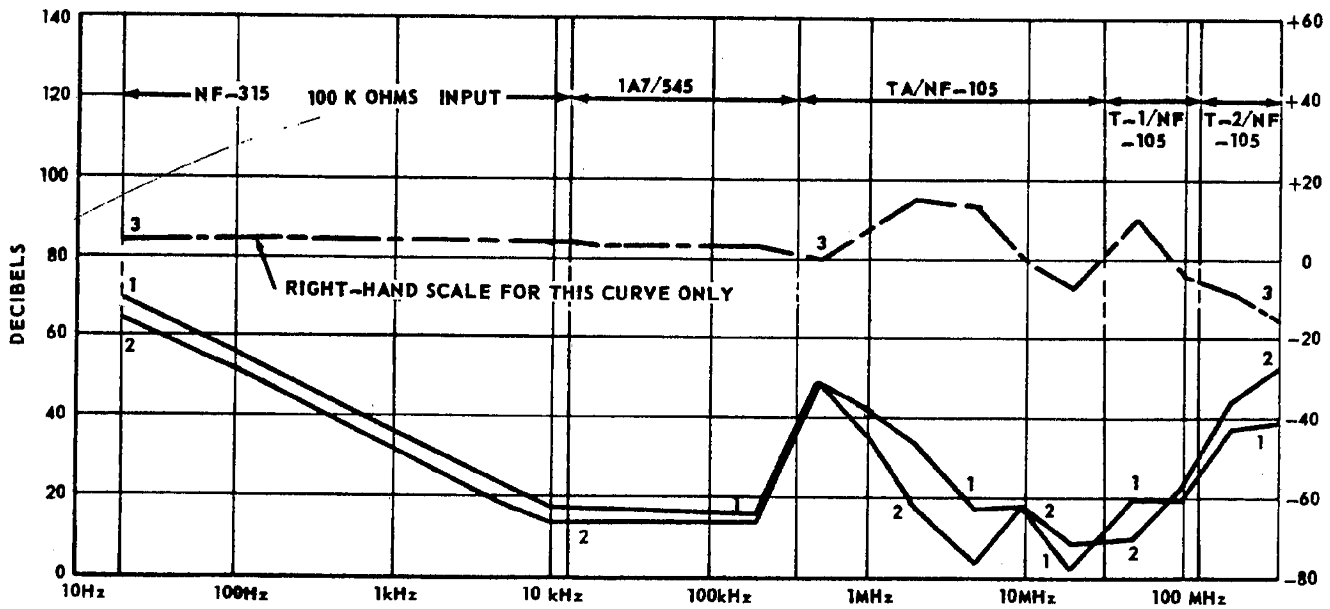
SENSING CABLE-SOURCE IMPEDANCE 0-OHM, LOAD IMPEDANCE 50-OHMS.

1 —— UNSHIELDED CABLE MEASUREMENT

2 —— UNSHIELDED CABLE (FIG 3-28)

3 - - - SPACING

FIGURE 3-38. Magnetic crosstalk reduction - stacked unshielded cables - 0.1875-inch dielectric spacer.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTORS IN TWO UNSHIELDED METHODE PD-825HC2525C40403H0023 CABLES SEPARATED BY 0.1875 INCH OF FIBERGLASS BOARD. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE ∞OHMS.

SENSING CABLE-SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

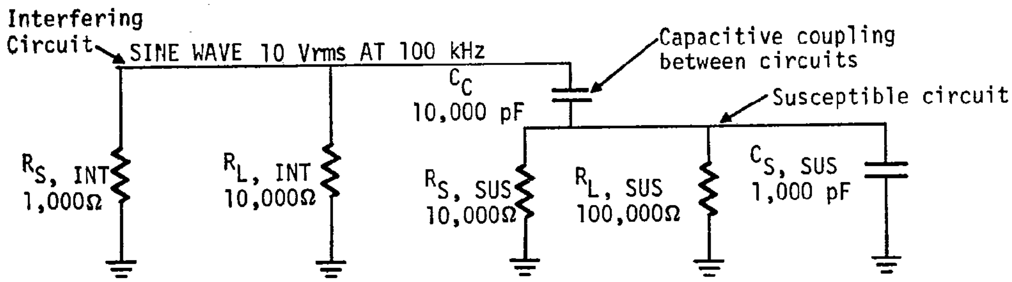
SEPARATING

1 —— UNSHIELDED CABLE MEASUREMENT

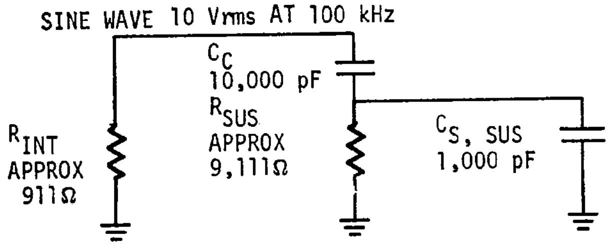
2 —— UNSHIELDED CABLE (FIG 3-29)

3 - - - SPACING

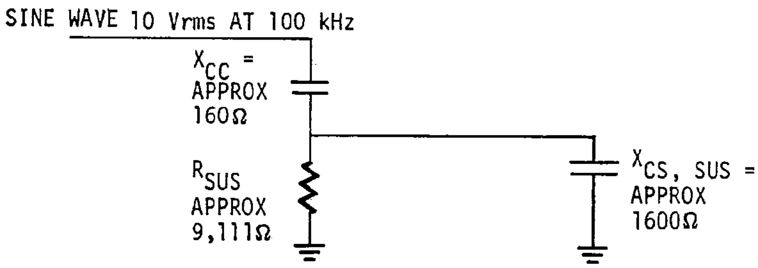
FIGURE 3-39. Electrostatic crosstalk reduction - stacked unshielded cables - 0.1875-inch dielectric spacer.



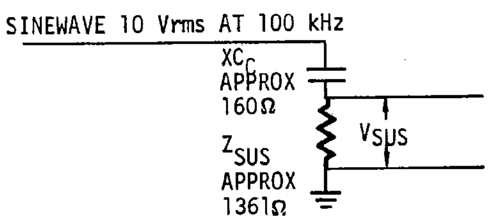
(A) Initial Circuit



(B) AN EQUIVALENT CIRCUIT

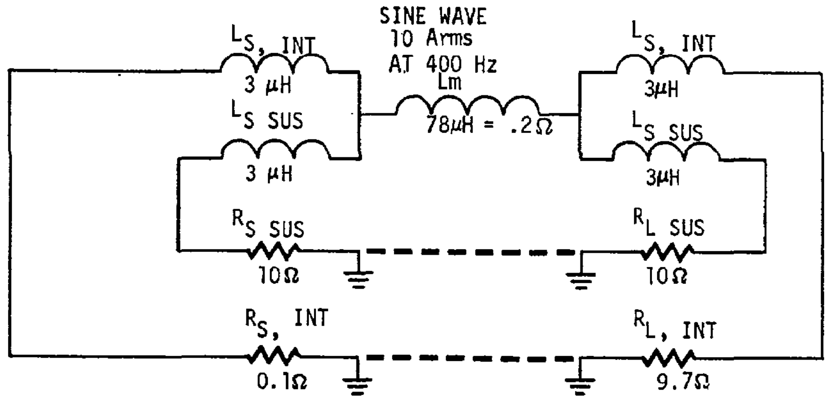


(C) Refined Equivalent Circuit

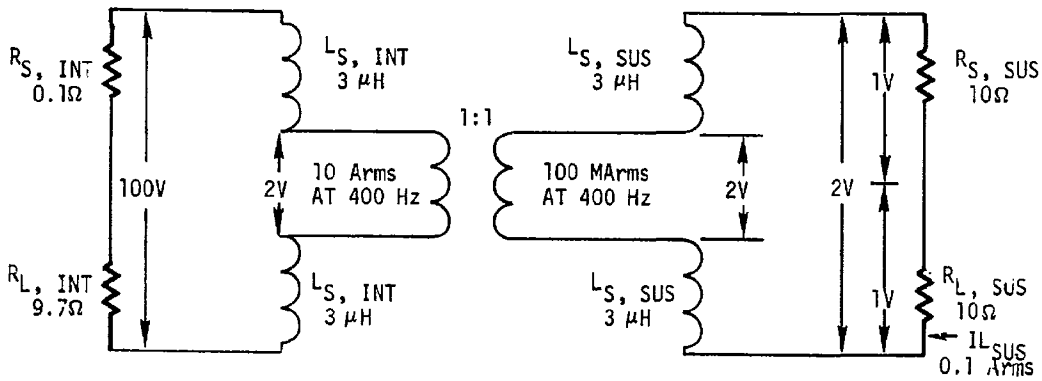


(D) Final Equivalent Circuit

FIGURE 3-40. Electric-field crosstalk.



(A) Initial Circuit



(B) Equivalent Circuit

$$V_{Lm} = I_{INT} \times XL_m$$

$$V_{Lm} = 10 \times 0.2\Omega$$

$$V_{Lm} = 2V$$

$$I_{SUS} = \frac{2V}{R_{S,SUS} + R_{L,SUS}}$$

$$I_{SUS} = \frac{2V}{10\Omega + 10\Omega}$$

$$I_{SUS} = \frac{2V}{20\Omega} = 0.10 \text{ Arms}$$

FIGURE 3-41. Magnetic-field crosstalk.

$R_{L,\ INT} = 9.7\Omega$

$R_{L,\ SUS} = 10\Omega$

$R_{S,\ INT} = 0.1\Omega$

$R_{S,\ SUS} = 10\Omega$

$L_{S,\ INT} = 3\ \mu H + 3\ \mu H = 6\ \mu H$

$L_{S,\ SUS} = 3\ \mu H + 3\ \mu H = 6\ \mu H$

$X_{Lm} = 0.2\Omega$

$L_m = 78\ \mu H$

$V_{INT} = 100V$

$F_{INT} = 400\text{-Hz sine wave}$

In this case, a signal of 0.10 ampere was generated in the susceptible circuit. Reactance values can be read from a reactance chart or calculated. Phase shift was not considered because the coupling impedance and susceptible circuit impedance were widely different values. The loop or series inductance L_S was negligible at 400 Hz and was not considered. Reasonable approximations were used for convenience because a high degree of precision was not required.

3.2.3.2.3 Shielding of Cables. Shielded conductors can reduce the spurious coupling of electric and/or magnetic energy from one conductor to another, compared to equivalent unshielded conductors. This reduction in coupling occurs when the electromagnetic environments of the two conductors are isolated by insertion of a shielding medium between the conductors.

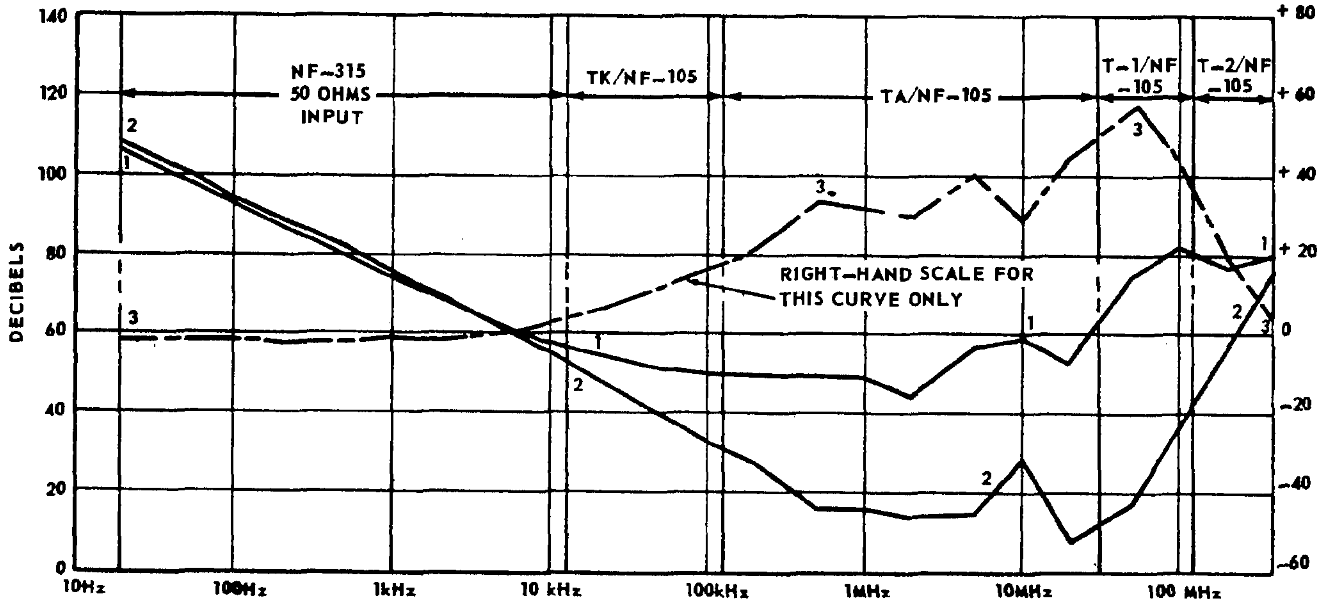
The figure of merit used to measure shielding is "shielding effectiveness." This is given in terms of decibels reduction in received energy at a conductor when a shielded conductor is substituted for the equivalent unshielded conductor.

Measured shielding effectiveness between centrally located conductors in stacked cables for a variety of cable configurations is shown in Figures 3-42 through 3-51.

3.2.3.2.3.1 Detailed Shield Design. The shielding effectiveness of any given solid-shield configuration versus frequency for magnetic, electric, or plane-wave fields can be plotted quickly with the aid of the nomographs of Figures 3-52 through 3-55. Similar nomographs with reduced ranges were originally prepared by Robert B. Cowdell of the Genisco Technology Corporation. The following paragraphs explain the use of Figures 3-52 through 3-55.

3.2.3.2.3.2 Practical Shield Design. Shielding effectiveness, or attenuation, is the sum of the reflection and absorption losses of the shield material selected. Reflection losses are not critically dependent on material thickness, but are dependent on a low-reluctance, circumferential, magnetic path through the shield. Absorption losses are proportional to material thickness. After the reflection loss versus frequency is plotted for the type of field under consideration, it is possible to determine whether additional losses are required at some frequencies. If the reflection losses are inadequate, absorption losses must be utilized to achieve the desired level of shield attenuation and the thickness of the material becomes significant.

3.2.3.2.3.3 Plane-Wave Reflection Losses. Plane-wave reflection losses are dependent only on the type of shield material selected, and on frequency. A straight edge, connecting a point on the G/u (material) scale to a point on the frequency scale, will also intersect the dB (attenuation) scale to provide the plane-wave reflection loss (Fig. 3-52). Under most conditions, this reflection loss will provide adequate plane-wave attenuation; therefore, absorption losses are not significant, and the thinnest material capable of meeting nonelectrical requirements is satisfactory. Thickness-dependent absorption losses are rarely required.



MAGNETIC COUPLING BETWEEN CENTER CONDUCTORS IN ONE UNSHIELDED METHODE PD825CH-252540403H0023 CABLE AND ONE NASA/METHODE SPEC 220 COPPER SHIELDED CABLE WITH OPEN EDGES. EXCITED CABLE WAS SHIELDED.

CABLES WERE 6 FEET LONG CABLES. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0-OHM.

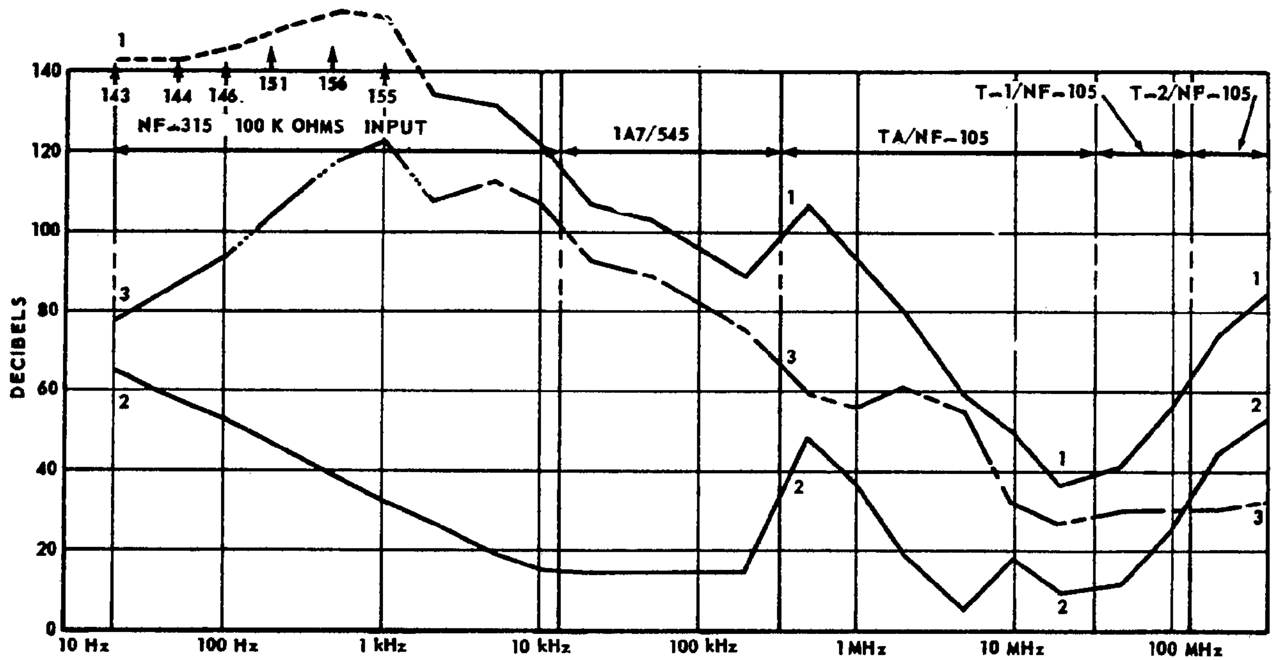
SENSING CABLE-SOURCE IMPEDANCE 0-OHM LOAD IMPEDANCE 50-OHMS.

1 UNSHIELDED CABLE MEASUREMENT

2 UNSHIELDED CABLE (FIG 3-28)

3 SHIELDING EFFECTIVENESS

FIGURE 3-42. Magnetic shielding effectiveness - solid copper shielded cable - open edges.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTORS IN ONE UNSHIELDED METHODE PD825CH252540403H0023 CABLE AND ONE NASA/METHODE SPEC 220 COPPER SHIELDED CABLE WITH OPEN EDGES. EXCITED CABLE WAS SHIELDED.

CABLES WERE 6 FEET LONG CABLES. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE – SOURCE IMPEDANCE 50 OHMS, LOAD IMPEDANCE ∞ OHMS.

SENSING CABLE – SOURCE IMPEDANCE ∞OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— UNSHIELDED CABLE MEASUREMENT
1 — - — DYNAMIC RANGE OF INSTRUMENTATION
2 ——— UNSHIELDED CABLE (FIG 3-29)
3 — — — SHIELDING EFFECTIVENESS
3 - - - - SHIELDING EFFECTIVENESS IN EXCESS OF VALUES SHOWN

FIGURE 3-43. Electrostatic shielding effectiveness - solid copper shielded cable - open edges.

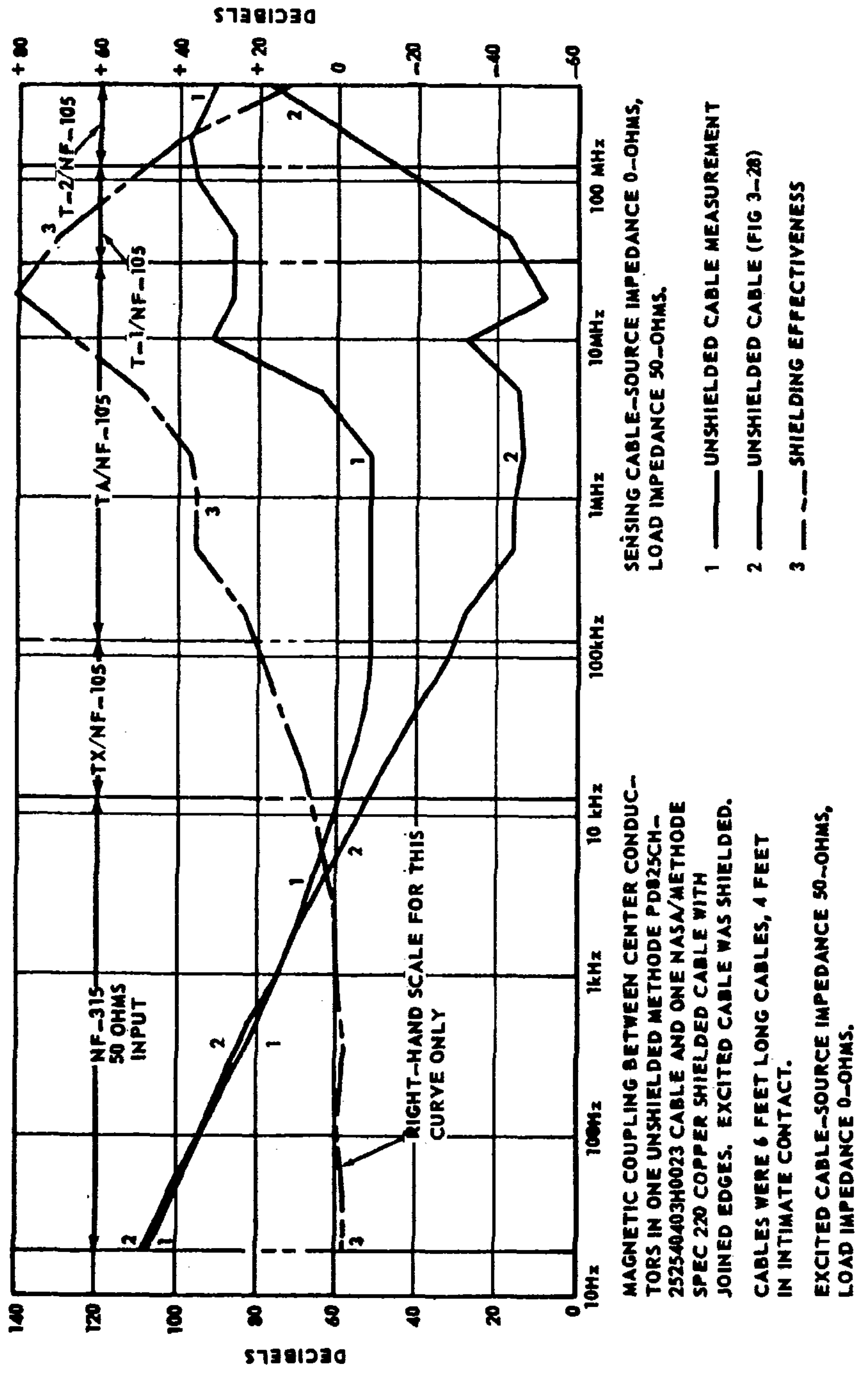
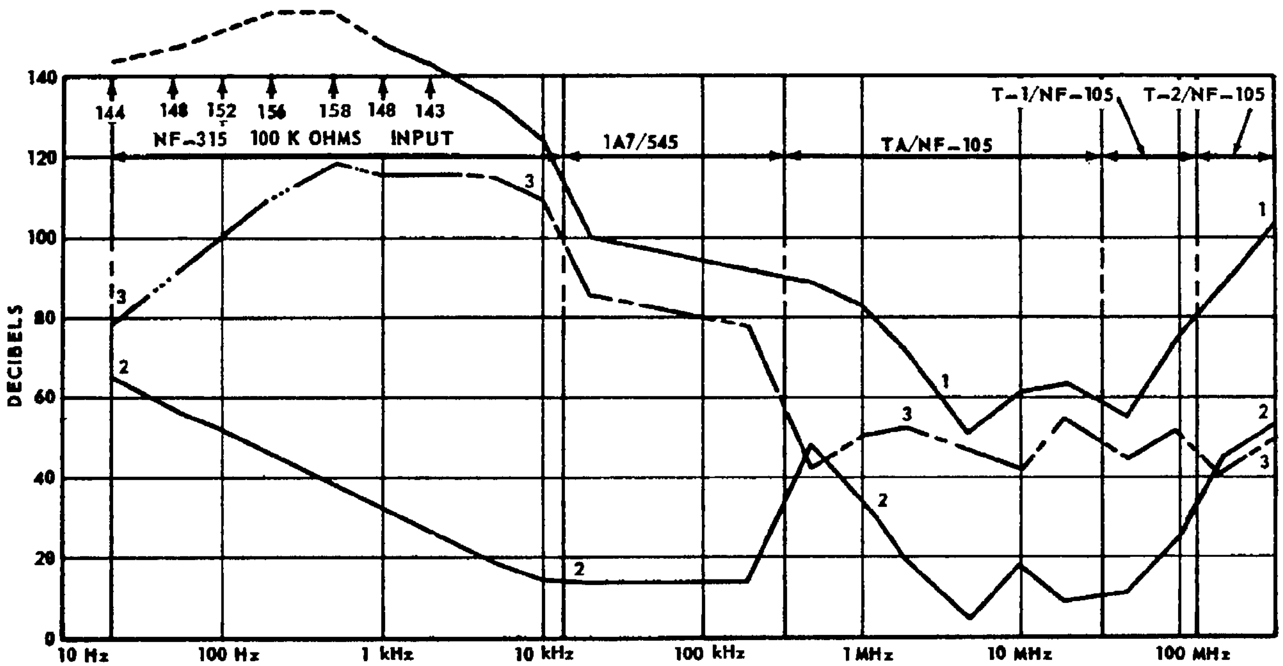


FIGURE 3-44. Magnetic shielding effectiveness - solid copper shielded cable - joined edges.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTORS IN ONE UNSHIELDED METHODE PD825CH252540403H0023 CABLE AND ONE NASA/ METHOD SPEC 220 COPPER SHIELDED CABLE WITH JOINED EDGES. EXCITED CABLE WAS SHIELDED.

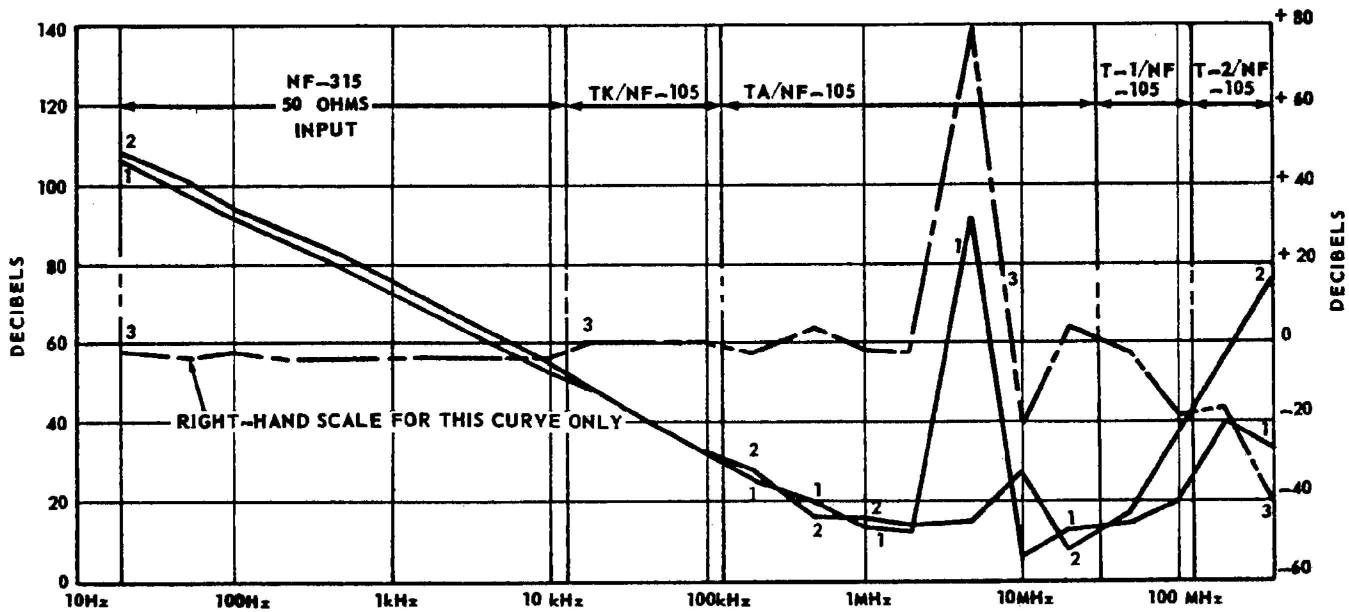
CABLES WERE 6 FEET LONG CABLES, 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE – SOURCE IMPEDANCE 50–OHMS, LOAD IMPEDANCE ∞ OHMS.

SENSING CABLE – SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— UNSHIELDED CABLE MEASUREMENT
1 – – – – DYNAMIC RANGE OF INSTRUMENTATION
2 ——— UNSHIELDED CABLE (FIG 3–29)
3 —— – — SHIELDING EFFECTIVENESS
3 —···— SHIELDING EFFECTIVENESS IN EXCESS OF VALUES SHOWN

FIGURE 3-45. Electrostatic shielding effectiveness - solid copper shielded cable - joined edges.



MAGNETIC COUPLING BETWEEN ONE CONDUCTOR OF A SUPRENANT 2S-RC4538N (300) JA 10 (15) SHIELDED TWISTED PAIR BOUND WIRE CABLE AND AN ADJACENT 20-GUAGE SINGLE UNSHIELDED ROUND CONDUCTOR. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0 OHM .

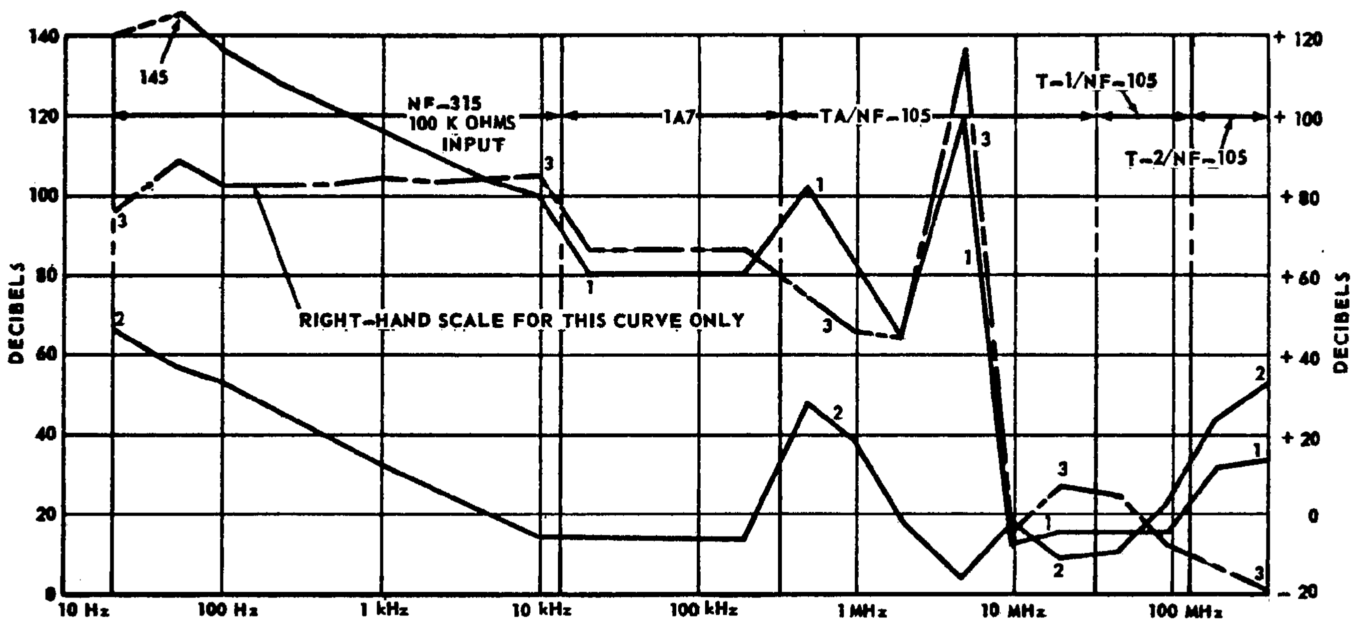
SENSING CABLE-SOURCE IMPEDANCE 0 OHM LOAD IMPEDANCE 50-OHMS.

1 ——— UNSHIELDED CABLE MEASUREMENT

2 ——— UNSHIELDED CABLE (FIG 3-28)

3 — — — SHIELDING EFFECTIVENESS

FIGURE 3-46. Magnetic shielding effectiveness - woven copper shielded cable - RWC.



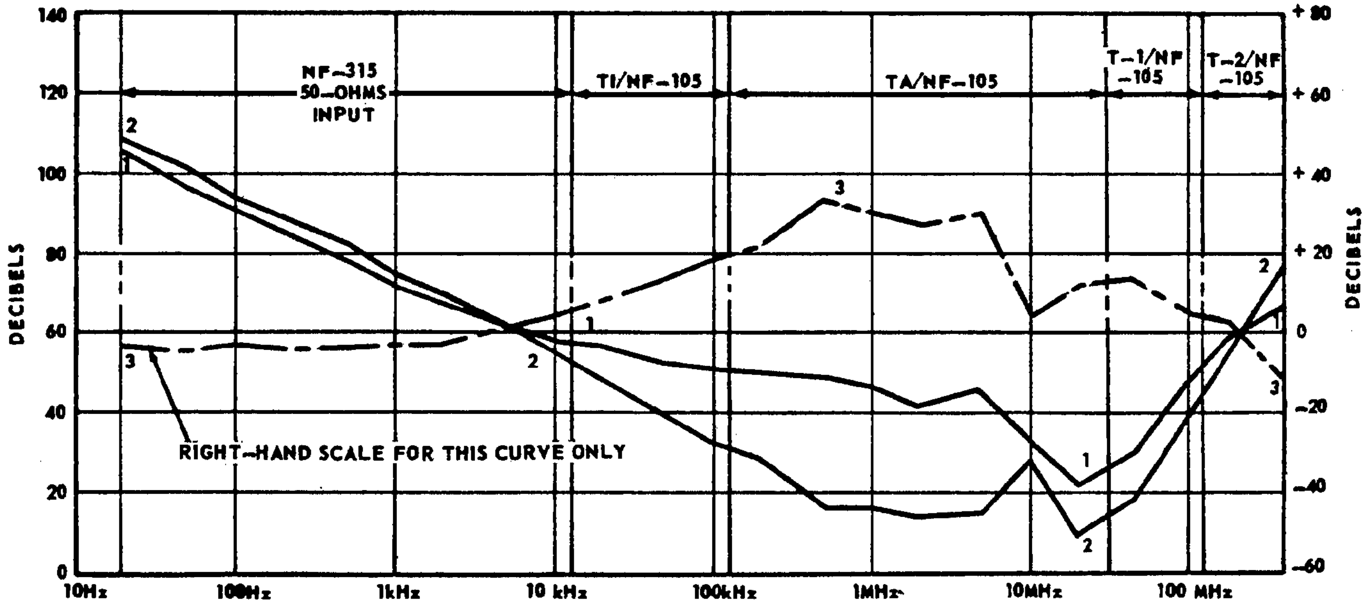
ELECTROSTATIC COUPLING BETWEEN ONE CONDUCTOR OF A SUPRENANT 2S-RC4538N (300)' JA 10 (15) SHIELDED TWISTED PAIR ROUND WIRE CABLE AND AN ADJACENT 20-GUAGE SINGLE UNSHIELDED ROUND CONDUCTOR. CABLE LENGTH 6 FEET. 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50 OHMS, LOAD IMPEDANCE ∞ OHMS.

SENSING CABLE-SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— SHIELDED CABLE MEASUREMENT
1 – – – DYNAMIC RANGE OF INSTRUMENTATION
2 ——— UNSHIELDED CABLE (FIG 3-29)
3 — — SHIELDING EFFECTIVENESS
3 —·—·— SHIELDING EFFECTIVENESS IN EXCESS OF VALUES SHOWN DUE TO TO INSTRUMENTATION LIMITATION

FIGURE 3-47. Electrostatic shielding effectiveness - woven copper shielded cable - RWC.



MAGNETIC COUPLING BETWEEN CENTER CONDUCTOR IN AN UNSHIELDED METHODE PD825HC25-25C40403H0023 CABLE AND A SECOND CENTER CONDUCTOR IN A SECOND UNSHIELDED METHODE PD825HC2525C40403H0023 CABLE. CABLES ISOLATED BY A 2-INCH WIDE 1 MIL THICK COPPER FOIL. CABLE LENGTH 6 FEET. 4 FEET IN INITIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0-OHMS.

SENSING CABLE-SOURCE IMPEDANCE 0-OHMS, LOAD IMPEDANCE 50-OHMS.

1 —— UNSHIELDED CABLE MEASUREMENT

2 —— UNSHIELDED CABLE (FIG 3-28)

3 - - - SHIELDING EFFECTIVENESS

FIGURE 3-48. Magnetic shielding effectiveness - stacked unshielded cables - metallic spacer - one side.

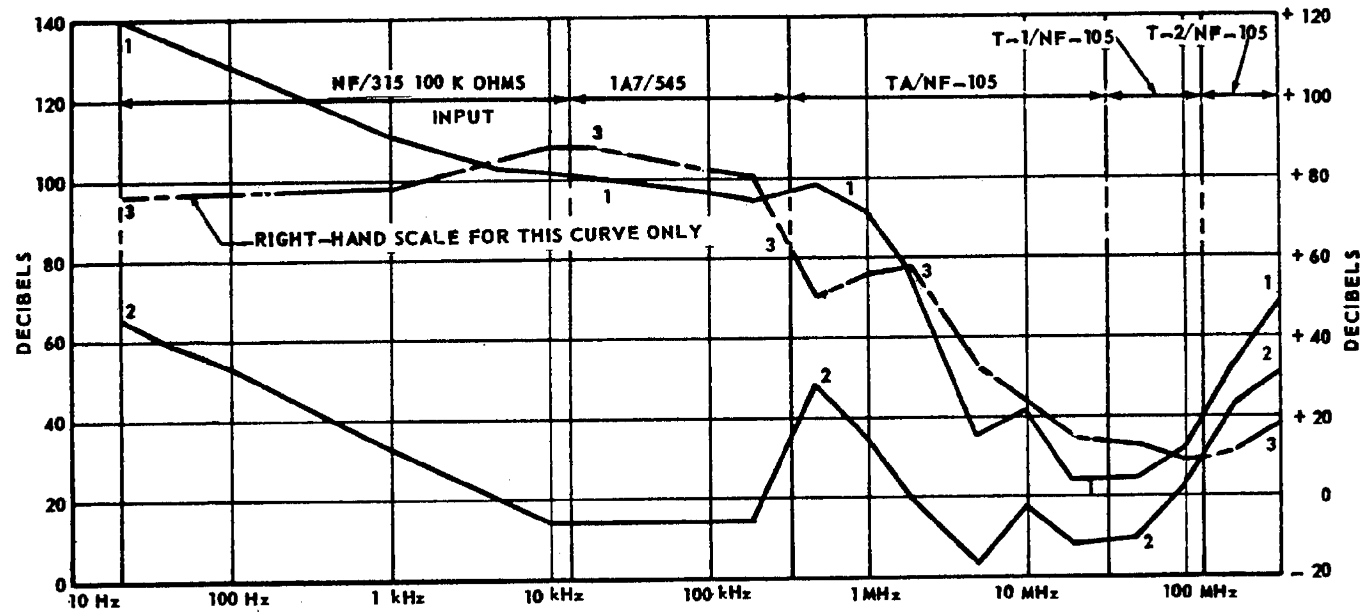
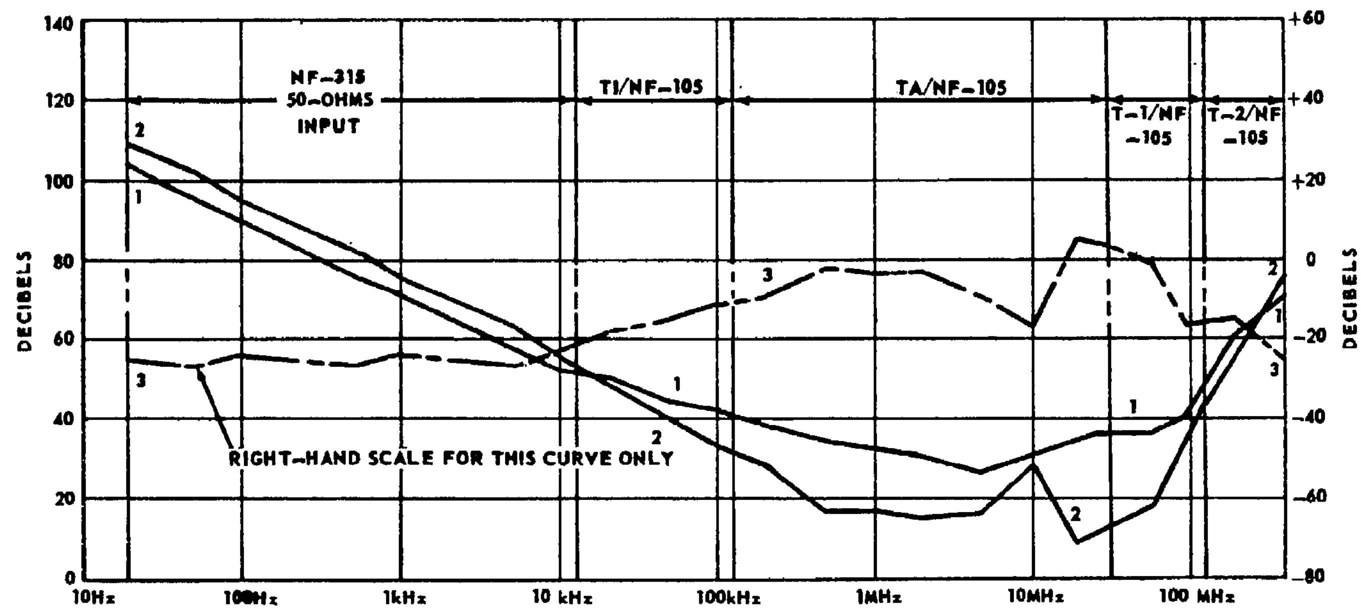


FIGURE 3-49. Electrostatic shielding effectiveness - stacked unshielded cables - metallic spacer - one side.



MAGNETIC COUPLING BETWEEN CENTER CONDUCTOR IN A SOLID 4-79 PERMALLOY SHIELDED METHODE C252C040403H2723 CABLE WITH OPEN EDGES AND ALUMINUM NASA/DAC CONNECTORS, 5-FEET LONG WITH 3-INCH SHIELD GROUNDS AT BOTH ENDS, AND CENTER CONDUCTOR IN AN UNSHIELDED METHODE PD825HC2525C40403-H0023 CABLE 6 FEET LONG WITH 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE-SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE 0 OHM .

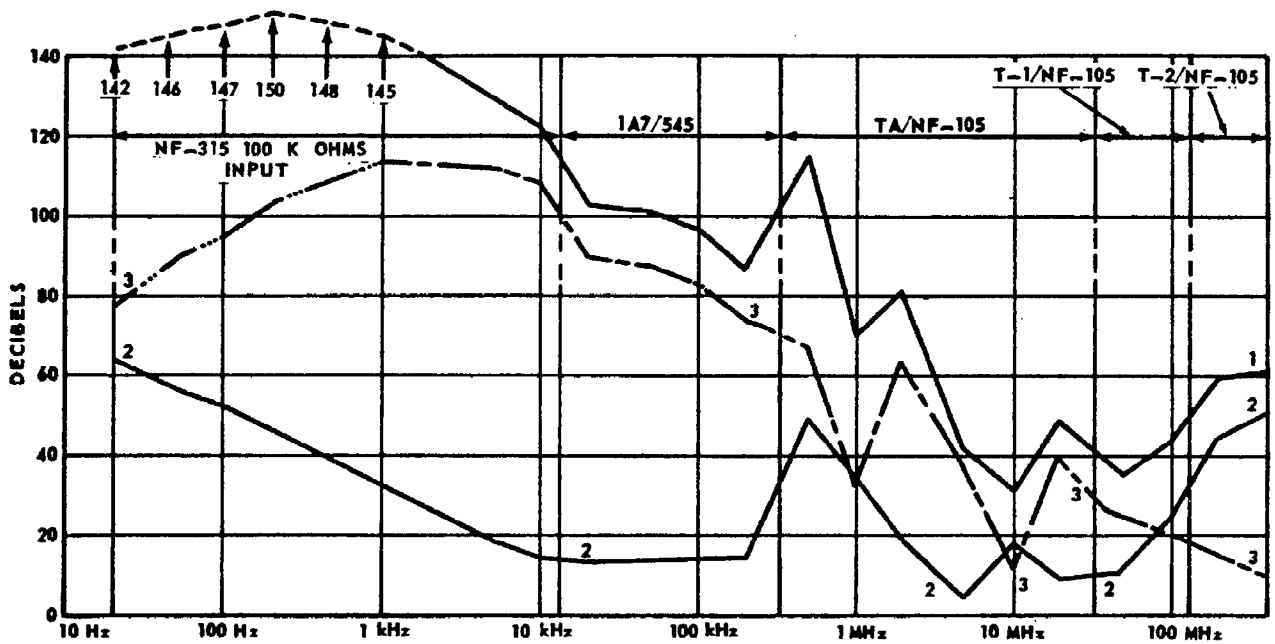
SENSING CABLE-SOURCE IMPEDANCE 0 OHM LOAD IMPEDANCE NOTED ON CURVE.

1 —— UNSHIELDED CABLE MEASUREMENT

2 —— UNSHIELDED CABLE

3 - - - SHIELDING EFFECTIVENESS

FIGURE 3-50. Magnetic shielding effectiveness - solid 4-79 Permalloy shielded cable - NASA/DAC aluminum connectors.



ELECTROSTATIC COUPLING BETWEEN CENTER CONDUCTOR IN A SOLID 4-79 PERMALLOY SHIELDED METHODE C2520C40403H2723 CABLE WITH OPEN EDGES AND ALUMINUM NASA/DAC CONNECTOR, 5 FEET LONG WITH 3-INCH SHIELD GROUNDS AT BOTH ENDS, AND CENTER CONDUCTOR IN AN UNSHIELDED METHODE PD-825HC2525C40403H0023 CABLE 6 FEET LONG WITH 4 FEET IN INTIMATE CONTACT.

EXCITED CABLE - SOURCE IMPEDANCE 50-OHMS, LOAD IMPEDANCE ∞ OHMS.

SENSING CABLE - SOURCE IMPEDANCE ∞ OHMS, LOAD IMPEDANCE NOTED ON CURVE.

1 ——— UNSHIELDED CABLE MEASUREMENT

2 ——— UNSHIELDED CABLE (REF)

3 —-·— SHIELDING EFFECTIVENESS

FIGURE 3-51. Electrostatic shielding effectiveness - solid 4-79 Permalloy shielded cable - NASA/DAC aluminum connectors.

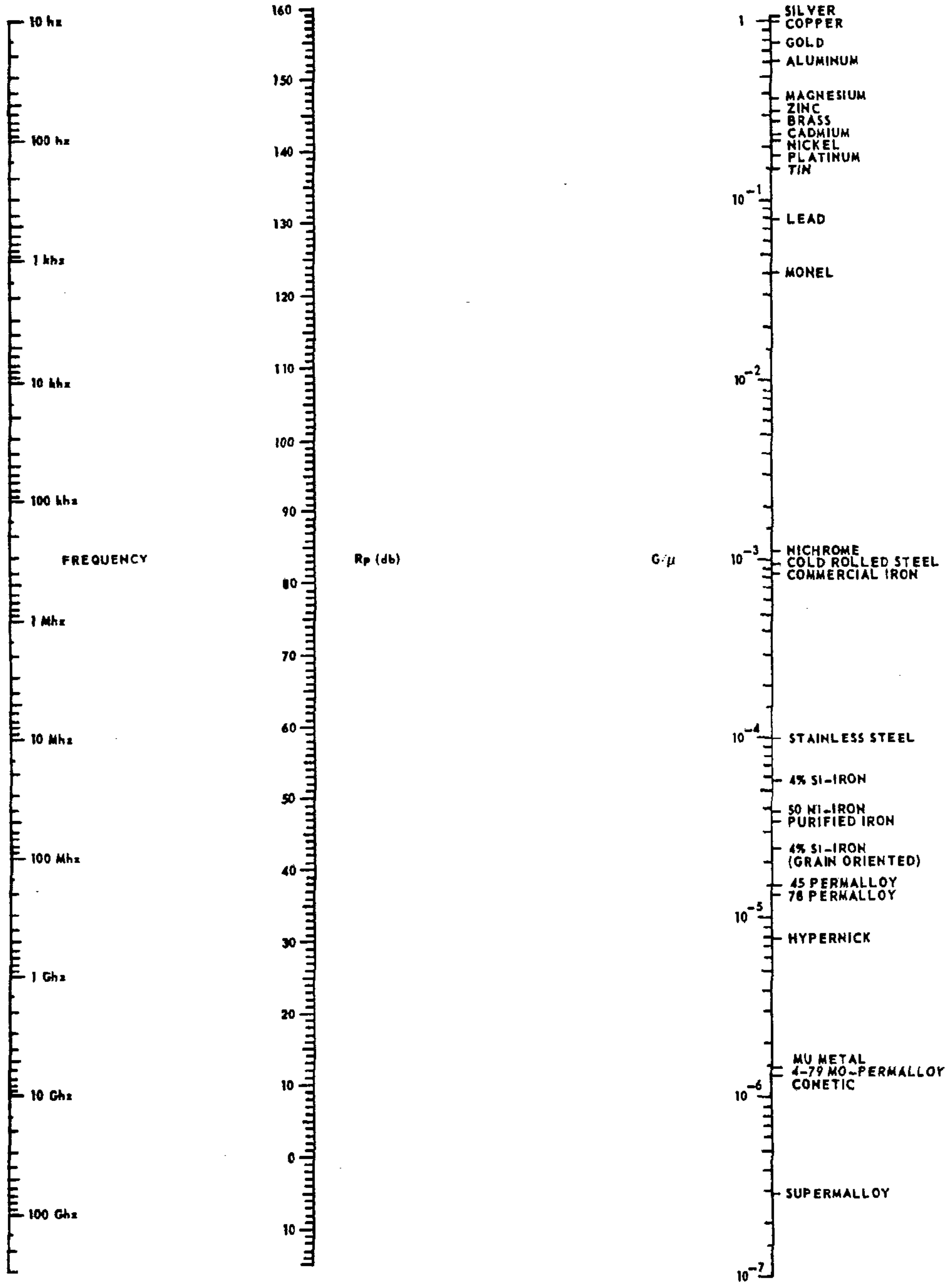


FIGURE 3-52. Plane-wave reflection losses.

3.2.3.2.3.4 Electric-Field Reflection Losses. Electric-field reflection losses are dependent only on the spacing between the source of interference and the shield, the type of shield material, and frequency. A straight edge, connecting a point on the inches (separation distance) scale to a point on the G/u (material) scale, will also intersect a point on the uncalibrated vertical scale (Fig. 3-53). A straight edge, connecting this point on the uncalibrated vertical scale to a point on the frequency scale, will also intersect the dB (attenuation) scale to provide the electric-field reflection loss. Under most conditions, this reflection loss will provide adequate electric-field attenuation; therefore, absorption losses are not significant, and the thinnest material capable of meeting nonelectrical requirements is satisfactory. Thickness-dependent absorption losses are rarely required.

3.2.3.2.3.5 Magnetic-Field Reflection Losses. Magnetic-field reflection losses are dependent only on the spacing between the source of interference and the shield, the type of shield material, and frequency. Shield thickness is not critical, but a low-reluctance circumferential path through the shield is required. A straight edge, connecting a point on the inches (separation distance) scale to a point on the G/u (material) scale (Fig. 3-54), will also intersect a point on the uncalibrated vertical scale. A straight edge, connecting this point on the uncalibrated vertical scale to a point on the frequency scale, will also intersect the dB (attenuation) scale, providing the magnetic-field reflection losses. Under most conditions, this reflection loss will not provide adequate magnetic-field attenuation; therefore, absorption losses are required and material thickness is significant, unless special high-permeability alloys are utilized.

The magnetic-field reflection loss, when plotted against frequency, has a peculiar shape when compared with the electric-field and plane-wave reflection-loss curves. Since the shield impedance is low compared with the high-impedance electric and plane-wave fields, and exhibits a rising characteristic but does not achieve an impedance match, these reflection losses have a magnitude inversely proportional to frequency. The magnetic field has a relatively low impedance that matches the shield impedance at some frequency in the useful spectrum, producing a magnetic reflection-loss null. At this null, the shield is magnetically transparent and unfortunately, most shields lack useful absorption-loss characteristics.

At low frequencies, the shield impedance is lower than the magnetic-field impedance but exhibits a rising characteristic; therefore, the impedance match between the shield and magnetic field improves as frequency increases, and a more efficient transfer of energy occurs. At these lower frequencies, the magnetic reflection-loss curve resembles the electric field and plane-wave reflection loss curves. In the midfrequency range, the shield impedance matches the magnetic-field impedance, an efficient transfer of power occurs, and the shield magnetic reflection loss is negligible. Because of secondary reflections within the shield, a slight transmission gain through the shield may occur at the tip of the null. At the high frequencies, the shield impedance is higher than the magnetic-field impedance, and exhibits a rising characteristic; therefore, the impedance match between the shield and magnetic field becomes worse as frequency increases, and a less-efficient transfer of energy occurs. At these frequencies, the magnetic reflection-loss curve becomes the inverse of the electric-field and plane-wave reflection-loss curve.

The magnetic reflection-loss null usually occurs in the audio or lower video frequency spectrum when conventional shielding materials are utilized; therefore, adequate shield absorption losses are essential for the achievement of useful degrees of shield attenuation. High-permeability materials have the triple advantage of raising the frequency of the magnetic-field reflection-loss null beyond the upper response limit of much system hardware, increasing the absorption loss significantly, and increasing significantly the inductive losses exhibited by conductors adjacent to the high-permeability shield.

3.2.3.2.3.6 Absorption Losses. Absorption losses are dependent only on the type of shield material, frequency, and shield thickness. A straight edge, connecting a point on the G/u (material) scale to a point on the thickness scale, will also intersect a point on the uncalibrated vertical scale (Fig. 3-55). A straight edge, connecting this point on the uncalibrated vertical scale to a point on the frequency scale, will also intersect the dB (attenuation) scale, providing the absorption loss through the shield material.

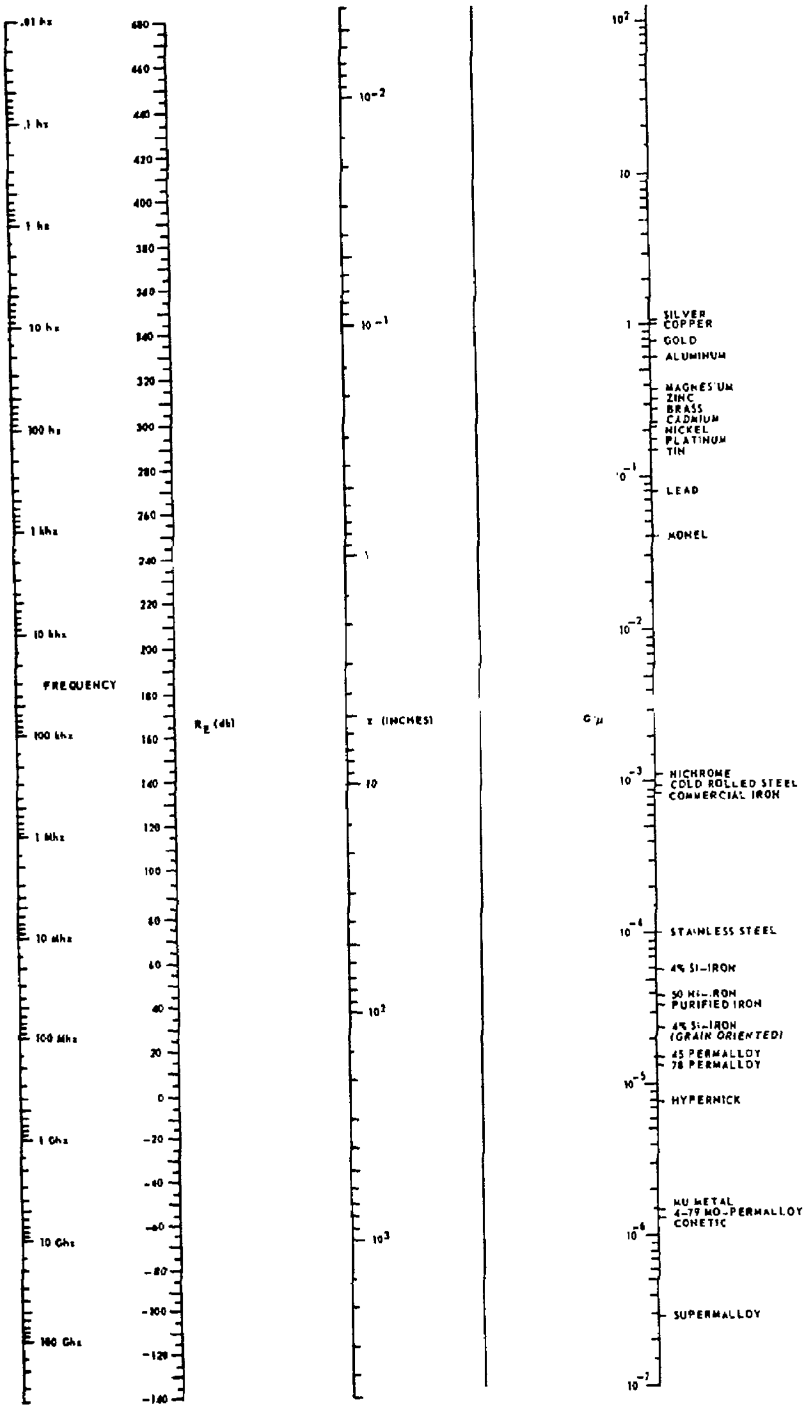


FIGURE 3-53. Electric-field reflection losses.

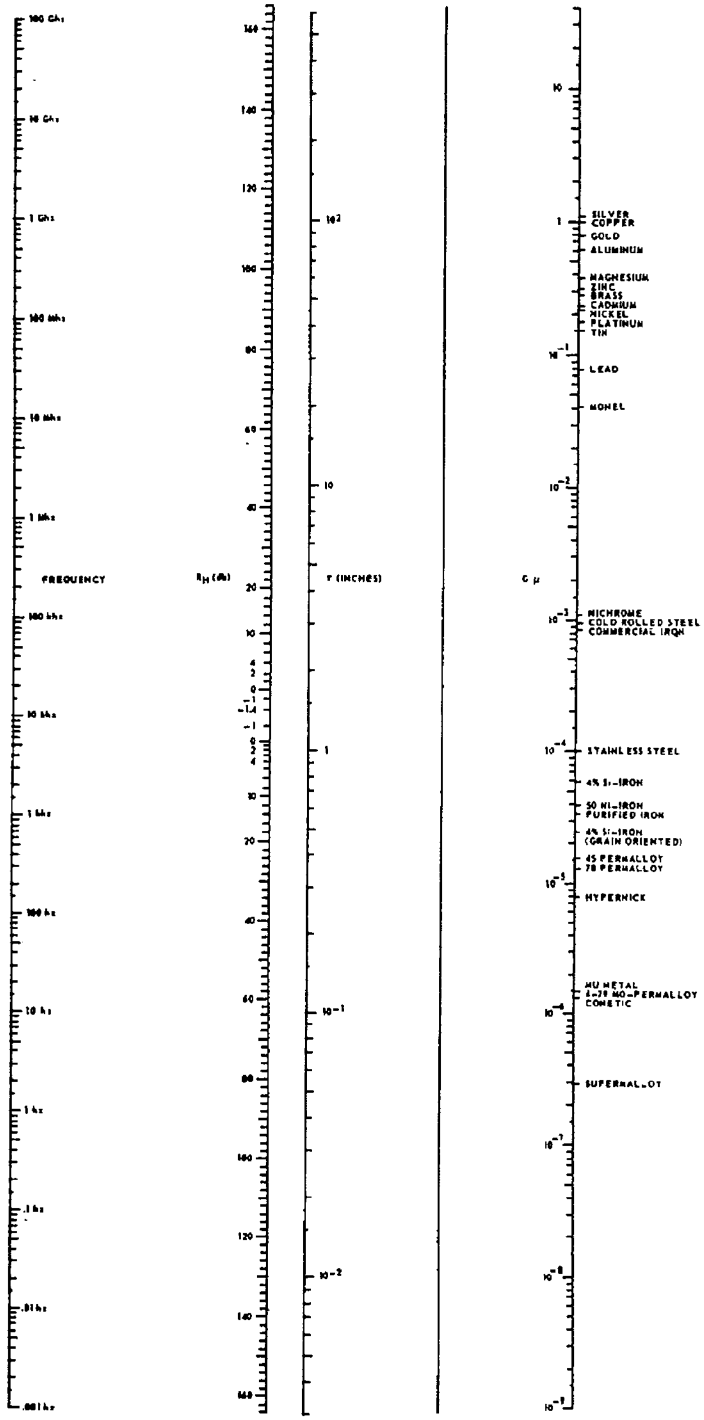


FIGURE 3-54. Magnetic-field reflection losses.

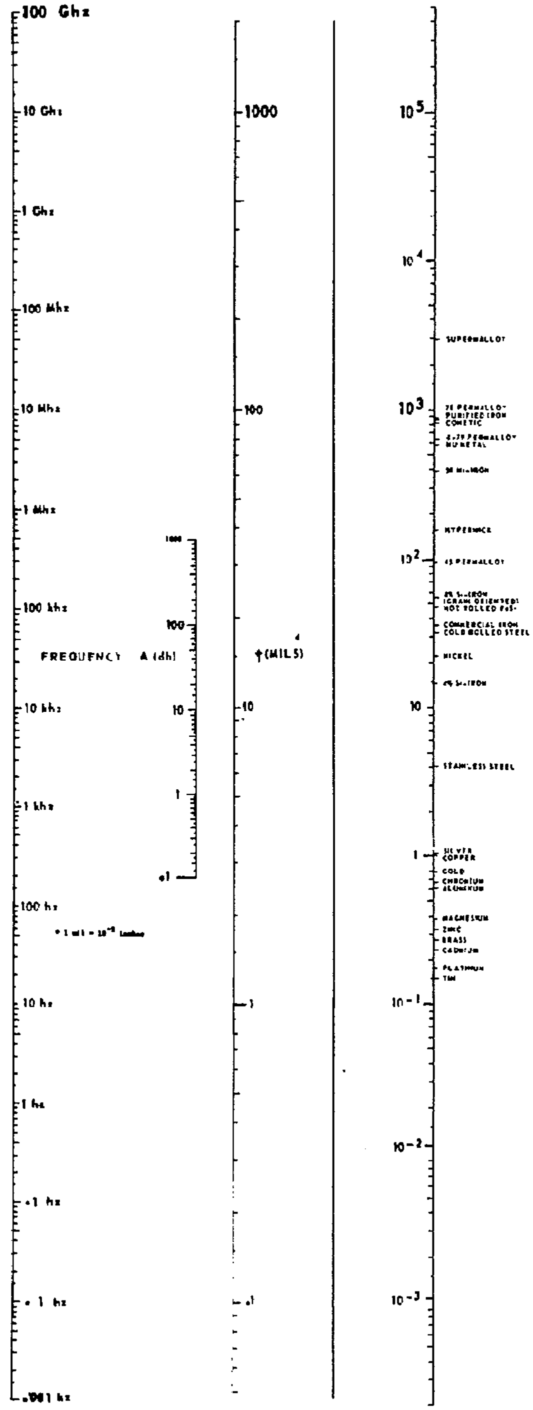


FIGURE 3-55. Absorption losses.

Absorption losses are a function of the material selected; they are proportional to thickness and increase rapidly with frequency, as noted previously. The use of ferrous metals, having high permeabilities, produces the greatest absorption losses for a given thickness of shielding material at a given frequency. Increasing the shield thickness also increases absorption losses, but prohibitive shield thickness may be required to provide adequate magnetic-field attenuation at audio frequencies, unless the material is selected carefully. Since absorption losses rise rapidly as frequency increases, and since high-permeability materials have high magnetic-reflection-loss null frequencies, the use of high-permeability materials produces a shield with relatively high absorption losses at the higher frequencies, where the magnetic-reflection-loss null of these materials tends to occur.

Ordinarily, absorption losses need to be considered only where magnetic-field attenuation is required. Electric-field and plane-wave reflection losses are usually adequate, even when absorption losses are negligible.

3.2.3.2.3.7 Multiple-Layer Shields. A single layer of shield material has reflection losses from both sides and an absorption loss proportional to thickness. Doubling the shield thickness does not increase the number of reflection losses or magnitude of total reflection losses, but merely doubles the attenuation because of absorption losses. Dividing the same double thickness of material between two independent layers of shield doubles the number of reflection losses and the magnitude of total reflection losses, in addition to doubling the attenuation because of absorption losses.

The use of multiple layers provides the opportunity to select electrically complementary materials, each of which supplements the characteristics of the other. This is also necessary to prevent fusing adjacent layers of similar material into a single, thicker layer. Nonferrous materials are analogous to a dielectric when inserted between ferrous materials. Since reflection losses are a dominant factor in shield attenuation, this increased number of interfaces is highly desirable.

Each layer of material is treated independently during calculations, with the adjacent layer considered as the source of interference. Attenuation versus frequency is plotted for each layer. The sums of the attenuations of the layers are plotted to provide a curve of the total shielding effectiveness versus frequency for the type of field (magnetic, electric, or plane wave) being considered.

3.2.3.2.3.8 Shield Perforations. The shielding effectiveness of an unperforated shield is degraded seriously when perforations are introduced. Magnetic-shielding effectiveness is extremely dependent on shield integrity, because of the flow of leakage currents through the perforations; these couple the induced currents on one shield surface to the opposite shield surface, from which magnetic radiation and magnetic coupling occur.

Electric-shielding effectiveness is also dependent on shield integrity; however, the presence of a surrounding shield structure provides a partially effective shadowing effect for the open areas analogous to the cone of protection provided by a lightning rod. The degree of protection supplied is dependent on the ratio of perforation size to shield thickness.

A thick shield with small perforations is analogous to looking through a long tube with a restricted field of view. The fringe capacitance is virtually eliminated and only the effective plate-to-plate capacitance, limited by the aperture size, is available to couple the electric field between objects isolated by the shield.

Plane-wave shielding, that eliminates predominantly capacitive coupling, at the higher frequencies where plane-wave geometry may exist, is affected by the same basic factors controlling electric-field shielding, with the addition of increased high-frequency coupling through the perforations. Above the frequency where the largest perforated, cross-sectional dimension exceeds a half wavelength, the perforation becomes a low-loss coupling path between the shield-isolated objects.

Shield perforations are equivalent to a waveguide attenuator with the same cross-sectional dimensions as the perforations, and the same length as the shield thickness. The large variety of potential perforated shield designs places detailed analyses of perforation effects beyond the scope of this publication. Numerous proceedings for the many conferences on radio interference reduction and electromagnetic compatibility, conducted by the Armour Research Foundation of the

Illinois Institute of Technology under triservice sponsorship, contain much valuable information related to shielding effectiveness.

3.2.3.3 Network Interconnection System. The wiring interconnection systems vary from complex multibranched wire-harness assemblies (Fig. 3-56) to simple two-ended wire-harness assemblies (Fig. 3-57).

In the past, the multibranched harnesses have been used extensively for airborne and other mobile vehicles, while two-ended harnesses have been commonly used for ground support, with provisions for interconnections provided by wire-wrap panels, patch panels, etc. Of course, many programs have used a compromise system with fixed branched harnesses in critical circuits less likely to change, and circuit-change devices in instrumentation and other systems more likely to change.

When considering FCC, it is essential to understand how the various harness-system requirements can be satisfied. First, the two-ended harnesses are ideally adaptable to the FCC system. Lengths of the required cable widths can be cut and terminated to plugs to make the simplest, lightest, most reliable, and most economical harnesses possible. FCC can also be applied to the large multibranched harnesses. Multiple cable widths can be terminated in each FCC plug to provide the required multiplicity of interconnections; however, the FCC harness complexity would be increased by the many cable segments required.

The early selection of the minimum number of multibranched harnesses is often made with the purpose that more important matters can then be persued; furthermore, this system has always worked in the past. One object of this handbook is to discourage such thinking and action and to promote careful and early consideration of the optimum interconnecting network system.

3.2.3.4 Connector Selections. This selection will be influenced by: the program requirements; the availability of connector hardware; and the company's manufacturing capability. The conductivity and voltage requirements will dictate the contact size and spacing. The handling and service requirements will dictate the ruggedness and configuration of the connector housings. Minimum space and weight requirements will dictate the degree of miniaturization required. The FCC connector system selected should accommodate the following requirements:

a. The preparation and termination of FCC conductors by layer.

b. The capability of accommodating various cable segments, both shielded and nonshielded or a combination, in the same cable layer (Fig. 3-58).

c. The capability of accommodating FCC with conductor centerlines a multiple of the connector contact centerlines. This may be accomplished in the conductor-contact connector by properly preparing the cable end to form the required number of conductors as shown in Figure 3-59. The pin-and-socket connector system can meet this requirement by making multiple contact terminations through the insulation or to the properly prepared conductor ends.

3.2.3.5 Cable Selection. The proper FCC must be selected to meet the program environmental, handling conductivity, and special requirements. The conductor material will usually be bare or plated copper. The cable construction must be compatible with the cable-end termination preparation requirements. The shielding material and conductor cross-section must meet the electrical requirements.

The decision on whether to use FCC for the larger conductor sizes (greater than AWG 20) must be made. If the conductivity is required to limit voltage drop rather than for high currents, FCC power cables defined in Section II can be used with existing FCC connector designs by using parallel contacts. FCC can be used for high-current applications with proper termination techniques.

3.2.3.6 Termination Systems. The termination system to be utilized with FCC is dictated by the type of connectors selected. With the NASA/MSFC conductor-contact system, the conductors are stripped and plated prior to plug assembly, and act as the plug contact. In other molded-on FCC plug concepts, such as that used by Rogers Corporation, the nonstripped cable is molded to the plug; the cable is then stripped and plated in the contact area. Pin-and-socket connectors

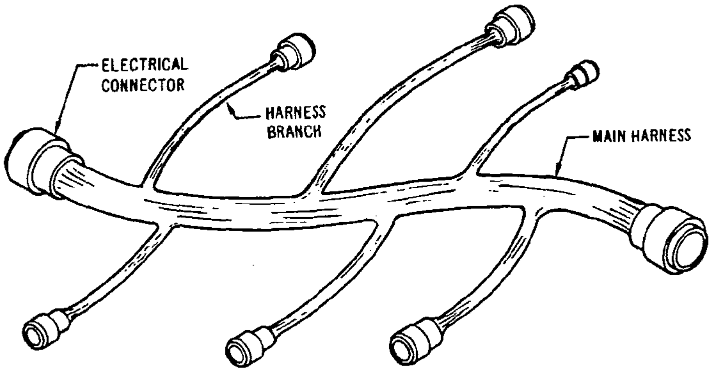


FIGURE 3-56. Multibranched wire harness assembly.

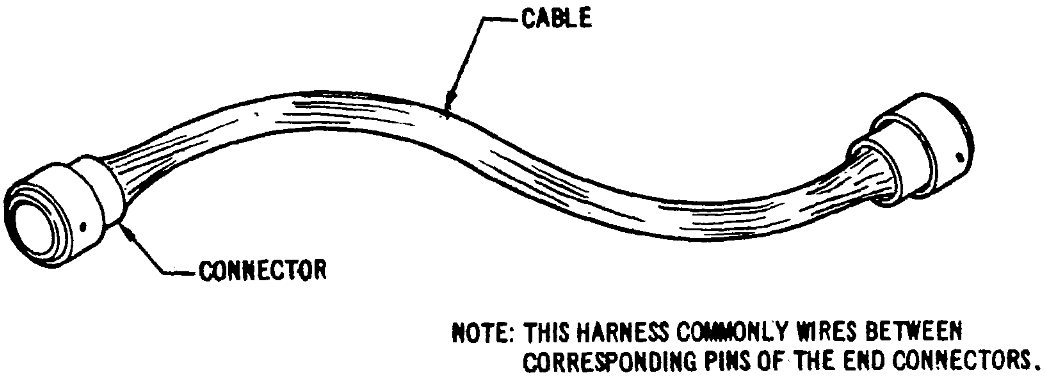
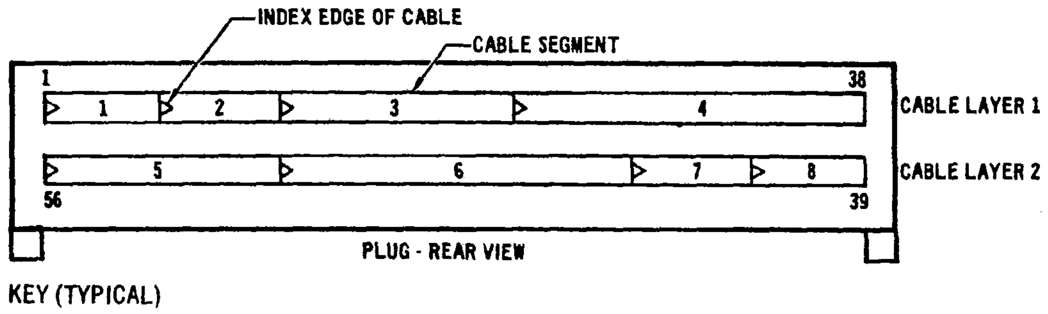


FIGURE 3-57. Two-ended wire-harness assembly.



CABLE SEGMENT	WIDTH	SHIELD TYPE	CONDUCTOR CENTER LINE	DENSITY	CONDUCTOR THICKNESS
1	1/2	2S	.075	STD	.003
2	1/2	2S	.075	STD	.003
3	1	NON-S	.075	STD	.004
4	1-1/2	NON-S	.150	HIGH	.006
5	1	NON-S	.075	STD	.004
6	1-1/2	NON-S	.150	HIGH	.006
7	1/2	2S	.075	STD	.003
8	1/2	2S	.075	STD	.003

FIGURE 3-58. FCC connector versatility.

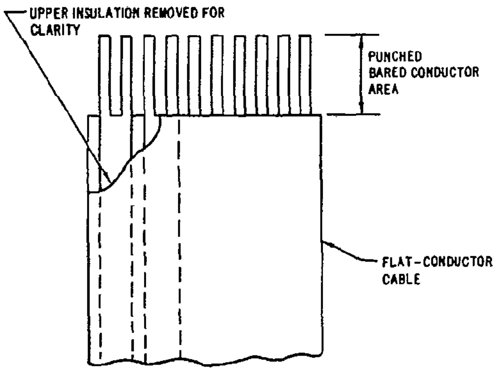


FIGURE 3-59. FCC reduced center cable preparation.

utilize various types of termination systems including crimping, soldering, ultrasonic welding, and and insulation penetrations. The termination system to be used will strongly influence the selection of the FCC and connectors.

3.2.4 FCC Power Cables. Various FCC power cables have been designed by NASA/MSFC and prototypes manufactured by Methode Electronics. These cables are 1, 2, and 3 inches wide with two or three power conductors in each cable with equivalent AWG conductor sizes ranging from Nos. 8 through 15 (Fig. 2-6).

Figure 3-60 is a graph for selecting various FCC cross-sections for equivalent AWG sizes 8 through 18. The centerline spacing and distance between adjacent conductors would be based on the termination system hardware and on the system electrical requirements.

Table 3-13 lists various FCC cross-sections for equivalent AWG wire sizes from Nos. 8 through 23. Conductor thickness is 10 mils. For installations not requiring frequent flexing, the conductor thicknesses could be more than 10 mils.

There are numerous installation advantages to be realized in using FCC power cables. Bonding the cable directly to the primary structure provides the following advantages:

a. A minimum of space is required.

b. Very little, or no, support on attaching structure is required.

c. The structure will provide an efficient heat sink for conductor heat dissipation.

Using FCC power cables with the equivalent 20-gage and smaller MIL-C-55543, FCC simplifies harness fabrication, routing, and support (see Paragraph 3.2.6).

Electrical advantages of FCC power cables are:

a. Electrical characteristics can be accurately predicted.

b. For dc and relatively low-power frequencies, the capacitance between conductors and between conductors and ground automatically provides a very efficient noise-suppression filter.

Preliminary calculations for typical cable requirements for dc power frequencies up to 400 Hz indicate acceptable line losses.

For characteristic impedances most acceptable for system faults and general system performance, it is recommended that the configurations shown in Figure 3-61 be used.

For power frequencies above 400 Hz, special considerations must be given to skin effect and capacitive high-frequency losses. These can be calculated from the FCC harness cross-section and length by using formulas in published electrical handbooks.

For FCC power cable termination in relatively low current applications, MIL-C-55544 FCC connectors can be used with multiple, parallel contacts for each power conductor. This is illustrated in Figure 2-8 for the MSFC conductor-contact plug assembly. For high-current applications, the FCC conductors can be terminated to bus-bar type terminals for bolting directly to the utilizing equipment, or transition can be made to RWC by welding, crimping, etc., for routine RWC terminations. All termination areas should be properly sealed for corrosion and strain relief.

The use of FCC power cables with aluminum conductors offers additional advantages in weight, cost, and availability. By maintaining an efficient seal over the conductors and the termination areas, the FCC power cable system can overcome previous corrosion problems associated with the use of aluminum for electrical conductors.

In conclusion, the use of FCC power cables presents many potential advantages over RWC. The mechanical, electrical, and hardware requirements should be detailed early in the program to determine those areas in which FCC power cables can be efficiently used.

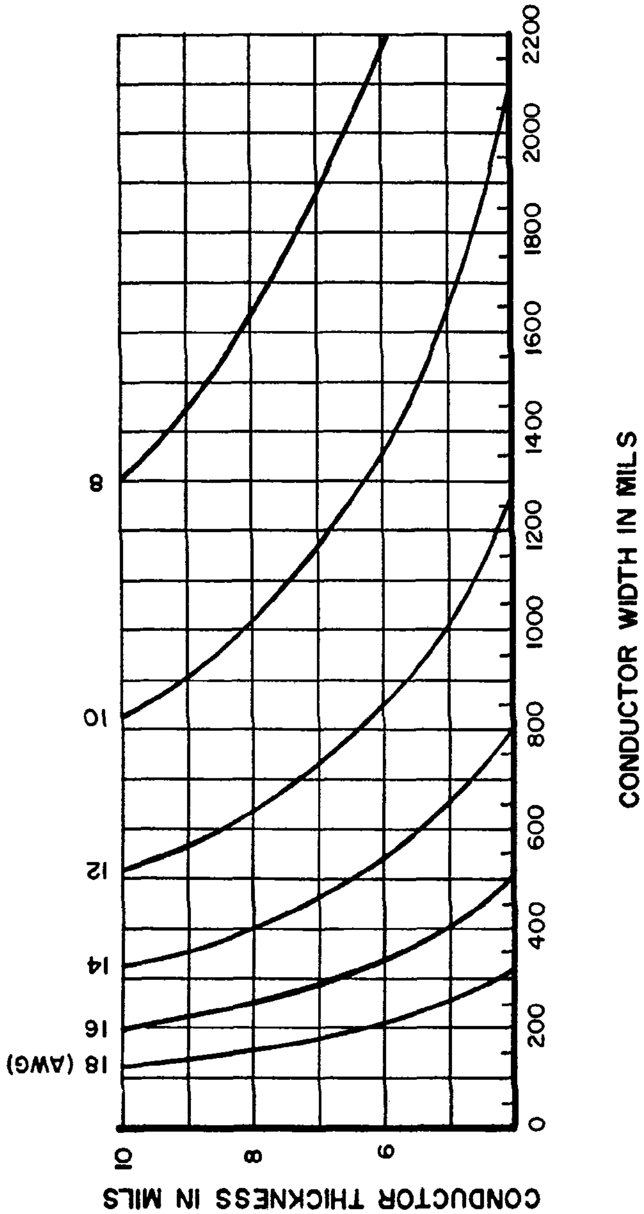
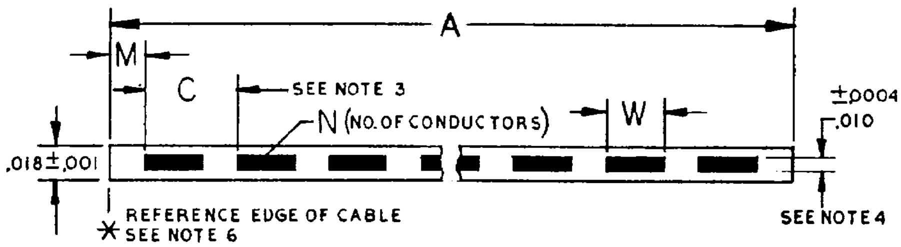


FIGURE 3-60. FCC cross-sections-equivalent AWG 8 through 18.

TABLE 3-13. FCC POWER CABLE CONDUCTOR CROSS SECTIONS



NOTES:
1. Material: Polyimide/Fluorinated Ethylene Propylene Insulated, Nickel Coated Strip-Copper Conductor
2. Dimensions are in inches.
3. Typical, non cumulative.
4. Thickness of insulation on each side of the conductors shall be uniform within 0.001 inch.
5. Based on conductor cross-section.
6. Cable marking shall be placed along reference edge of cable.
7. Per requirement of MIL-C-55543 except "Flexing."
8. Presently, no military specification items.

Cable Width "A" ±0.005	No. of Conductors "N"	Conductor Width "W" ±0.002	Basic Spacing "C" ±0.005	Cable Margin "M" ±0.005	Nearest Awg. Wire Size (Note 4)	Max. Cond. DC Resistance Ohms/1000 ft. at 20°C	Max. Cable Weight Lbs/1000 ft.
0.5	2	0.190	0.225	0.0425	16	4.29	19.2
0.5	3	0.115	0.150	0.0425	18	7.08	18.2
0.5	6	0.040	0.075	0.0425	23	20.40	15.2
1.0	2	0.415	0.450	0.0675	13	1.96	40.3
1.0	3	0.265	0.300	0.0675	15	3.07	39.3
1.0	4	0.190	0.225	0.0675	16	4.29	38.3
1.0	6	0.115	0.150	0.0675	18	7.08	36.3
1.0	12	0.040	0.075	0.0675	23	20.40	30.3
1.5	2	0.640	0.675	0.0925	11	1.27	61.5
1.5	3	0.415	0.450	0.0925	13	1.96	60.5
1.3	4	0.265	0.300	0.0675	15	3.07	51.9
1.5	6	0.190	0.225	0.0925	16	4.29	57.5
1.5	9	0.115	0.150	0.0925	18	7.08	54.5
1.5	18	0.040	0.075	0.0925	23	20.40	45.5
1.9	2	0.865	0.900	0.0675	10	0.94	81.1
1.9	3	0.565	0.600	0.0675	12	1.44	80.1
1.9	4	0.415	0.450	0.0675	13	1.96	79.1
2.0	5	0.340	0.375	0.080	14	2.40	81.9
1.9	6	0.265	0.300	0.0675	15	3.07	77.1
1.9	8	0.190	0.225	0.0675	16	4.29	75.1
1.9	12	0.115	0.150	0.0675	18	7.08	71.1
2.0	25	0.040	0.075	0.080	23	20.40	61.9
2.5	2	1.165	1.200	0.0675	9	0.70	108.3
2.4	3	0.715	0.750	0.0925	11	1.14	101.2
2.5	4	0.565	0.600	0.0675	12	1.44	106.3
2.4	5	0.415	0.450	0.0925	13	1.96	99.2
2.4	6	0.340	0.375	0.0925	14	2.40	98.2
2.5	8	0.265	0.300	0.0675	15	3.07	102.3
2.4	10	0.190	0.225	0.0925	16	4.29	94.2
2.5	16	0.115	0.150	0.0675	18	7.08	94.3
2.5	32	0.040	0.075	0.0675	23	20.40	78.3
3.0	2	1.390	1.425	0.0925	8	0.59	129.4
2.8	3	0.865	0.900	0.0675	10	0.94	120.8
2.8	4	0.640	0.675	0.0675	11	1.27	119.8
2.8	6	0.415	0.450	0.0675	13	1.96	118.0
2.8	9	0.265	0.300	0.0675	15	3.07	114.8
2.8	12	0.190	0.225	0.0675	16	4.29	111.8
3.0	19	0.115	0.150	0.0925	18	7.08	111.7
3.0	38	0.040	0.075	0.0925	23	20.40	93.4

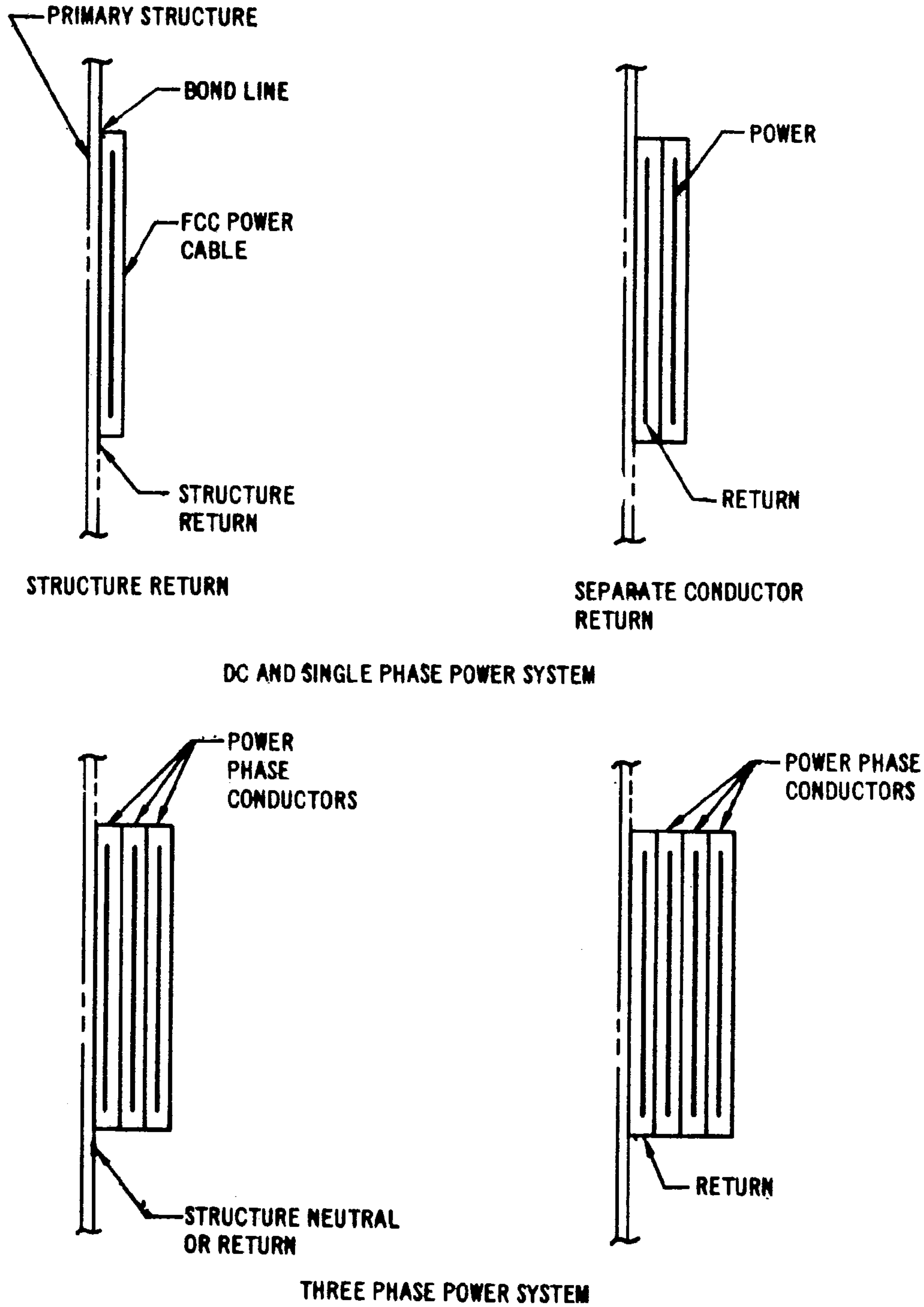


FIGURE 3-61. FCC power cable installations configurations.

3.2.5 Harness Design. Prior to the interconnecting harness detail design, the overall system design must be accomplished so that all components comprising the functional system are grouped or packaged together, located relative to each other, and interconnections established to provide a logical and simple flow of power, control, sensing, etc. Requirements for heat dissipation, weight distribution, and accessibility for installation and service must be considered. The importance of the initial system design cannot be overemphasized, and its efforts will be rewarded manifold in subsequent development and detail design.

Since this document deals primarily with FCC application, it will be assumed that an efficient system design has been accomplished to define (1) the packaged electronic units and components in each system, (2) the interconnecting requirements of each system, (3) the interconnecting requirements between systems, and (4) the interface requirements to units or systems mating with the end item under design. The design of the interconnecting FCC harness network can then proceed as defined in the following subparagraphs.

3.2.5.1 Interconnecting Wire Requirements. The system design should define all system components (units requiring cable network interconnecting) and the interconnecting requirements within and between systems, and to electrical interfaces. This definition should provide a designation number for each system component, together with the number of circuits, circuit functions, classification for grouping, conductivity, and any other special consideration requirement for the interconnecting circuits. See Table 3-14 for typical interconnecting requirement tabulation.

The zoning classification philosophy for grouping is explained in Paragraphs 3.2, 3.2.1 and 3.2.10.2. Each system has its own peculiarities which must be thoroughly analyzed to establish the circuit classifications and zonings required to provide adequate system performance. In the past, the random conductor registration in conventional round-wire bundles has resulted in overdesign.

Excessive shielded cable was specified and, where space permitted, an excessive number of bundles was routed and supported separately. Testing accomplished by MDC on existing missile and aircraft systems indicated that up to 75 percent of the existing round-wire shielded cable could be eliminated with FCC interconnecting harnesses. The FCC system, with its positive registration control of each conductor, permits the interconnecting harness to be considered as a predictable, repeatable system component.

The complete definition of the program systems interconnecting requirements (Table 3-14) and the establishment of the proper zoning classification for each circuit conductor is a major task. Once this is accomplished and recorded, work can begin on the wiring layout.

3.2.5.2 Wiring Layout. With the end-item interconnecting electrical wiring requirements defined in a series of tabulated charts typified by Table 3-14, work can begin on the wiring layout. A simple example will be given to illustrate a logical method of procedure.

An initial wiring layout is made as shown in Figure 3-62. This figure contains the basic elements required for the analysis and design of the interconnecting network. Each electronic unit is shown in its area, the required interconnect paths are indicated, and the number and zone classification of each circuit with conductivity requirements are defined.

In most modern systems, there would be many more units to be interconnected and more zoning classifications than the three as follows:

Class	Definition
A	Interference circuits
B	Noncritical circuits
C	Susceptible circuits

Figure 3-62 also assumes that only two conductor conductivities are required; 200 square mils (AWG 26) for symbol 1 and 840 square mils (AWG 20) for symbol 2. In most instances, there would be additional conductivity requirements, including those for power, which may be many times the average required for general use. Power cables are given in Paragraph 3.2.4 and other special configurations are given in Paragraph 3.2.8.

TABLE 3-14. TYPICAL INTERCONNECTING REQUIREMENTS

System (Note 1)	Component Unit (Note 2)	Interconnecting Requirements: Circuit No.	Circuit Function	Minimum Square Mil Conductor Cross-Section	Zoning Classification (Note 3)	Special Requirements (Note 4)	Termination (Note 5)
1	1	1	5 Vdc TM	150	A2		6-1-3
		2	-20 Vdc test	150	A4		8-3-8
		3	2000 Hz TM, continued	150	A7		10-2-15
	2	1	20 Vdc output	1500	A5		5-3-6
		2	20 Vdc return	1500	A5		5-3-7
		3	RAGS #1 continued	800	A3		4-2-9
	3	1	Trans input	800	B3		6-3-10
		2	Cal Sig Rtn	100	C8		4-2-7
		3	Cal Sig Continued	100	C8		4-2-8
	Additional Units						
2	1	1	Meas hr	75	C4		4-2-7
		2	Pwr Xfer Com	190	A4		3-3-9
		3	Mstr Rtn continued	800	C3		4-2-15
	2	1	Ball test	150	A2		7-2-3
		2	Bolt test	150	A2		7-2-7
		3	Meas rms continued	75	C4		7-2-10
	3	1	Coax Input	NA	D	RG-59	3-2-1
		2	Out to 1		D	RG-59	3-5-2
		3	Out to 2 Continued		D	RG-59	3-6-2
	Additional Units						
Additional Systems							

Notes:
1. Electronic system identification.
2. Particular electronic unit of a system which requires network interconnections.
3. Zoning classification. (Ground rules for grouping and isolation must be established for each program, see Paragraph 3.2.3.2.1.)
4. Special requirements (coded or defined).
5. Termination designation indicates the system, unit, and unit circuit number to which the circuit terminates.

The callouts listed in the table do not represent actual systems but are given as examples of typical callout.

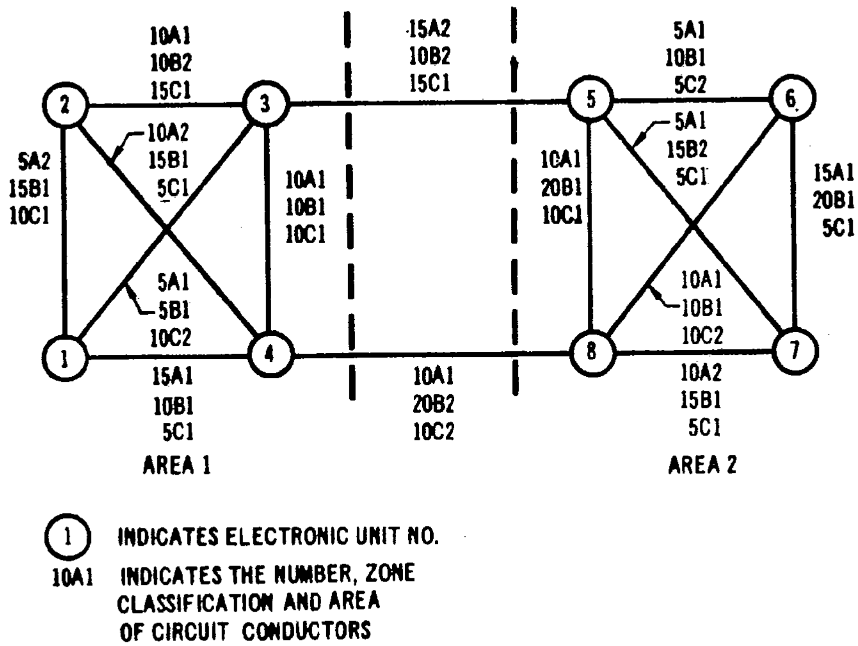


FIGURE 3-62. Initial wiring layout.

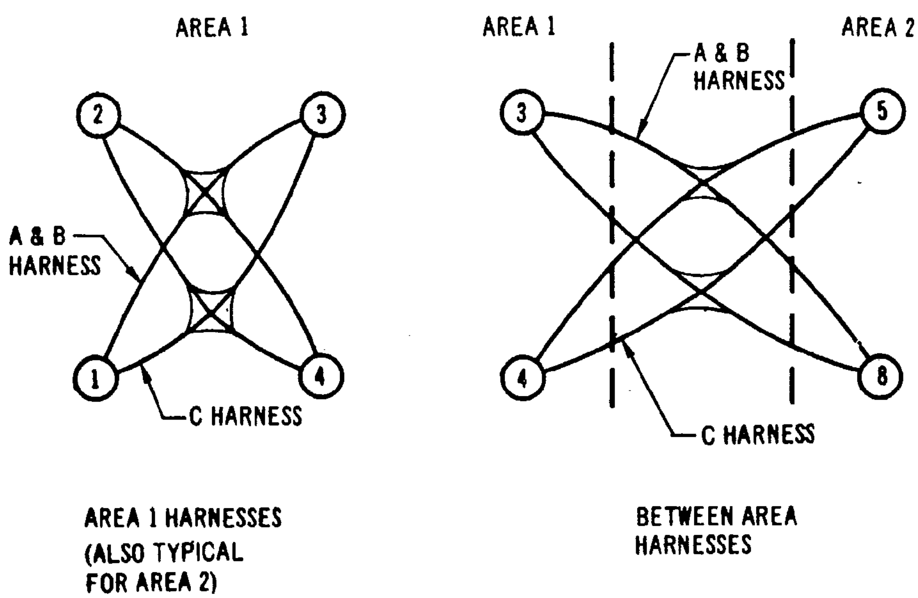


FIGURE 3-63. RWC wiring layout.

3.2.5.2.1 Multibranched Harnesses. If the system shown in Figure 3-62 were to be interconnected with the conventional RWC system, it would utilize multibranched harnesses in each area and between areas as shown in Figure 3-63. No. 22 AWG (500 square mils) wire could be selected for the No. 1, and No. 20 AWG (804 square mils) wire for the No. 2 conductivity requirements. The number and sizes of connectors would be selected to accommodate the number of conductors and the zoning requirements.

There would be a minimum of two RWC harnesses each in areas 1 and 2 and two harnesses to interconnect areas 1 and 2, a total of six harnesses with a minimum of 24 connectors. The use of two harnesses in each area would provide the required circuit isolation.

With multibranched FCC harnesses utilizing multiple cable segments, as required in each FCC connector contact layer, the number of branched harnesses could be reduced to three; one each in areas 1 and 2, and one to interconnect areas 1 and 2. No attempt will be made to design this harness, but Figure 3-64 shows the wiring layout, and Figure 3-65 shows the concept. The circuit conductivity and zoning requirements per Figure 3-62 are shown in Figure 3-65 at electronic unit No. 1 and through the harness run between units 2 and 3. The circuit isolation in the multibranched FCC harnesses is provided by conductor registration.

By using the method described in subsequent paragraphs, the cable and connectors can be selected from Tables 3-2, 3-15, 3-16, and Figure 3-5, and the harness design completed. For example, the FCC connectors at unit 1 (Fig. 3-62) would require a minimum total of 95 contacts on 0.075 centerline (2 for each circuit with a conductivity requirement of 2). Table 3-16 shows that this requirement might be satisfied with a 3-inch wide, 3-layer connector or two 2-inch-wide, 2-layer connectors. The cable layer segments would be selected from Tables 3-2 and 3-15. Many narrow-width cable segments may be required to provide the cable branching.

So we see that the FCC-branched harness can reduce by 50 percent the number of harness runs and the number of connectors over that required by the RWC branched harnesses. If transitions with pin-change capabilities are made to round connectors, or if the electronic units can readily be rewired internally, then the system flexibility can be retained with FCC-branched harnesses. All the advantages of weight, space, and reliability can be realized with the branched FCC harnesses. Although the manufacturing cost will increase slightly due to the handling of the multiple-cable segments, the major cost saving will still be realized.

With all these advantages, it is important to recognize the system requirements' imposed by the use of the FCC-branched harness described above. To efficiently utilize this system, the pin assignment and connector selection at each electronic unit would be controlled by the FCC-branched harness design; the pin assignments at each electronic unit could not be made until after the harness design was completed and, once defined, the pin-assignment changes would be limited to those which could be accomplished by reversing or relocating cable segments (not individual conductors) in the FCC plugs. Section IV defines FCC wire-change methods that can be used to accomplish isolated changes; however, in general, the multibranched FCC harnesses described should be used on those programs requiring many identical end items, and those which can permit pin-assignment control by the interconnecting harness networks.

3.2.5.2.2 Branched Harnesses with Distributors. Many existing airborne designs utilize branched interconnecting harness networks with distributors or other circuit-changing capabilities incorporated into those systems most likely to change during the program. Typical systems, which change frequently, are instrumentation and control. Figure 3-66 shows such a branched harness system with partial system distributors located in separate units. Electronic unit 2 and distributor unit I, and electronic unit 4 and distributor unit II can be located within the same box structure.

Figure 3-66 is a compromise design that has evolved over many years experience with RWC interconnecting systems. This system is flexible in permitting pin-assignment changes in the primary of "fixed" systems during design, and in the secondary or "changeable" systems after the design is completed and essentially frozen.

The FCC system can be readily adapted to the "branched harness with distributor" design. Adjacent to the distributors, the two-ended harnesses will provide all the advantages of FCC.

TABLE 3-15. FCC CABLE SELECTOR CHART

Cable Width (in.)	Number of Conductors			
	50-Mil C_L Spacing	75-Mil C_L Spacing	100-Mil C_L Spacing	150-Mil C_L Spacing
0.25		3		
0.50	7	6	4	3
1.00	17	12	9	6
1.50	27	18	14	9
2.00	37	25	19	12
2.50	47	32	24	16
3.00	57	38	29	19

TABLE 3-16. FCC CONNECTOR SELECTOR CHART

Number of Contacts											
50-Mil C_L Contact Spacing				75-Mil C_L Contact Spacing				100-Mil C_L Contact Spacing			
Cable Width (in.)	No. of Layers			Cable Width (in.)	No. of Layers			Cable Width (in.)	No. of Layers		
	1	2	3		1	2	3		1	2	3
0.25				0.25	3	6	9	0.25			
0.50	7	14	21	0.50	6	12	18	0.50	4	8	12
1.00	17	34	51	1.00	12	24	36	1.00	9	18	27
1.50	27	54	81	1.50	18	36	54	1.50	14	28	42
2.00	37	74	111	2.00	25	50	75	2.00	19	38	57
2.50	47	94	141	2.50	32	64	96	2.50	24	48	72
3.00	57	114	171	3.00	38	76	114	3.00	29	58	87

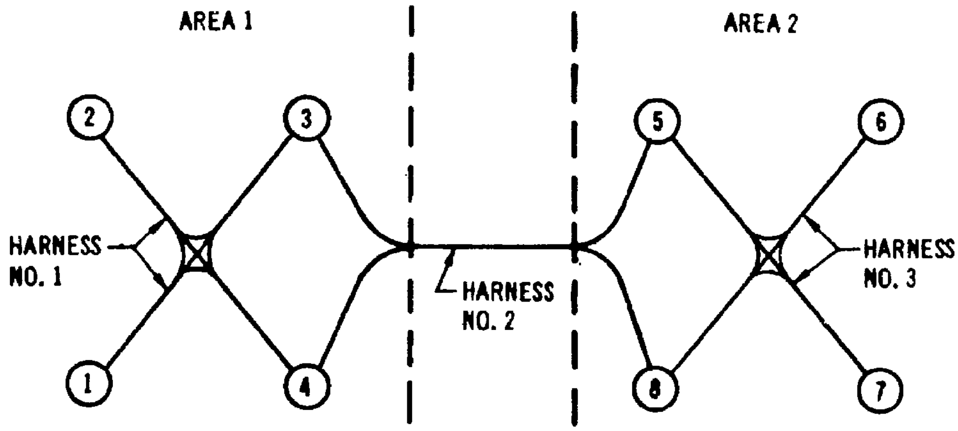


FIGURE 3-64. Multibranched FCC wiring layout.

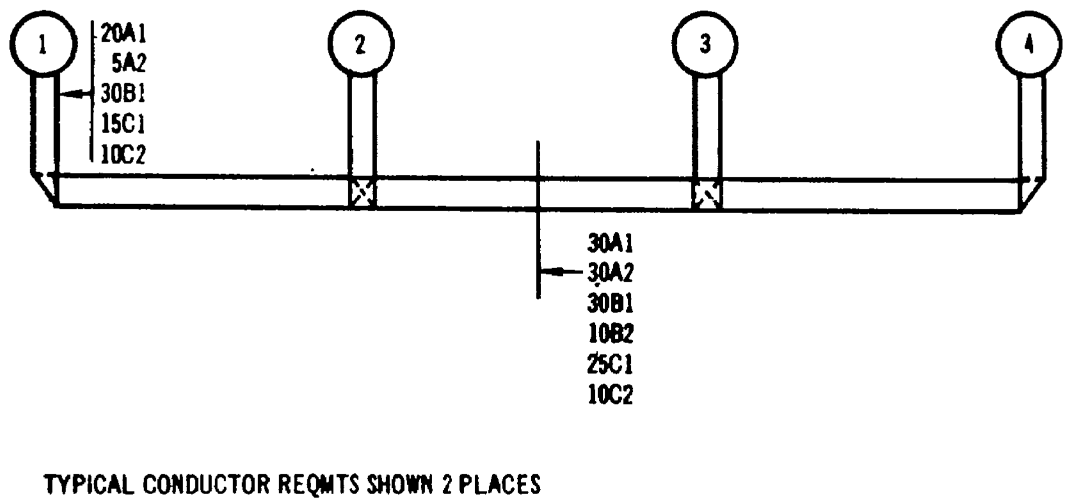


FIGURE 3-65. FCC branched harness.

3.2.5.2.3 Two-Ended Harnesses with Distributors. Returning to the example initial wiring layout (Fig. 3-62), a third design approach will be taken using distributors for all circuits.

For definition purposes, a distributor is a device used in the electrical interconnecting network that simplifies the wiring harnesses and facilitates wiring changes. A thorough description of the objectives and proposed design for distributor systems is given in Section IV.

Figure 3-67 shows the distribution unit, equivalent wiring layout of Figure 3-2. An examination of Figure 3-67 shows that 4 each FCC harnesses are required in areas 1 and 2, and one between the two areas. The most important advantages of distributors are:

a. Harnesses are two-ended and can be terminated in a predetermined configuration for all program connectors.

b. The electronic unit pin assignments can be selected for optimum circuit zoning that will automatically provide optimum zoning in the FCC harnesses.

c. All circuit or pin-assignment changes can be made in the distributors without affecting the FCC harnesses or electronic units.

d. The FCC harnesses between the distributors can be designed and installed prior to the final circuit designs of the electrical systems. The optimum cable widths and connector sizes can be used on these harnesses.

e. The minimum number and smallest sizes of connectors can be used on each electronic unit.

f. Electrical characteristics will be practically identified on subsequent installation of the same configuration.

The advantages listed above are very important and make a major contricution to the wiring breakthrough that is so badly needed. Many agents, both government and prime contractor, responsible for overall electrical systems in space, defense, and commercial programs, are convinced that for the complicated systems of tomorrow, the distributor design system is needed, whether the RWC or FCC interconnecting systems are used.

3.2.5.3 Selection of Cables and Connectors. The FCC harness design will now be made for the wiring layout with distributors shown in Figure 3-67.

The selection of cable and connectors requires close coordination. First, the centerline spacing of the cable must be the same as, or a multiple of, that of the connector and, second, the cable construction and insulation system must be compatible with the termination system used by the connector.

For this program, let us assume that the NASA/MSFC conductor-contact connector system will be used.

Figure 3-67 shows that two conductivity sizes are required; No. 1 requires 200-square-mil cross-section, and No. 2 requires 840-square mils as previously stated. From Table 3-2, these requirements can be met by:

a. 200 square mils - 50-mil centerline, 5- by 40-mil high density
- 75-mil centerline, 5- by 40-mil standard density

b. 840 square mils - 150-mil centerline, 6- by 140-mil high density.

The 75-mil centerline NASA/MSFC conductor-contact connector system is selected with the 5- by 40-mil standard density and the 6- by 140-mil high-density cables. Two conductor contacts will be used in parallel for the 150-mil centerline cable (see Paragraph 3.2.3.4.c). The cable type will be selected to meet the program environmental requirements. For this example, the type selected is polyimide/FEP insulated, laminated, nickel-plated copper conductor cable.

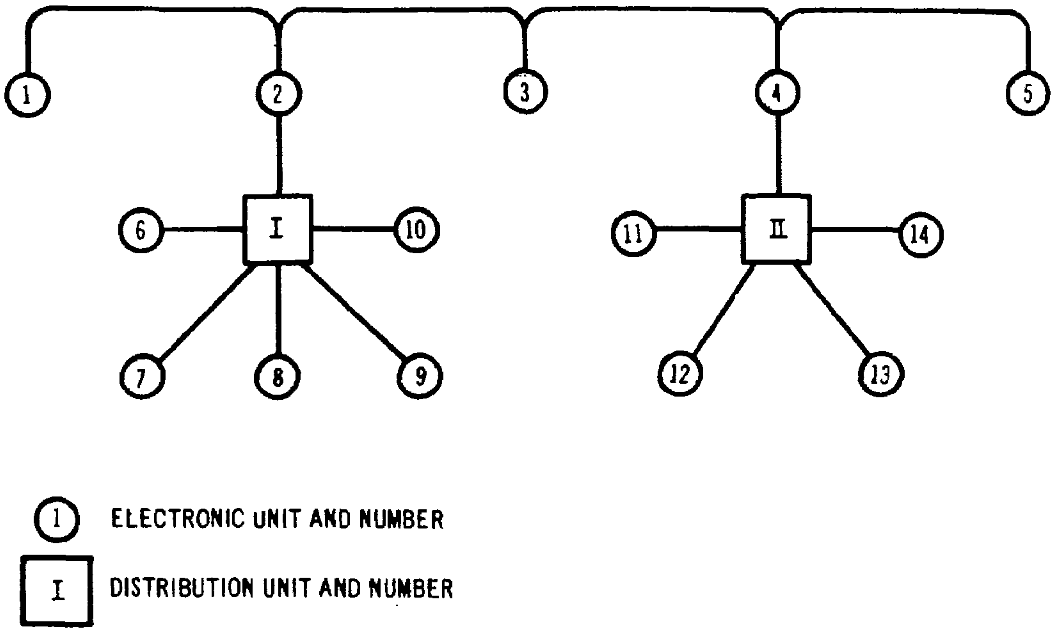


FIGURE 3-66. Branched harness with distributors.

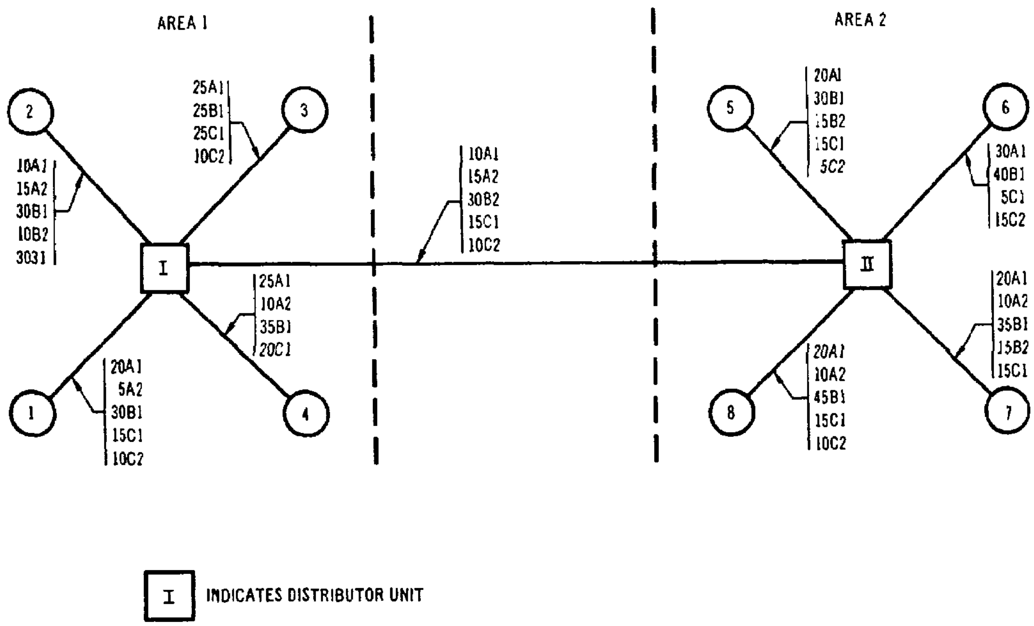


FIGURE 3-67. Wiring layout with distributors.

Now the connector sizes and cable segments can be selected for each FCC harness. First, consider the harness (1-I) between electronic unit 1 and distributor I. The circuit requirements are:

20A1	30B1	15C1
5A2		10C2

Since the number 2 conductivity will require two 0.075-centerline spacing contacts, the total number of contacts is 95. From Table 3-16, two 2.50-inch two-layer connectors are selected. Next, by using the cable information from Table 3-15, Table 3-17 can be prepared to provide the cable segments to meet the conductivity and zoning requirements. The cable segments selected are shown together with their registration to the plug. The selection shown provides the conductivity, zoning isolations, and spare conductors in each conductivity size and in each zoning category.

The connectors, cable segments, and zone grouping can be selected in a similar manner for the remaining eight harnesses.

3.2.5.4 Pin Assignment and Zoning. During the process of the selection of the cable segments, the zoning requirements were already considered. After the connector sizes and cable segments have been selected and registered, the circuit pin assignments can be added to the interconnecting wiring requirement data of Table 3-14. The pin assignment should be made, where possible, to obtain even greater isolation. If the most susceptible circuits are placed at one extreme edge, and the worst interference circuits at the other extreme edge of the interconnecting harness, then the maximum isolation will have been achieved. In cases where this is not possible, shielded FCC may be used. It should be noted that the connector and zoning selection provides the optimum design, both inside and outside the electronic unit.

It remains only to carry the established zoning through the harness routing with other cables.

3.2.5.5 Wire Harness Drawings. The FCC wire harness drawings are similar to RWC harness drawings. This drawing can be a computer printout drawing, showing a tabulation for point-to-point interconnection between all terminating items such as connectors, ground lugs, etc.; parts list; picture presentation of wire harness; and production test requirements for the completed harness. Figure 3-68 shows the essential elements of an FCC harness drawing. The harness requirements were taken from the upper plug of Table 3-17. These are 2.5-inch plugs at each end with one cable segment in layer 1 and two in layer 2, as shown.

The wire list shown in Figure 3-68 defines the point-to-point interconnections for each cable to control the exact cable-segment registration in the connectors; to provide a means of circuit tracing; and for production testing requirements. Two connector pins are required for each conductor of cables 1 and 3 that have conductors on 150-mil centers. The cable conductor number is positively identified in each cable by counting 1, 2, 3, etc., from the part number identification edge of the cable. This identification is required on all FCC during manufacture. Each cable segment is also identified with the harness and cable numbers so that each circuit can be positively identified without stamping the wire numbers on individual conductors. If the program requires a wire number identification for each conductor segment, it can be added as shown in Figure 3-68.

3.2.6 FCC Harness Installation. Concurrent with the electrical design of the FCC harnesses, consideration should be given to harness development, routing, and installation. The largest effort to date for development and installation of FCC harnesses has been on studies performed by MDC for NASA/MSFC. In one study over 100 FCC harnesses were developed, manufactured, and installed in a 180-degree mockup section of the aft skirt of the S-IV-B (Figs. 1-1 and 1-2). In another study, FCC was considered for all harnesses on a proposed S-IV-B baseline vehicle to be used with special kits to meet the mission requirements. The following paragraphs include information from these two programs, together with additional information obtained from other FCC programs and studies.

TABLE 3-17. CABLE SELECTION AND ZONING — HARNESS 1-I

Plug No.	Layer	Zone A	Zone B	Zone C	Cable Segments
1	1	5A2	(S2-6)	5C2	(1) 2.5 - 0.150
	2	10A1	8B1 | (S2-1)	5C2	(1) 1.5 - 0.075, (1) 1.0 - 0.150
2	3	10A1	11B1	(S1-1) 10C1	(1) 2.5 - 0.075
	4	(S1-3)	11B1	(S1-6) 5C1	(1) 2.0 - 0.075

2.500

Plug Key

Vertical line indicates assignment division within cable.

NOTES: Layers 1 and 2 are used for Plug No. 1

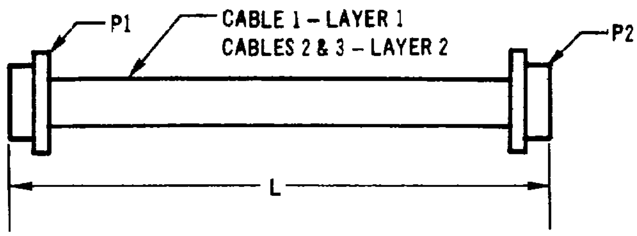
Layers 3 and 4 are used for Plug No. 2

S2-6 indicates 6 spare conductors on 0.150 centerlines.

S1-3 indicates 3 spare conductors on 0.075 centerlines.

▶ Indicates identifications edge of cable.

CABLE ASSY



WIRE LIST

REF DES – PIN	REF DES – PIN	CABLE CONDUCTOR	WIRE NO.
P1-1 & 2	P2 – 32 & 31	1-1	110A
P1 – 3 & 4	P2 – 30 & 29	1-2	111A
P1 – 29 & 30	P2 – 4 & 3	1-15	323C
P1 – 31 & 32	P2 – 2 & 1	1-16	324C
P1 – 64	P2 – 33	2-1	37B
P1 – 63	P2 – 34	2-2	38B
P1 – 48	P2 – 47	2-17	16C
P1 – 47	P2 – 48	2-18	17C
P1 – 43 & 44	P2 – 54 & 53	3-1	42A
P1 – 41 & 42	P2 – 56 & 55	3-2	43A
P1 – 39 & 38	P2-60 & 59	3-4	75D
P1 – 35 & 36	P2-62 & 61	3-5	76D

REFERENCE DESIGNATION

P1	PART NO.	2-1/2" PREMOLDED PLUG
P2	PART NO.	2-1/2" PREMOLDED PLUG
CABLE 1	PART NO.	2-1/2" 150 MIL CENTER HIGH DENSITY (16 CONDUCTORS)
CABLE 2	PART NO.	1-1/2" 75 MIL CENTER STD DENSITY (13 CONDUCTORS)
CABLE 3	PART NO.	1" 150 MIL CENTER HIGH DENSITY (6 CONDUCTORS)

PLUG ASSY (CABLE SEGMENTS)

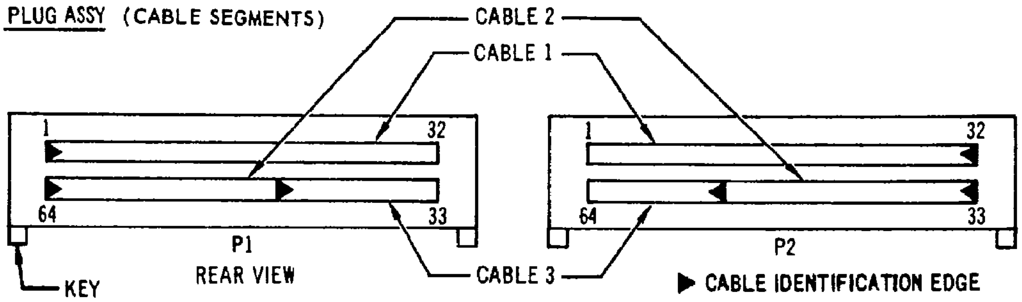


FIGURE 3-68. FCC wire harness drawing.

3.2.6.1 Electromechanical Layout. The installation engineer is primarily concerned with the outline, installation, and interconnecting requirements of the electronic units. The inboard profile drawing, included with the program detail specification, is usually the first scaled drawing for the general arrangement of the end item.

When the program is approved and preliminary design is begun, a scaled electromechanical layout is prepared to show the basic structure, other technology installations, and all electronic units and electrical interfaces. All external electrical connectors, defined by the harness drawings, are shown. By making transparent overlays over the basic layouts, various wire-harness routing and support schemes can be considered. Figure 3-69 shows a typical layout section of FCC harness routing and support. All units would be identified with their external connectors shown and defined.

3.2.6.2 Objectives of FCC Harness Development. Three separate development schemes were tried on the S-IV-B mockup before the final configuration was selected. The general FCC harness development objectives resulting from this program are listed as follows:

a. Keep each harness assembly as simple as possible with none or a minimum number of branches.

b. Route all harnesses inboard of structural cutouts, etc., so that cable-end threading through openings is eliminated or reduced to a minimum.

c. Do not route harnesses behind or under installations that would require removal of equipment or supports for FCC harness installation or removal.

d. Join or group individual harness assemblies in main bundle runs to permit installation, removal, and replacement of separate harnesses with the minimum of disturbance to the other harnesses in the bundle run.

e. Route FCC harnesses close to structure for bundle ground-plane effect.

f. Have wide axis of FCC connectors on electronic units parallel to main bundle runs to permit routing with simple folds.

g. Utilize existing structure sections where possible for FCC support. Add simple lightweight angles, "Z" sections, or hat sections for additional supports. Modular clamp mounting holes should be provided to accommodate clamp-size changes without making new holes in mounting brackets.

3.2.6.3 Full-Scale Development Fixture or Mockup. Although much preliminary design can be accomplished on drawing layouts and transparent overlays, it is highly desirable to use a full-scale, three-dimensional development fixture or mockup for the actual routing, support, and harness definitions. The mockup development should be coordinated with manufacturing and inspection personnel.

A mockup is usually made early in the program from wood and other materials to simulate the structure support and all equipment installations. Very close dimensional control is not required; however, approximate dimensions must be maintained. A development fixture utilizes structure and support essentially in accord with the production drawings with dimensional control so that tubing and wire harnesses developed on the fixture can be installed directly on the production units.

3.2.6.3.1 Initial Installation. By using the manufacturing development techniques defined in Section VI, all FCC harnesses are prepared from the wire-harness drawings and installed per the schemes developed on the engineering layout drawings. The general development objectives of Paragraph 3.2.6.2 and any special program requirements are used in this development.

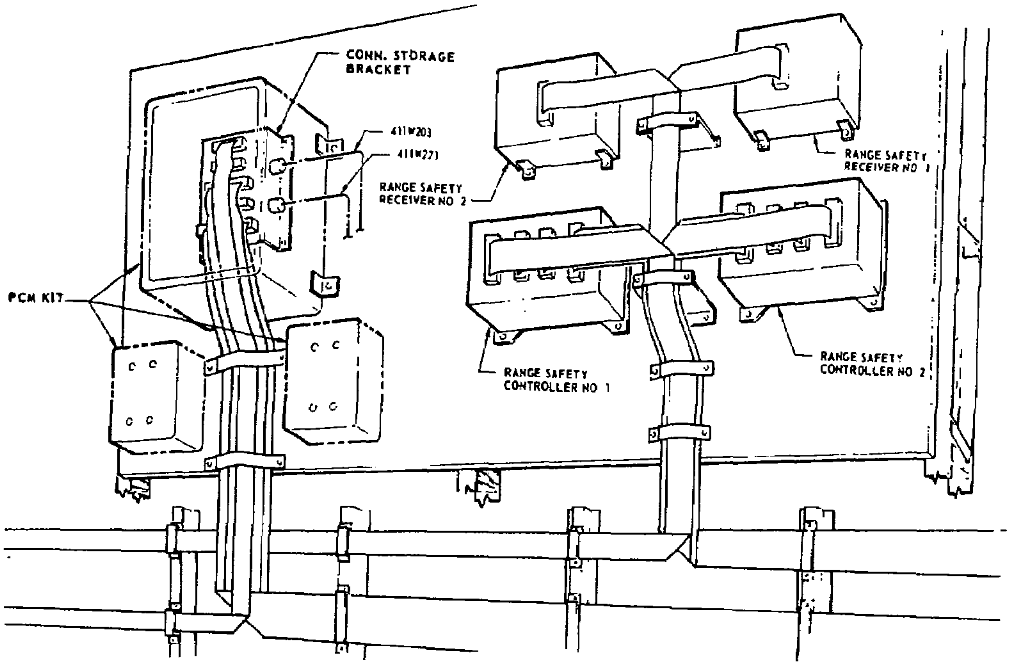


FIGURE 3-69. Typical FCC installation.

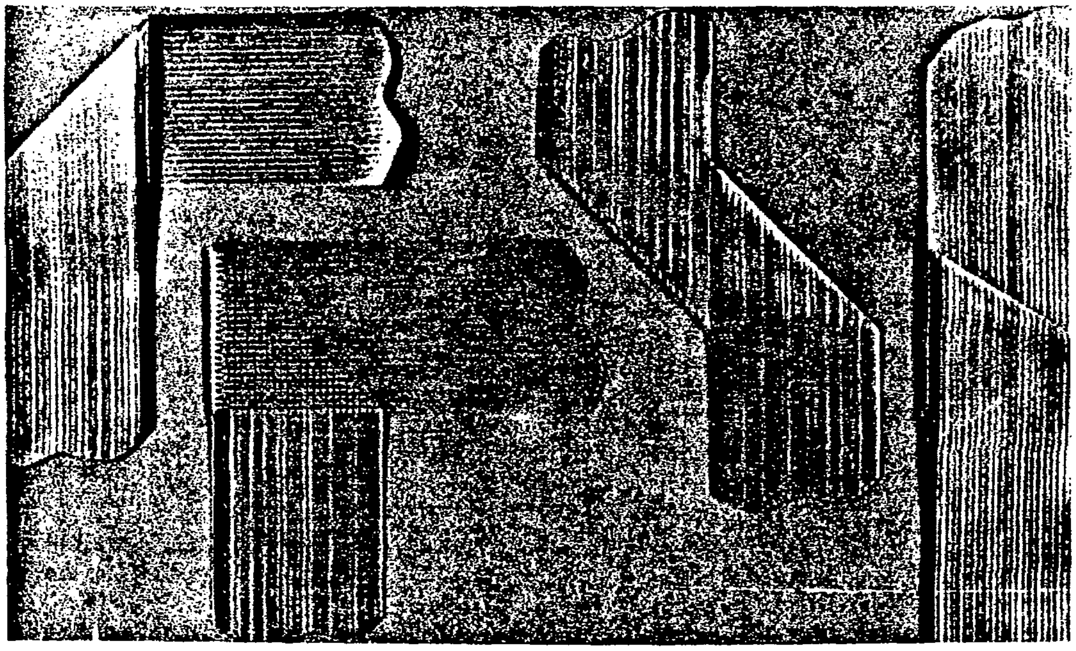


FIGURE 3-70. Cable folding techniques.

3.2.6.3.2 Folding Techniques. Various cable-folding techniques are used, as shown in Figure 3-70, to provide the direction changes and cable registration required. Nonshielded FCC can be folded flat on itself with no bend radius required. Shielded FCC should always be folded with a minimum bend radius, usually 1/8 inch. A permanently installed filler or other device should be used to assure that this radius will be maintained. In those areas where cables branch out of major runs, or where the major run changes its direction by folding, there are two methods to be considered, as shown in Figure 3-71. Folding by group provides neater bundles and additional support, with fewer exposed edges. Folding by cable makes it much easier to install, remove, and replace individual cable assemblies.

3.2.6.3.3 Clamping and Supports. Maximum utilization should be made of existing primary and secondary structure and existing brackets, etc., for FCC harness support. Generally, all that is required is a 5/8-inch-wide flat surface with the rigidity or strength provided by angles, Z's, or other cross-sections. Simple lightweight support sections can be added as required for additional support (Fig. 3-72). By providing modular-spaced mounting holes in these sections, the required clamp sizes and main-bundle-run spacing can be revised without changing the support brackets.

Various type clamps are shown on Figure 3-73 for general FCC support. They are: lap clamps, both single and multiple, for low temperature (100°C max) application; and metal clamps, both cushioned and noncushioned, for high-temperature (200°C) application. Additional information on these clamps and others is contained in Section II. All clamps shown in Figure 3-73 have captivated hardware and are suitable for tabulated widths to accommodate the standard cable widths.

To assist in the proper registration of the cable segments in the FCC harness runs, adhesive tape can be used under all clamps and between clamps. This will assure that cable segments will remain in the proper harness layer and will help maintain each segment in its proper layer position.

3.2.6.3.4 Cable-Segment Registration. It is very important to maintain the cable-segment registration in the harness run as required by the engineering design (Fig. 3-74). It is mandatory that this registration be accomplished on the final mockup or development fixture harnesses since the production units will be patterned from them. This will require that each cable segment be identified together with its index edge. The use of adhesive tape will aid in maintaining this registration during development and installations.

3.2.6.3.5 Final Approval. After the final development has been accomplished, engineering approval is required prior to removal of developed FCC harnesses, and subsequent to their use for patterns in making the production harnesses. At this time, the cable segment registration should be checked in each bundle-run section and at each connector, as well as the general routing and support. Figure 3-75 shows a section of a completed final mockup development.

3.2.7 Other Drawings.

3.2.7.1 Cable Network. The cable network drawings required by many programs show all electronic units listed by title and reference designation number in each area or zone of the end item, each interconnecting harness, and the reference designation for each external electrical connector. For FCC application, it is necessary only to establish a code so that the FCC and RWC harnesses can be easily differentiated.

3.2.7.2 Schematics. Unit schematics define the components and interconnections inside electronic units with no reference to external harnesses; therefore, these drawings are not affected by FCC application to interconnecting harness networks.

Advanced functional schematics define the electrical interconnections between and through electronic units on a system or subsystem basis. It is necessary only to establish a code for FCC so that it can be distinguished from RWC.

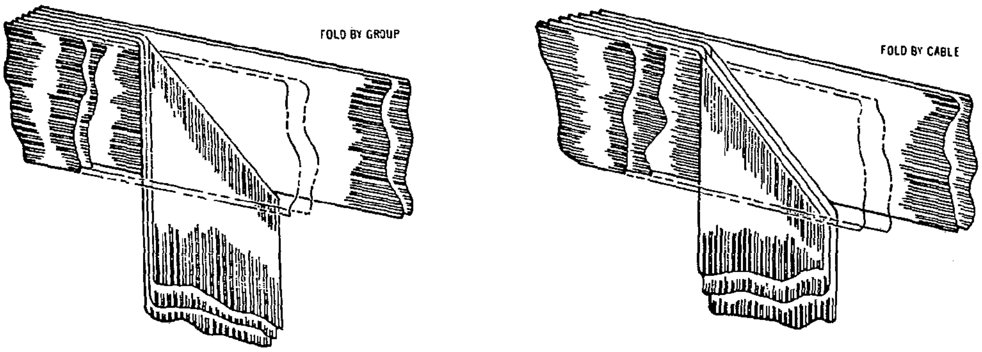


FIGURE 3-71. FCC branchout from bundle run.

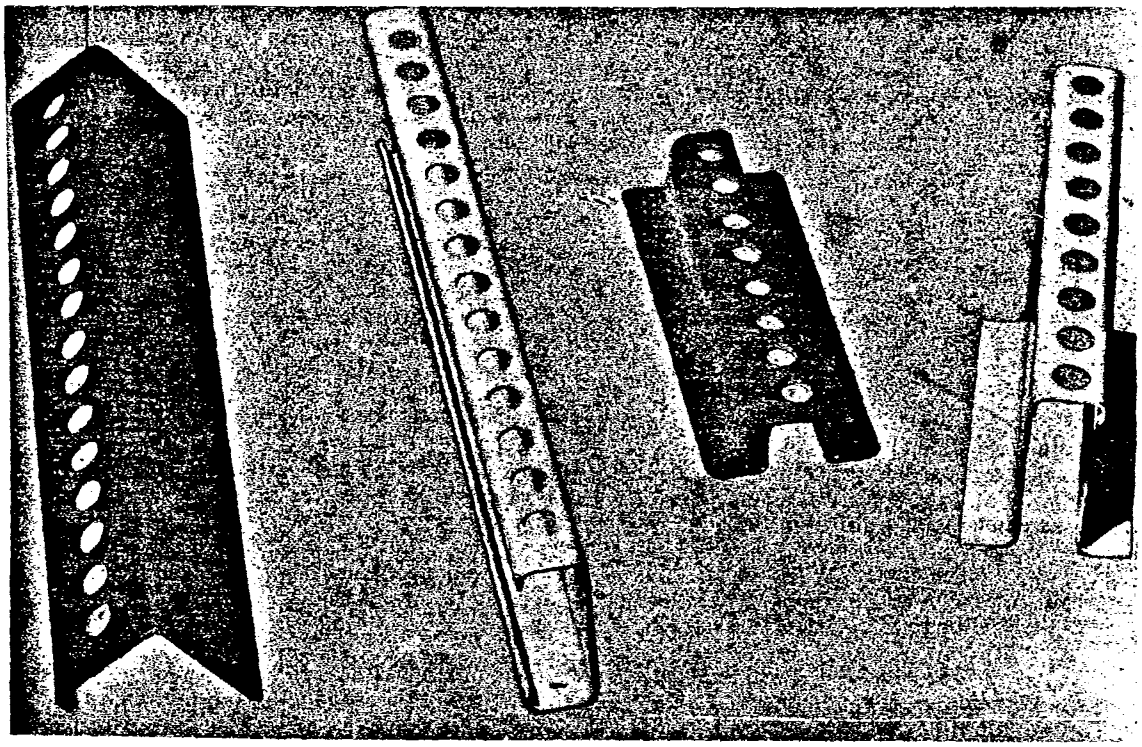


FIGURE 3-72. Sections for FCC support.

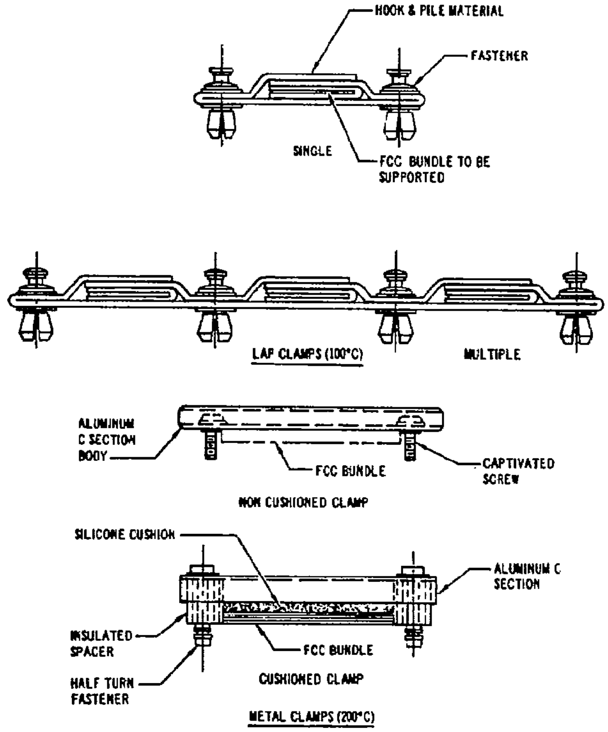


FIGURE 3-73. FCC clamp types.

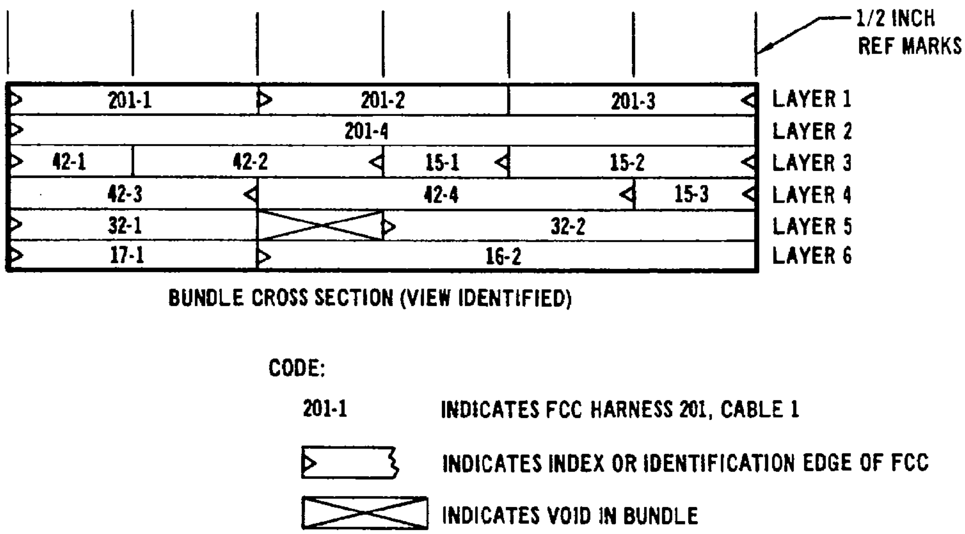


FIGURE 3-74. FCC cable registration.

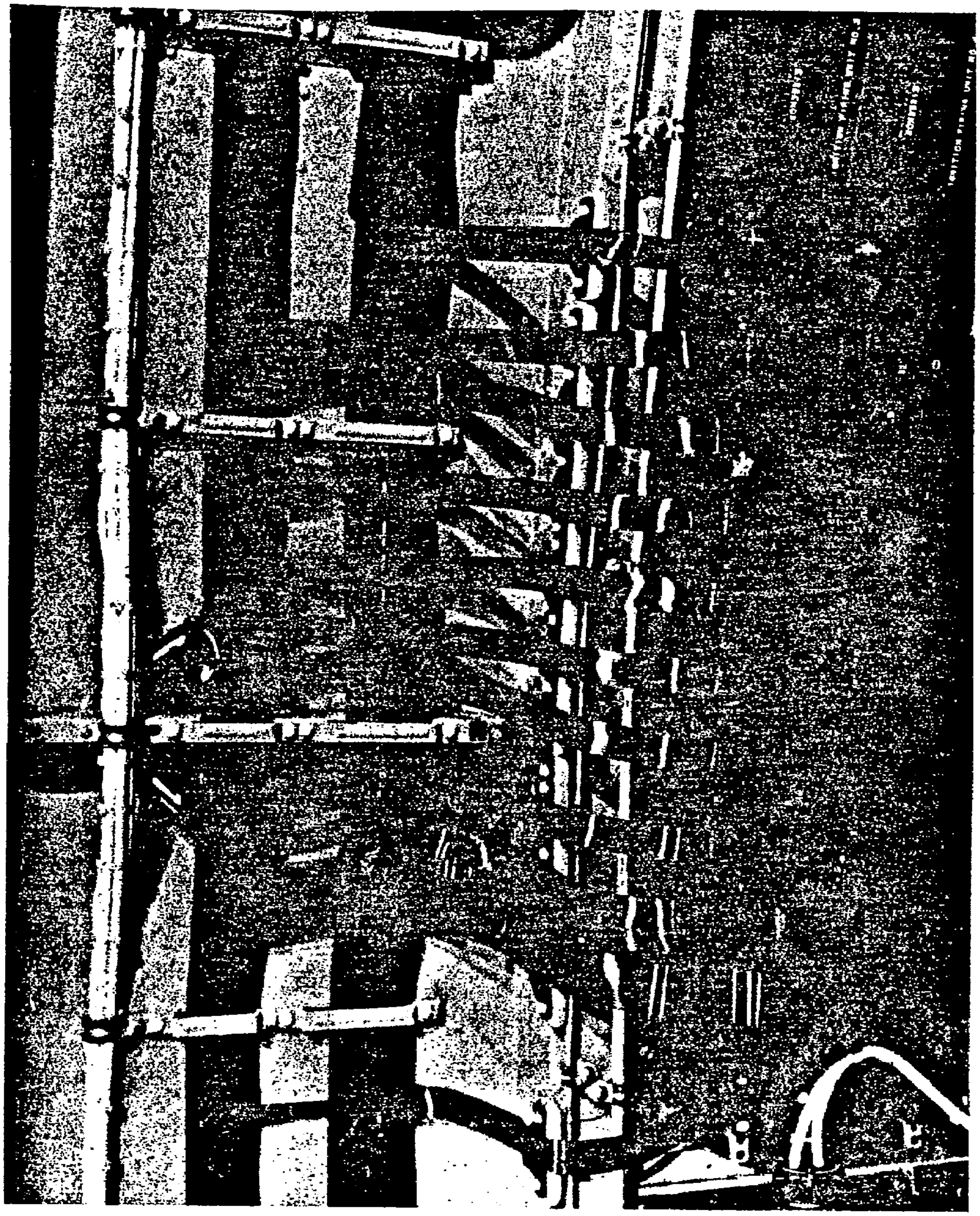


FIGURE 3-75. Final development mockup.

3.2.7.3 Electrical Interface. The electrical interface drawings define the pin-assignment functions and electrical connectors that interconnect with other items such as umbilicals, flight disconnects, or assembly disconnects that mate on joining. These drawings are essentially the same for FCC or RWC systems. If both type interfaces are used, the proper differentiation should be made.

3.2.8 Special Applications. The electrical and mechanical properties of FCC, and the many possible configurations in which it can be manufactured, make it adaptable to numerous special applications.

3.2.8.1 GSE Cabinet Cables. FCC has been used in many GSE cabinet applications to provide electrical conductors between fixed structure and hinged panels or electrical drawers that are usually mounted on slides.

Figure 3-76 shows a current application by the Librascope Group of General Precision for the Mark 48 Fire Control System. The shielded FCC assemblies were fabricated by Ansley West with continuous, very small corrugations at right angle to the cable length to provide the flexibility required. Both panel rotation and drawer translation, plus rotation movements, have been accommodated.

By using insulation materials, such as Teflon and Mylar which can be heat-formed to provide a built-in memory, both corrugated and convoluted coils can be fabricated from FCC to provide retractable cable assemblies for drawer application. Figures 3-77 and 3-78 show examples of the memory-type retractable cable assemblies.

A standard FCC cable can be used in a loop or U-shaped configuration to accommodate drawer extension as shown in Figure 3-79.

3.2.8.2 Storage and Deployment. Requirements for stowage and deployment of electrical interconnecting cables must be accommodated on many programs. The systems to be described are especially simple and efficient. Generally, they are not self-retractable.

Bendix designed an FCC cable-and-stowage reel to meet these requirements on a lunar application (ASLEP) to interconnect lunar experiments to a central data package. Figure 3-80 shows the stowage-reel concept used. Deployments up to 60 feet with FCC, having 32-AWG conductors, were accommodated with the advantages of simplicity, lightweight, small space, and high reliability. These advantages will warrant consideration of this system for all future stowage and deployment requirements.

A sample corrugated FCC configuration (Fig. 3-81) offers unique advantages. The sample 2-inch-wide cable with 50-mil centerline conductors can be compressed to 1.25 inches for stowage. The free length is 10 inches; the extendible without exceeding the elastic limit of the corrugated cable is 15 feet; and the total cable length is 30 feet. It is difficult to envision how any other system could stow, for reliable deployment, the number and length of conductors in a 1.25- by 2.0- by 2.0-inch stowage volume.

3.2.8.3 Hinge Applications. The geometry and physical characteristics of FCC make it ideally suited for use as a hinge medium, providing both the hinge and the means of transferring many electrical signals across the hinge line.

Two basic configurations have been developed by NASA/MSFC and are shown in Figure 3-82. The FCC can be bonded directly to the adjacent structure to absorb the required sheer load and to provide simple cable support. The Type A hinge is suitable for low torque, small angular movement. The Type B hinge can be rotated through larger angles with greater torque required.

A little imagination by the designer will result in many practical FCC hinge-line applications for interwiring of electronic units and for external interconnecting harnesses.

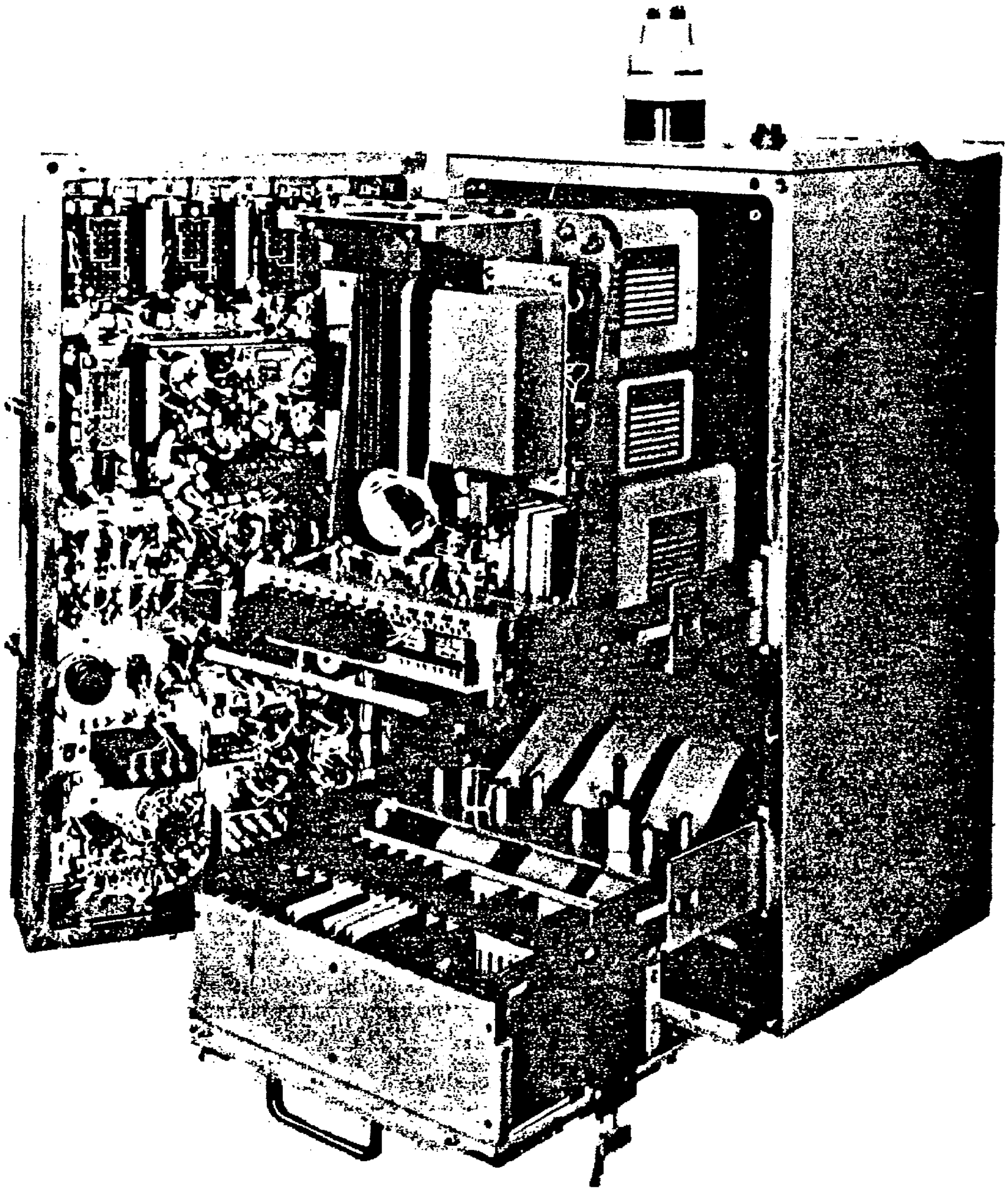


FIGURE 3-76. Mark 48 Fire Control - Libroscope Group of General Precision.

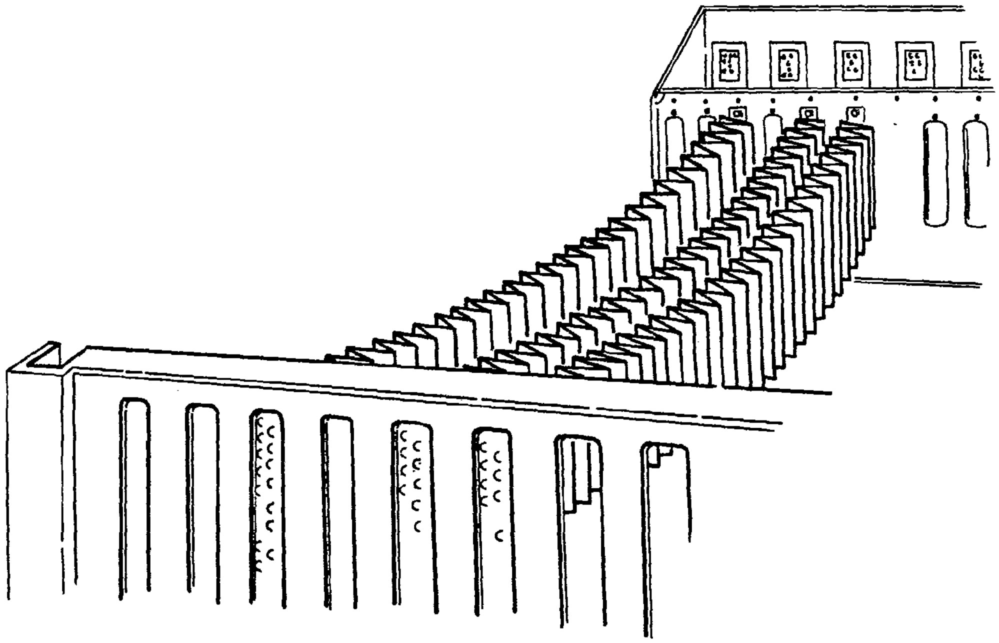


FIGURE 3-77. Retractable FCC rack-mounted drawer assembly.

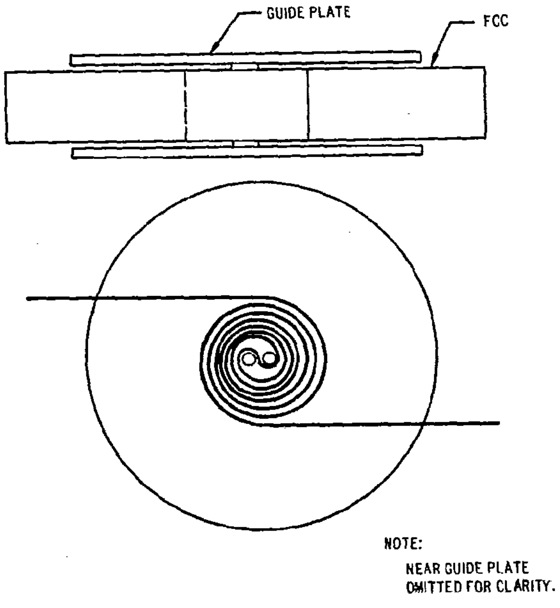


FIGURE 3-78. Convoluted coil.

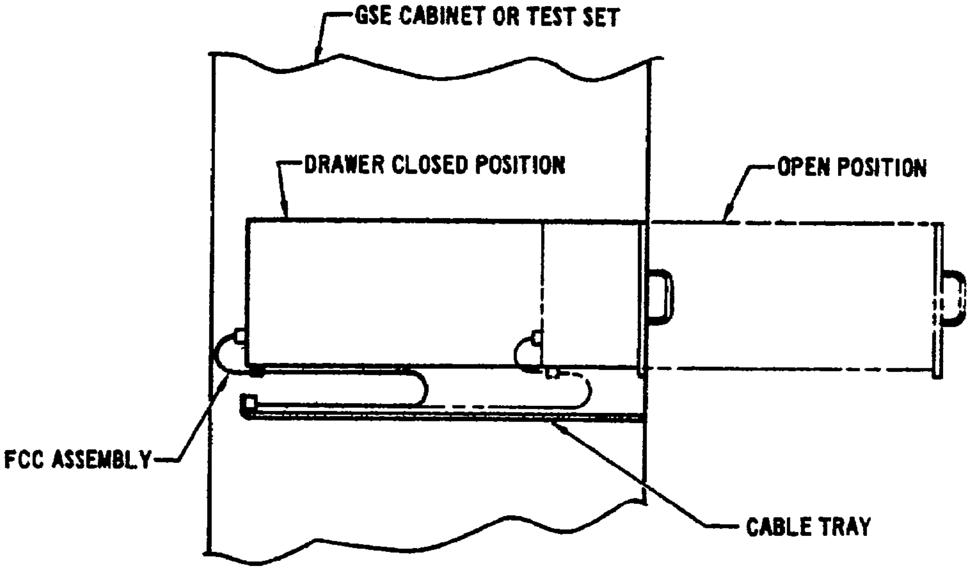


FIGURE 3-79. U-shape trailing cable.

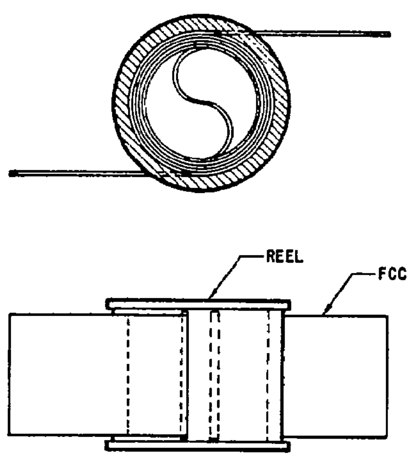


FIGURE 3-80. FCC stowage reel.

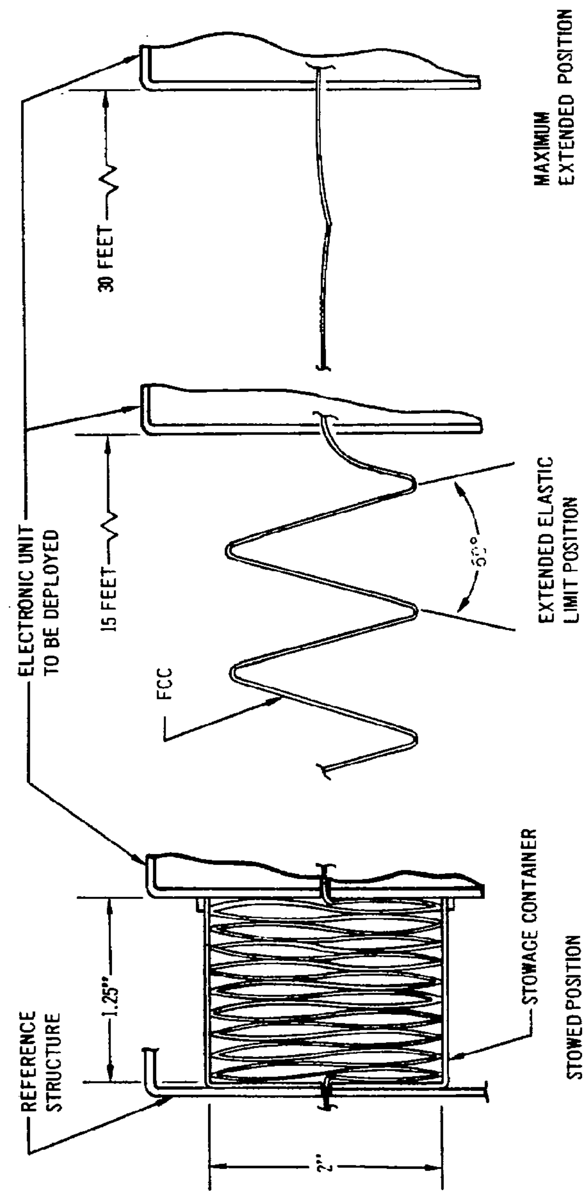
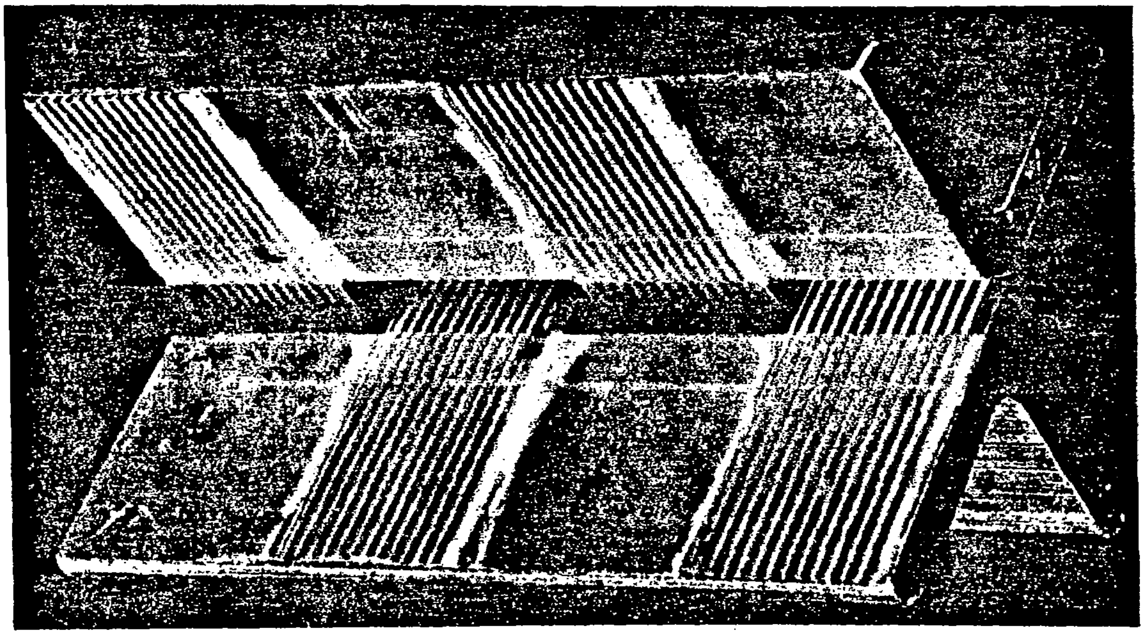
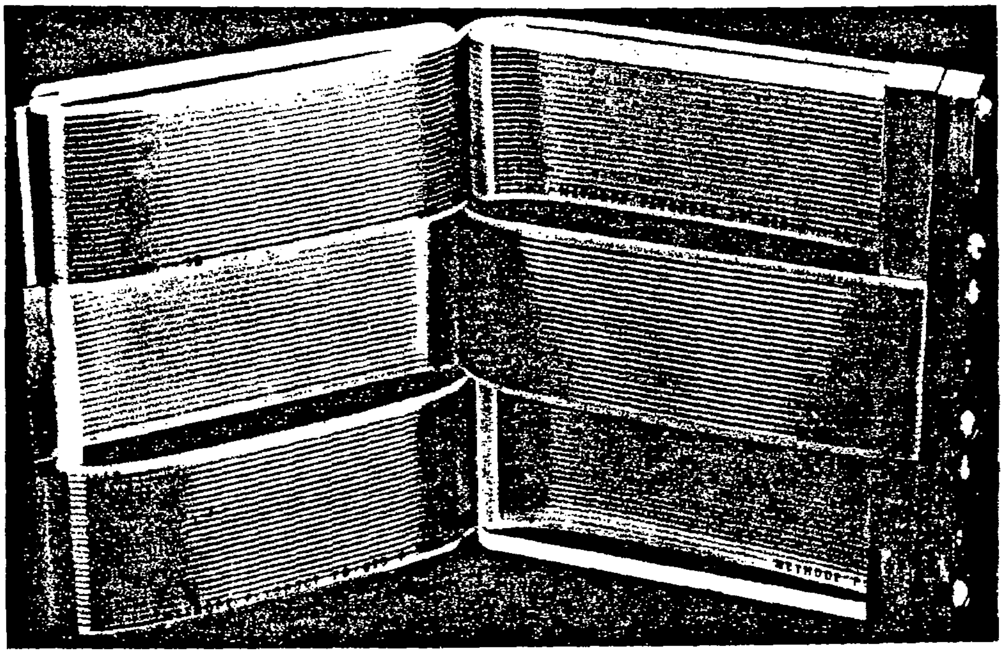


FIGURE 3-81. Corrugated FCC cable stowing.



TYPE A - LOW-TORQUE SMALL ANGLE OF ROTATION



TYPE B - HIGHER-TORQUE LARGE ANGLE OF ROTATION

FIGURE 3-82. FCC hinge applications.

3.2.8.4 Low-Torque Application. FCC is to be used on the Apollo Telescopic Mount (ATM) program by MSFC to transmit 2500 conductors across two sensitive gimbal systems. It was a requirement that the crossing electrical harness require a minimum of torque for gimbal rotation. Extensive studies indicated that the FCC system required approximately one-tenth the torque required for the conventional RWC system. Figure 3-83 shows the harness configuration which can be used for gimbal crossings. Figures 3-84 and 3-85 show a method used for determining and the values required for rotation and bending of the FCC harness.

3.2.8.5 Angular Rotation. The physical characteristics of FCC make it especially suitable for applications requiring the transfer of electrical signals across a rotating joint. Continuous oscillation of 180 degrees is used frequently for gun turrets, radar antenna arrays, etc. One shot or limited operations can be made for spin-up and other requirements of many rotations for missile, satellite, and other applications. Figure 3-86 shows the basic configuration used for accommodating limited rotation with FCC.

For the limited rotation case of 180 degrees, the design is essentially noncritical, and a sample experiment with a mockup FCC harness will determine the drum and arbor diameters and the number of FCC turns required.

For maximum angular rotation in one shot or limited operation, studies have indicated that up to 20 complete revolutions can be made with a drum diameter of 1.7 inches and an arbor diameter of 1 inch. Up to 50 complete revolutions can be made if the drum diameter is increased to 2 inches. For maximum rotation and reliability, the cable thickness should be kept to a minimum, and the insulation material should have as small a coefficient of friction as possible.

3.2.8.6 Special Electrical Configurations.

3.2.8.6.1 Minimum-Spurious-Coupling Configurations. Minimum-spurious-coupling configurations are discussed as follows:

a. Capacitive coupling - When two conductors, or other objects, are in close proximity to each other, they form a small but finite capacitor. The conductors are capacitor plates and the conductor insulation and other nonconductive material form the capacitor dielectric. Any varying voltage on one of the conductors is capacitively coupled into the impedances connected to the other conductor.

b. Magnetic coupling - The mere existence of a longitudinal conductor creates a small but finite inductor. When two conductors are in close proximity to each other, they form a transformer because of their coupling or mutual inductance. Any varying current flow in one conductor is inductively coupled into the other conductor as an induced voltage because of the transformer action.

c. Single-ended circuitry with a common return - Conventional circuitry frequently utilizes a structural ground plane as a reference point and circuitry return path.

   1. Capacitive coupling - Since any two objects have a mutual capacitance (sometimes referred to as series capacitance), a conductor has mutual capacitance to other conductors or objects that are a source of interference. The same conductor also has a mutual capacitance to the return path conductor and surrounding objects, other than the interference source, that is commonly known as shunt capacitance.

      Interference is capacitively coupled from the interfering conductor, through the series capacitance, to the susceptible conductor which has a parallel shunt capacitance between it and the circuit return path. The shunt capacitance is also normally paralleled by additional terminating impedances at each end of the conductor. The capacitive coupling circuit is basically a frequency-sensitive, capacitive voltage divider with an output loaded by the paralleled source and load termination impedances. Voltages appearing between the function conductor and the structural ground plane, or other common return path conductor, are known as common-mode voltages.

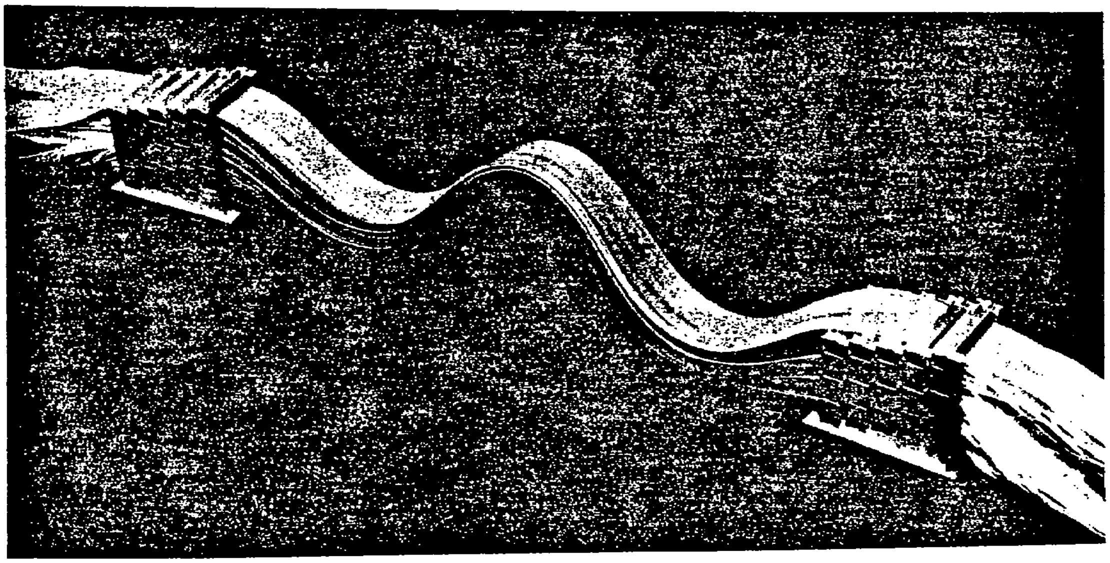


FIGURE 3-83. Low-torque FCC harness.

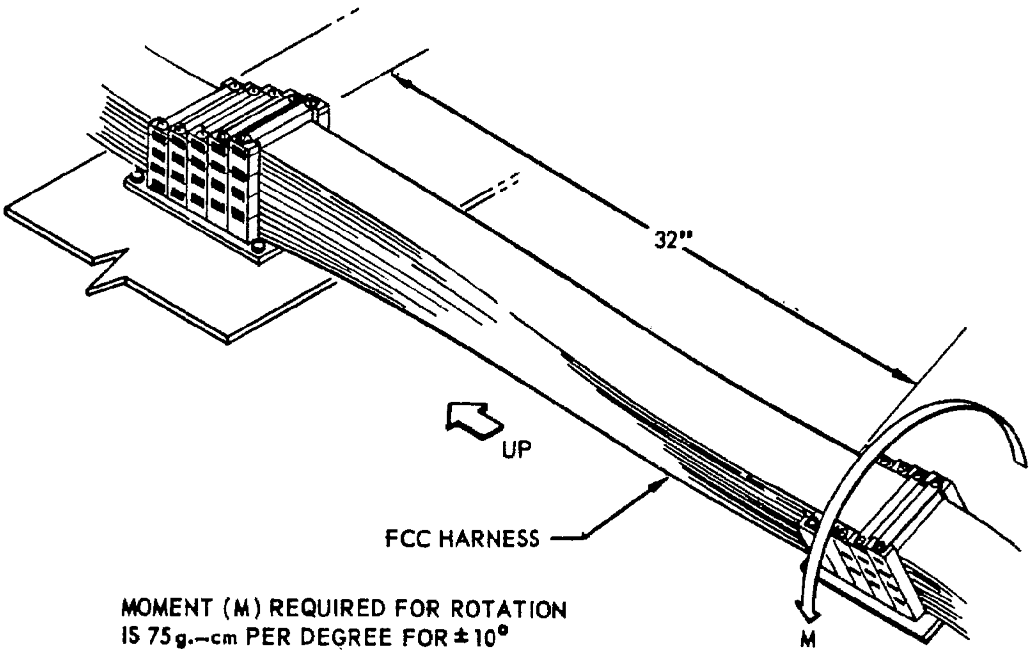
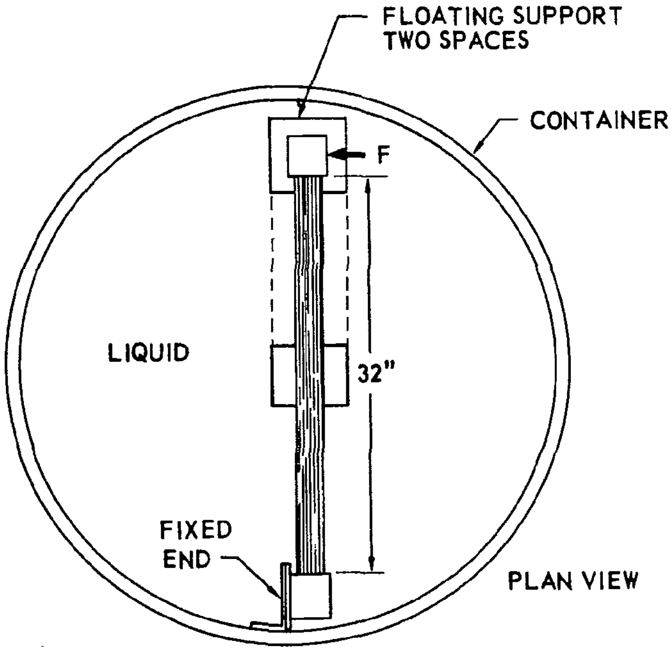


FIGURE 3-84. Torque required for rotation.



FORCE (F) REQUIRED IS 1.5 GRAMS PER DEGREE OF BENDING FOR MOVEMENTS LESS THAN 8 INCHES.

FIGURE 3-85. Force required for bending.

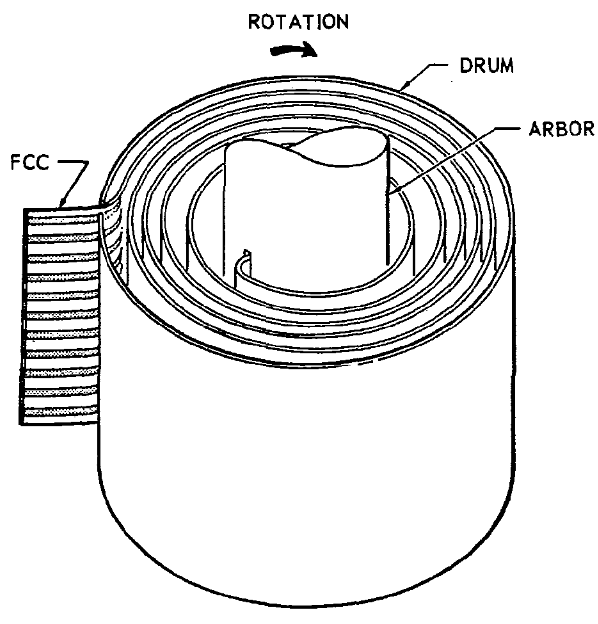


FIGURE 3-86. FCC application for rotational devices.

2. Magnetic coupling - Since any two objects also have a mutual inductance, a conductor has mutual inductance common to other conductors or objects that are a source of interference. The same conductor also has a loop-inductance component that appears in series with the conductor, but is not mutual or common to other conductors. The sum of the mutual inductance and loop inductance forms the self, or total, inductance of the conductor that interacts with circuitry in the termination hardware.

   The interference-carrying conductor is equivalent to a transformer primary winding. The susceptible conductor is equivalent to a transformer secondary winding with the same number of turns as the primary winding. If this transformer had unity coupling between windings, which would be the case if an iron core were available, virtually identical voltages and currents would appear in both windings if similar source and load impedances were connected to the transformer windings. Cable conductors do not have a ferrous core; therefore, the resultant air-core transformer has less-than-unity coupling.

   Currents flowing through the primary winding generate a magnetic field, but only a portion of this magnetic field intercepts the secondary winding because of the absence of an iron core capable of confining the magnetic field to a path that intercepts the secondary winding. Since only a portion of the energy in the magnetic field intercepts turns in the secondary winding, the resultant-induced voltages and currents are smaller than those present in the primary winding. This is the equivalent effect that would be produced by a transformer in which only part of the primary-winding turns and part of the secondary-winding turns were wound on a common iron core, while the remaining primary-winding turns and secondary-winding turns were magnetically isolated from each other.

   The resultant inductive Tee network has a common inductive reactance or mutual inductance that is equivalent to a unity-coupled transformer connected between the source and load terminations. A series, or loop, inductance appears between the primary winding of the transformer and the source termination. A second series, or loop, inductance appears between the secondary winding of the transformer and the load termination. The conductor equivalent to the transformer primary winding has a total, or self, inductance equal to the sum of the source circuit-loop inductance and the primary inductance of the mutual-inductance virtual transformer. The conductor equivalent to the transformer secondary winding has a total, or self, inductance equal to the sum of the load-circuit loop inductance and the secondary inductance of the mutual-inductance virtual transformer.

   Interference is inductively coupled from the interfering conductor, through the transformer action of the mutual inductance to the susceptible conductor, which has a termination impedance connected from each end to the common return path, forming a complete current loop. The inductive-coupling circuit is basically a frequency-sensitive, two-section, inductive voltage divider with an output loaded by the susceptible circuit source and load termination impedances.

Balanced Transmission Systems

Since the voltage induced in each conductor is proportional to the field intensity at the conductor, it is possible to induce identical voltages in two conductors if they can be made to occupy points of identical intensity within the field. If identical voltages are induced in both conductors, no difference exists between them; the functional circuit has no interference voltage impressed across it, and the induced interference voltages have been cancelled.

The FCC configuration that comes closest to causing both conductors to occupy the same point in space is an extremely low-profile cable with two layers of conductors, in registration, arranged to provide over-and-under pairs of conductors with a minimum dielectric thickness separating the paired conductors. If the conductor layers are in perfect registration, the field intensity generated by an interference source located at either edge of the cable will be essentially identical at both conductors. If the interference source were located above or below the cable, the difference in field intensity appearing at the two over-and-under conductors would be equal to the ratio of the vertical conductor center-to-center spacing to the geometric mean separation distance of the interference source. Since the vertical conductor separation is approximately 0. 10 millimeter, and the interference source separation distance is ordinarily orders of magnitude greater than this dimension, virtually perfect cancellation of the interference is achieved. Even when the source of interference is in the same cable stack, a useful reduction in the effective line-to-line mode, interference level will result from the use of this configuration.

The FCC configuration that provides the next closest approach to causing both conductors to occupy the same point in space is side-by-side conductors in the same layer of cable. If the conductors are in the same vertical plane, the field intensity generated by an interference source centered above or below the conductors will be identical at both conductors. If the interference source were located off either edge of the cable, the difference in field intensity appearing in the two side-by-side conductors would be equal to the ratio of the horizontal conductor center-to-center spacing to the geometric mean separation distance of the interference source. Since the horizontal-conductor separation is approximately 2 millimeters, and the interference source separation distance is ordinarily orders of magnitude greater than this dimension, virtually perfect cancellation of the interference is achieved. Even when the source of interference is in another edge adjacent layer of cable in the same cable assembly, a useful reduction in the effective line-to-line mode interference level will result from the use of this configuration.

Balanced or Differential Circuitry

Differential devices respond to differences in the absolute levels existing at the differential inputs and are extremely insensitive to absolute levels simultaneously present at the differential inputs within the dynamic range of the available circuitry. Until recently, the inherent advantages of balanced and/or differential devices could be used only infrequently because of increased circuit and hardware complexity.

Each balanced circuit is essentially two single-ended circuits connected face-to-face electrically. A differential circuit is basically a balanced circuit with additional circuitry for the optimization and maintenance of balance between halves of the basic balanced circuit. Since individual integrated circuits, medium-scale integrated circuit arrays, and large-scale integrated circuit arrays are becoming commercially available, the limitations previously imposed by increased circuit complexity are no longer critical factors.

Since balanced or differential circuitry is sensitive to line-to-line mode rather than common mode interference, the effective interference level at the susceptible circuit imputs is equal to the common mode interference amplitude divided by the reciprocal of the fractional circuit unbalance existing at the susceptible circuit inputs.

3.2.8.6.2 Transmission Lines. Transmission lines are conductors with controlled electrical characteristics used for the transmission of high-frequency or narrow-pulse type signals. The impedance of a transmission line is a function of the distributed series inductance and distributed shunt capacitance of either the balanced conductor pair or the single-ended conductor-and-shield ground plane as a pair. The characteristic impedances of typical conductor configurations, and the formula for deriving the characteristic impedance of a transmission line from the basic electrical properties of the conductors, are given in Paragraph 3.2.3.1. Many standard conductor configurations, both side-by-side and over-and-under, are suitable for transmission line use.

The distributed inductance and capacitance of a transmission line form a high-frequency resonant circuit. When the termination impedances at both ends of the conductor equal the characteristic impedance of the transmission line, a matched-impedance situation exists and the distributed resonant circuit is critically damped.

If the source and/or load terminations do not match the transmission line characteristic impedance, the distributed resonant circuit is not critically damped, and any rapid change in applied voltage or current causes the resonant circuit to ring and generate a damped wavetrain at the frequency of the resonant circuit. Typical cables have relatively high ringing frequencies; therefore, the damped wavetrain appears as a positive or negative spike, or fine fuzz, wherever rapid transitions in waveform amplitude occur. The resultant pulse distortion cannot be tolerated in many systems.

When high-frequency sinusoidal waveforms are applied to a mismatched transmission line, standing waves are distributed along the length of the conductor because of the reactive current flows and voltages that exist in a resonant circuit, and the function amplitude becomes dependent on cable length and frequency.

Impedance-mismatched transmission lines are highly reactive at most frequencies. At high frequencies, relative to cable length, the sign and magnitude of this reactance changes rapidly, causing the transmission losses and received function amplitude to fluctuate with frequency. Except at a few isolated frequencies where a coincidental impedance match occurs, the magnitude of these losses is extremely high and relatively difficult to predict.

Electromagnetic energy travels through free space at 300, 000, 000 meters per second. Most practical transmission lines have a velocity of propagation about two-thirds that of air, or approximately 200, 000, 000 meters per second. The transit time of digital pulses through even short lengths of cable can be significant in current high-speec digital systems. Variations in cable lengths can also cause digital pulses to arrive in the wrong time sequence where parallel pulse transmission is involved.

Nonferrous-shielded conductors have limited bandwidth, compared with unshielded conductors, because of the large shunt capacitances between the conductors and shields, and are therefore suitable only on low-speed digital systems. Ferrous-shielded conductors have a very restricted bandwidth due to both the large series conductor inductance and shunt conductor-to-shield capacitance; therefore, ferrous-shielded conductors are generally unsuitable for digital transmission systems. The high-resultant characteristic impedance of this system is generally incompatible with digital hardware.

Measured transmission loss for energy conducted by a centrally located conductor in a variety of cable configurations is shown in Figures 3-87 through 3-90.

3.2.9 Mechanized Design. A large portion of the design of FCC harnesses can be mechanized with the use of a digital computer and appropriate programs. This can aid designers of a complex electronic system by providing relief from much of the repetitive, tedious, and time-consuming phases of harness design processes.

3.2.9.1 Capability of Mechanized Design. A mechanized harness-design system can accomplish much of the routine assignment of identification information, bookkeeping, and drawing effort that would ordinarily be done by designers' aides.

A description of tasks that can be performed effectively by the computer system is offered. This system can:

a. Read, compile, and file (e.g., magnetic tape) information on approved parts, with appropriate performance characteristics and specifications from which harness assemblies may be fabricated.

b. Read, compile, and file point-to-point wiring requirements.

c. Process and analyze wiring requirements, and sort out those which cannot be met by available approved parts. The system can then analyze the remaining requirements to group conductors into cables, and within each cable, according to the location of each conductor termination and to EMC zoning criteria (see Paragraphs 3.2.3.2.1 and 3.2.10.2).

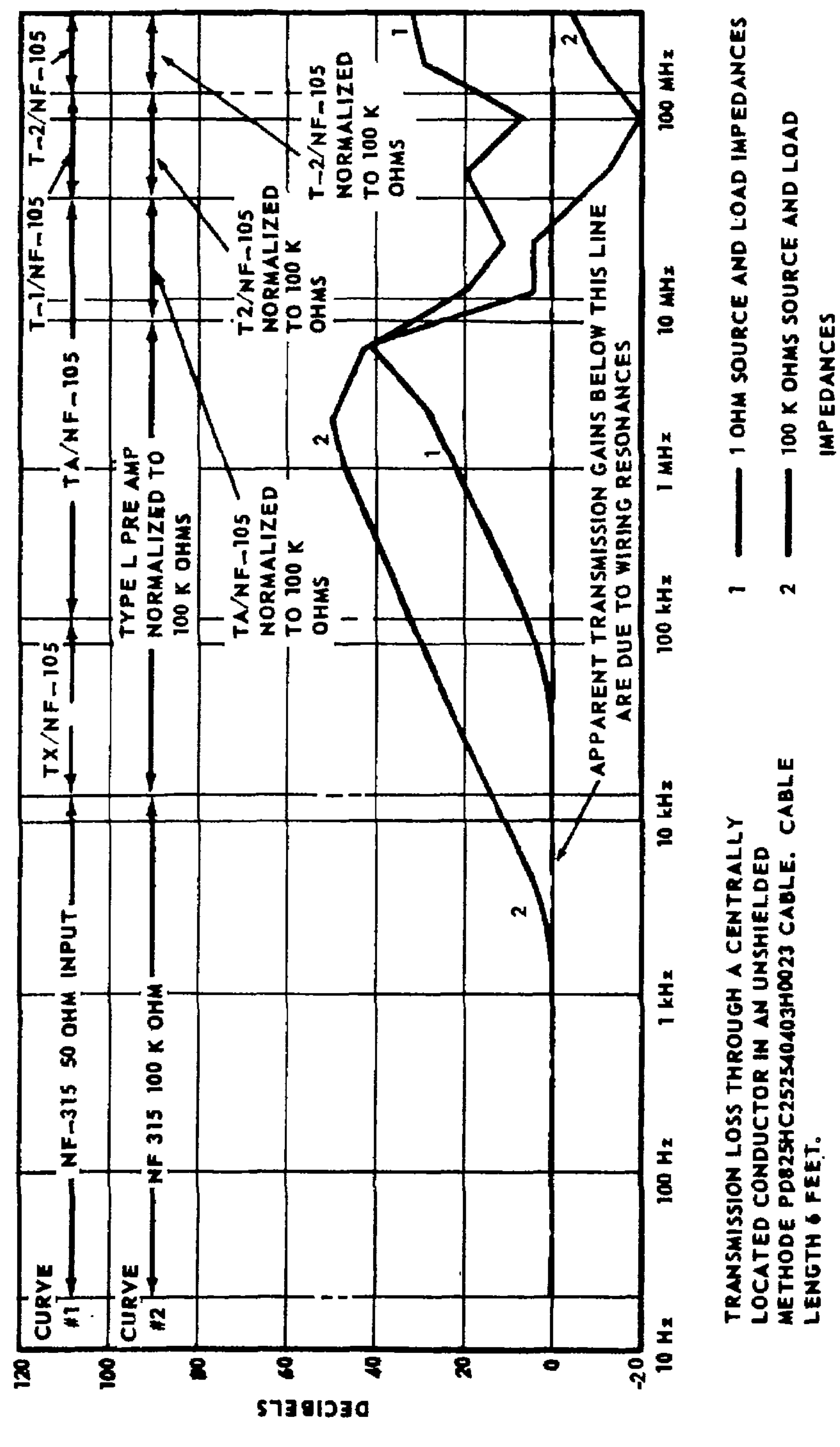
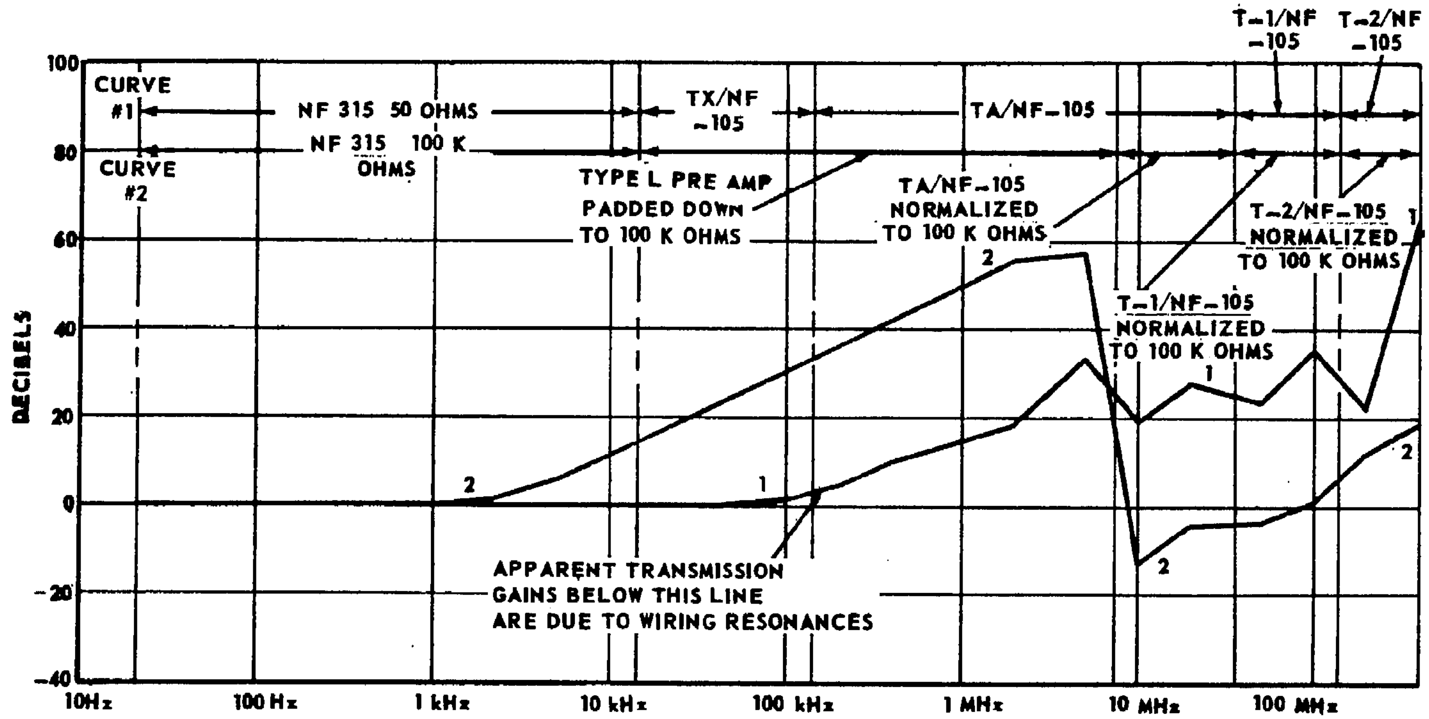


FIGURE 3-87. Transmission loss – unshielded cable.



TRANSMISSION LOSS THROUGH CENTER CONDUCTOR OF METHODE PD818H821T0292509 MESH SHIELDED CABLE. CABLE LENGTH 6 FEET.

1 —— 1 OHM SOURCE AND LOAD IMPEDANCES

2 —— 100 K OHM SOURCE AND LOAD IMPEDANCES

FIGURE 3-88. Transmission loss - mesh shielded cable.

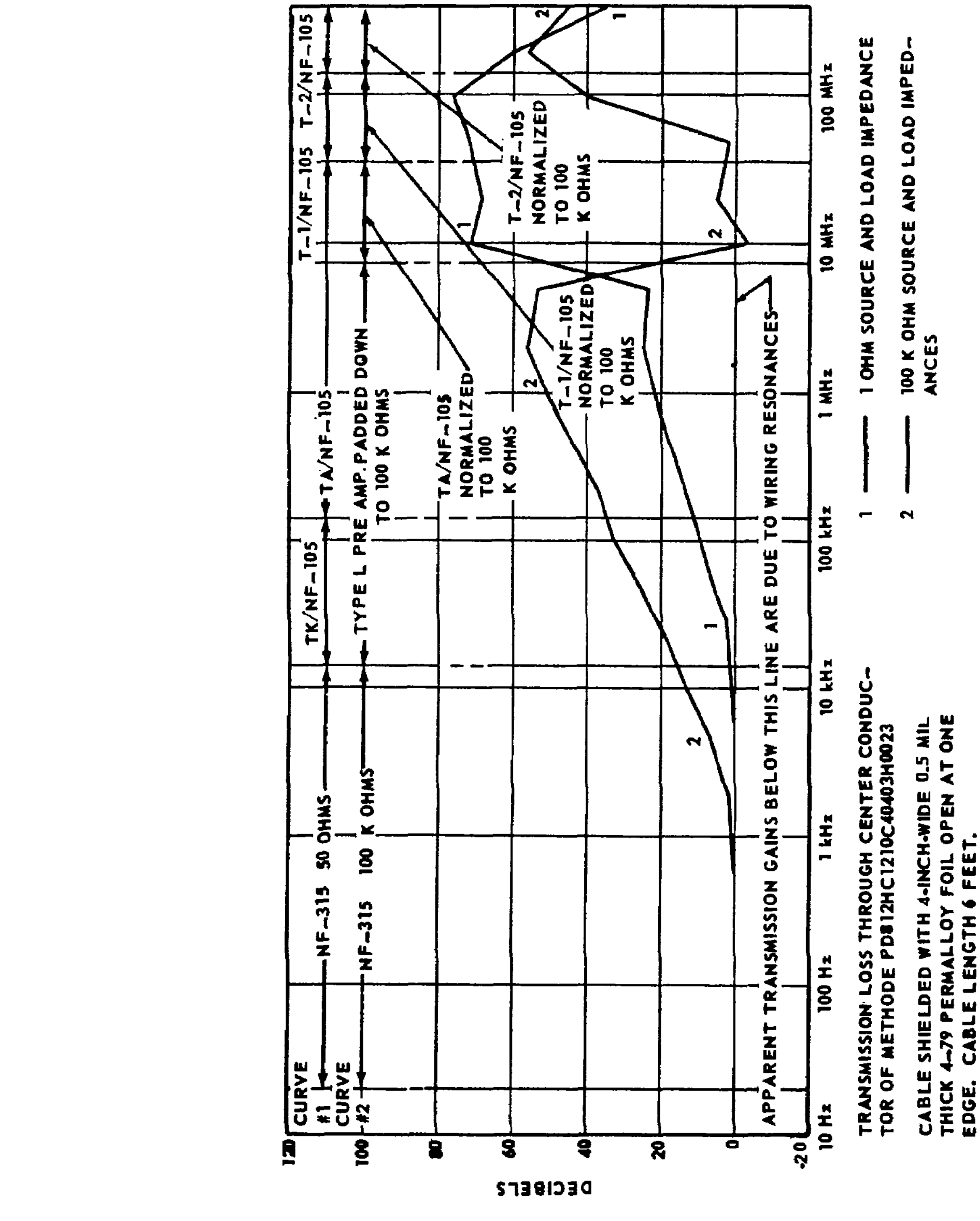
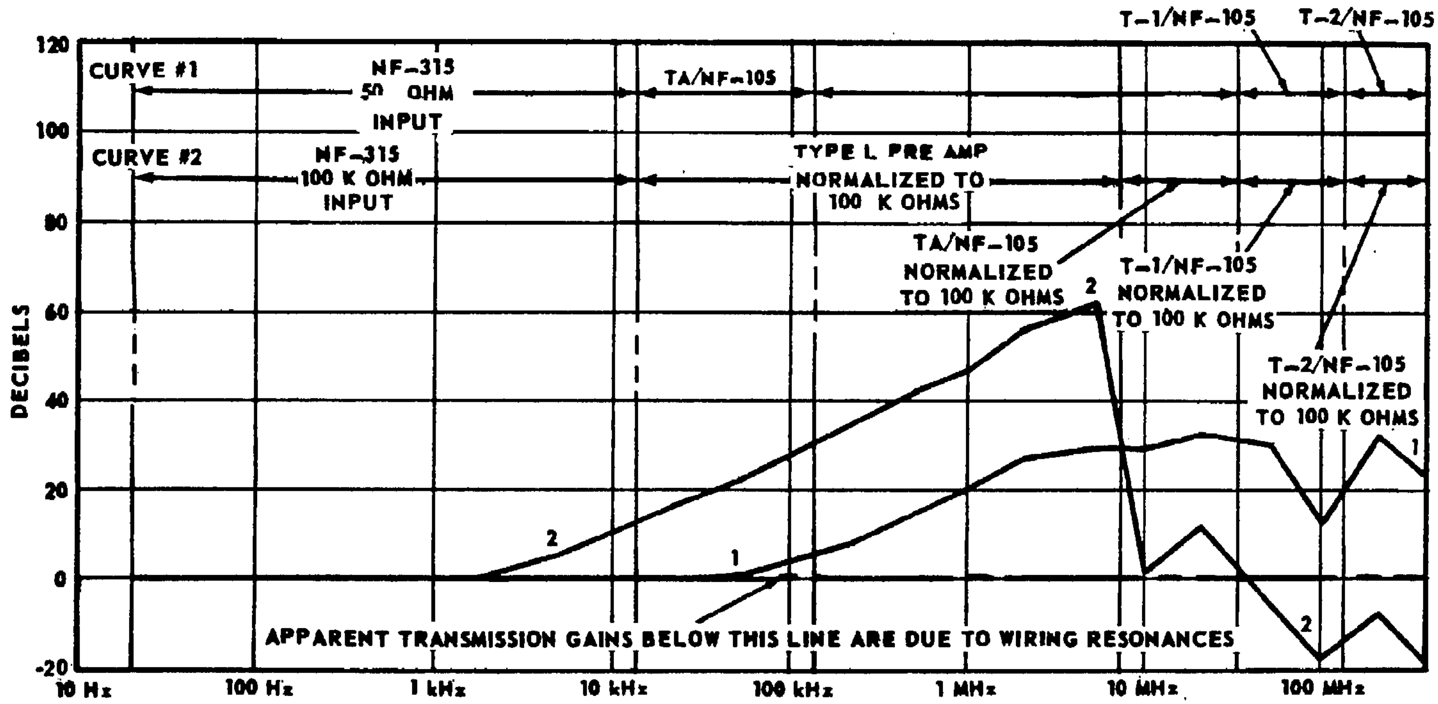


FIGURE 3-89. Transmission loss - solid 4-79 Permalloy shielded cable.



TRANSMISSION LOSS THROUGH ONE CONDUCTOR PF A SUPRENANT RC-4538N (300) JA 10 (15) SHIELDED TWISTED PAIR ROUND WIRE CABLE. CABLE LENGTH 6 FEET.

1 —— 1 OHM SOURCE AND LOAD IMPEDANCE

2 —— 100 K OHMS SOURCE AND LOAD IMPEDANCE

FIGURE 3-90. Transmission loss - woven copper shielded cable - RWC.

d. Assign cable network path routing from information generated in item c above including a specified quantity of spares for each network path. It can then assign, from the approved parts list, the type and quantity of cable.

e. The computer system can select the type and required quantity of approved connectors to meet the cable-termination requirements.

f. The computer system can sequentially assign identification numbers for each cable segment.

g. The computer system can prepare wiring and fabrication information for automatic placement and pictorialization on manufacturing drawings.

An optional, but desirable, subprogram within the mechanized design system would be a routine to optimize the cable routing and layout, in conjunction with equipment layout, according to some objective function (e.g., weight and total cost of materials and labor) within limits of specified constraints (e.g., location of mechanical obstructions, specified minimum percentage of spares in each path of the cable network, and EMC isolation requirements). This is compared with a simpler assignment of cable routing according to preestablished ground rules, which may give reasonably good, but less than optimal, results. Because of the complex nature of such a subprogram, it would be appropriate to add it to the system at a later date after the simpler routines are adequately checked out and operate satisfactorily.

3.2.9.2 Computer Program Design Requirements. The computer program and subroutines written to accomplish automated flat-cable design should be written and documented to meet the following requirements:

a. The program should provide the capability of allowing the user to extend the contents of data tables to add items previously undefined. This extended capability should be allowed with little or no program modification and without causing obsolescence of existing data files.

b. The program should be modularly constructed to facilitate addition of extended capabilities and to facilitate modifications. Each discrete function should become a subroutine. All subroutines should be under control of a supervisory routine or executive.

c. Programming should be done in a higher-level machine-independent language such as FORTRAN IV. This facilitates implementation of the program on more than one computer hardware configuration.

d. The program should be documented sufficiently to facilitate interpretation and modification. Comment cards should be associated with each decisive statement to reflect what the program is doing. Each subroutine should be documented in the following manner:

1. The purpose of the subroutine.

2. Input arguments.

3. Output arguments.

4. Error returns.

5. Internal variables used.

6. Restrictions to using the routine.

7. Names of all subroutines used by this subroutine.

3.2.9.3 Computer Description. The system described in this handbook, if written in a machine-independent language such as FORTRAN IV, could be run on almost any medium- or large-scale computer. The extent to which this system is implemented is the only major variable in the extent of machine configuration. Examples of machine configurations are the UNIVAC 1108, IBM SYSTEM 360 (MODEL 65), and the SDS 9300.

A basic system hardware configuration should include the following:

a. Console and mainframe - Used by the computer operator to control operation of the program.

b. 32K words of core memory - Holds system software and controls execution of program.

c. Card reader - Input options and control information.

d. Typewriter - Messages to operator for mounting of tapes, system errors.

e. Off-line printer - Generate printed output.

f. Magnetic tape units - Means for inputting standard files for program access.

g. Random access bulk storage unit - Store large amounts of data to be operated on by the program.

3.2.10 EMC Theory

3.2.10.1 EMC Fundamentals. As stated previously in Paragraph 3.2.3.2, a major source of electromagnetic incompatibility in a large electrical/electronic system is interconnection cabling within the system. This cabling network can be too massive for convenient laboratory testing, and so many spurious coupling problems may not be identified until late in the program; e.g., during acceptance testing or during early operational usage of the system hardware.

Analytical methods are available for use during design stages to help reduce the likelihood of serious system compatibility problems. These methods when judiciously applied can result in sizeable net savings of funds through the reduction of costly redesign and modification efforts. Moreover, their application can help avoid the compromise of system effectiveness or even personnel safety.

3.2.10.1.1 Spurious Coupling in Flat-Cable Systems. Spurious coupling in cabling is due to the sharing of a common conductor impedance, capacitive coupling between conductors, and magnetic coupling between conductors. It is also possible for the conductor to react to the electric and magnetic fields producing capacitive coupling and magnetic coupling to objects other than adjacent conductors as follows:

a. Common impedance coupling - When a conductor is shared by several circuits, the flow of current from one circuit through this common impedance produces a voltage drop that may affect the operation of other circuits sharing the same conductor. If the common impedance is a signal return for several similar channels, interchannel crosstalk will occur.

b. Electric coupling - When two conductors are in close proximity to each other, a small but definite capacitor is formed. The conductors are capacitor electrodes, and the cable insulation and any other nonconductive materials form the capacitor dielectric. Any varying voltage or one of the conductors is capacitively coupled into the impedances connected to the other conductor.

c. Magnetic coupling - The presence of a longitudinal conductor produces a small but definite inductance. When two conductors are in close proximity to each other, a transformer is produced because of the mutual inductance that exists between conductors. Any varying current flow in one conductor is magnetically coupled into the other conductor as induced voltage because of this transformer action.

d. Radiated susceptibility - A conductor immersed in an electric field acts like the output electrode of a capacitor, supplying energy to the terminating impedances at each end of the conductor. A conductor immersed in a magnetic field acts like the secondary winding of a transformer, supplying energy to the terminating impedances at each end of the conductor.

e. Radiated interference - When a potential is applied to a conductor, the conductor acts like the input electrode of a capacitor, creating an electric field that links the conductor to surrounding objects. When a current flows through a conductor, the conductor acts like the primary winding of a transformer, creating a magnetic field that links the conductor to surrounding objects.

3.2.10.1.2 Allowable Signal-to-Noise Ratio. The amplitude of the desired signal being transmitted by the conductor is a function of the terminating hardware design, and may vary between the extreme limits of a few hundreds of nanovolts to a few hundreds of volts, but will generally be between a few millivolts and a few tens of volts. Higher voltages require special cable and connector dielectric materials and configurations, while lower voltages require special cable and connector-shielding materials and configurations.

The transmitted signal resolution, accuracy, or signal-to-noise ratio determine what fraction of the total signal amplitude may be noise without significantly affecting system performance. The amplitude of the desired signal, and the fractional part of this amplitude which may be noise, determines the maximum allowable amplitude of noise in the susceptible circuit.

The total allowable amplitude of noise must be divided between the interference under discussion and the other sources of noise in the signal channel. If the sources of interference within the system and system environment have frequency spectrums outside the normal operational bandwidth of the susceptible circuit, the potentially desirable effects of susceptible circuit frequency discrimination in rejecting the undesired interference should be determined.

3.2.10.1.3 Required Decoupling Ratio Between Interference Source and Susceptible Circuit. The amplitude of the interfering signals being transmitted by adjacent conductors is a function of the terminating hardware design, and may vary between the extreme limits of a few milliamperes or millivolts and a few amperes or hundreds of volts, but will generally be between a few hundreds of milliamperes or millivolts and a few amperes or volts. Higher amplitudes often require special harness assemblies that would normally be routed separately, while lower amplitudes would not represent a significant hazard to other circuits and would often be classified as susceptible circuits. The amplitude of radiated interference is a function of the specific system environment, but generally has an equivalent conducted interference amplitude lower than the other conducted interference amplitudes found in the same system, except where high-power transmitters are involved. The amplitude which may appear as noise in the susceptible circuit without significantly affecting system performance determines the required decoupling ratio between the interference source and the susceptible circuit.

3.2.10.1.4 Spurious-Coupling Ratio of Interconnection Wiring. Any coupling circuit consists of a source, one or more transmission paths, and a load. Spurious coupling paths consist of common conductor impedances, mutual conductor capacitances, mutual conductor inductances, radiated electric fields, and radiated magnetic fields. Spurious signals from the sources of interference are coupled through these distributed transmission paths into the susceptible circuits. The amplitude of interference coupled into the susceptible circuit is determined by the amplitude of the source of interference and the ratio of interference division between the transmission path and the susceptible circuit terminating impedances.

3.2.10.1.4.1 Cable Capacitance. Cable capacitances for typical (0.075 C/L, 4-mil-thick Mylar) unshielded standard-density and high-density flat cable are given below:

Cable Type (Typical)	Cable Configuration	Mutual Capacitance PF/m
Standard-Density Unshielded	Side-by-side, same layer	21.5
	Over-and-under, tightly stacked multiple layer	165.0
High-Density Unshielded	Side-by-side, same layer	40.0
	Over-and-under, tightly stacked multiple layers	255.0

Specific values of mutual capacitance for many standard flat cable configurations, including several common conductor wiring connections for each cable configuration, are given in Paragraph 3.2.3.1.4.

Edge-to-edge capacitance is primarily a function of the dielectric thickness between conductors and the dielectric constant. Since the dielectric constant for commonly used insulating materials does not change drastically, and the dielectric thickness is determined primarily by the selection of either standard-density or high-density cable, only two values of edge-to-edge capacitance are required for most preliminary designs.

3.2.10.1.4.2 Cable Inductance. Cable inductance for typical unshielded standard and high-density flat cables running in a straight line is tabulated below:

Cable Type (Typical)	Cable Configuration	Mutual Inductance (μH/m)	Self Inductance (μH/m)	Coupling Coefficient
Standard-Density Unshielded	Side-by-side (normal cable lengths)	1.65	2.1	0.79
	Over-and-under (normal cable lengths)	1.95	2.1	0.93
High-Density Unshielded	Side-by-side (normal cable lengths)	1.66	2.0	0.83
	Over-and-under (normal cable lengths)	1.90	2.0	0.95

Typical copper and other nonferrous shielded cables should have inductance characteristics identical to unshielded cables, if the shield material is actually nonferrous. Inductance measurements on certain copper-shielded cables have indicated effective inductances approximately eight times greater than expected. The addition of copper foils, of known purity, to unshielded flat cable confirmed that the increased inductance was because of ferrous impurities in the copper shield foils and/or conductors.

Typical ferrous-shielded flat cables should have inductance values equal to the inductance values of unshielded flat cables, multiplied by the effective permeability of the ferrous shield. Since the ferrous shield has an extremely high permeability and an extremely thin-shield foil with a relatively small cross-sectional area, magnetic saturation, with a consequent reduction of shielding effectiveness and inductance at combined conductor currents in the order of tens of milliamperes, is a distinct possibility. Space isolation from nearby high-current conductors is necessary.

The high self-inductance of ferrous-shielded flat cable should reduce the bandwidth of the flat-cable transmission system significantly. The high mutual-inductance of conductors within ferrous-shielded flat cable should significantly reduce the frequency above which crosstalk becomes objectionable.

3.2.10.1.4.3 Cable-Shield Discontinuities at Terminations. When the shield is removed from a section of shielded flat cable to permit the installation of an unshielded connector or provide access to the conductors for other termination hardware, the stripped section is, in effect, unshielded flat cable and exhibits the electrical characteristics of the equivalent unshielded flat cable. Since the mutual capacitance and inductance (ferrous shielded only at low frequencies) of shielded flat cable are significantly lower than the equivalent unshielded flat cable, the insertion of even a short length of unshielded flat cable in a shielded transmission system reduced significantly the transmission loss through the spurious coupling path between conductors.

3.2.10.1.5 Terminating Impedances. Transmission lines are terminated in a source impedance, supplying the transmitted function, at one end and a load impedance, utilizing the transmitted function, at the other end. Complex transmission systems may interconnect multiple sources and loads. The magnitudes of complex termination impedances are frequency dépendent.

3.2.10.1.5.1 Function-Frequency and Time-Variable Characteristics. When the amplitude of the function exhibits a variation with time, this characteristic is defined in terms of either frequency or rate of change. Analog waveforms, exhibiting relatively smooth and continuous cyclic variations, are defined in terms of frequency and waveform. Digital and pulse waveforms, exhibiting rapid and discontinuous variations in instantaneous amplitude that are either cyclic, randomly repetitive, or nonrepetitive, are defined in terms of rates of change, waveform shape, and repetition frequency. These nonsinusoidal waveforms contain energy distributed over a broad frequency spectrum. The exact frequency versus amplitude distribution is dependent on the specific digital or pulse waveform and requires appropriate analysis for conversion from the time domain to the frequency domain. Where hardware is available, appropriate spectrum analyzers may be utilized to measure these functions directly in terms of frequency versus amplitude.

3.2.10.1.5.2 Frequency Dependence of Reactive Components. The resistive component of a termination is not frequency dependent; however, virtually all terminations contain reactive components, either lumped constant or distributed, that have a significant magnitude at some frequency of interest. The values of lumped-constant capacitances are readily obtained or measured. The reactance of a capacitance can be calculated or obtained from a reactance chart for the frequency of interest, and will exhibit a magnitude inversely proportional to frequency. The values of lumped-constant inductances are readily obtained or measured. The reactance of an inductance can be calculated, or obtained from a reactance chart for the frequency of interest, and will exhibit a magnitude proportional to frequency.

3.2.10.1.5.3 Transformers. Transformers are merely multiple inductors wound on a common core. If the inductance values are not specified, it is possible to measure the inductances of the windings if hardware is available, or to estimate the inductances if the transformer design details are available. With a knowledge of the transformer-winding inductances and interfacing circuit parameters, it becomes possible to calculate the reflected impedance presented by the connected transformer winding. The values of connected load resistances, frequency-dependent reactances, winding transformation ratios, and copper and core losses must be considered.

3.2.10.1.5.4 Distributed Parameters. Distributed capacitances and inductances frequently have significant reactances at surprisingly low frequencies when associated with either extremely high or low circuit impedances, or lumped constants having large reactive values of the opposite sign. Unfortunately, no comprehensive compilation of distributed parameter values for typical hardware configurations is in existence at this time. Therefore, the most practical approach to determining distributed parameter values is an estimate by personnel experienced in high-frequency design, radio-frequency interference, or electromagnetic compatibility.

3.2.10.1.5.4.1 Capacitors. The distributed series inductance of capacitors can be measured by placing a noninductive resistor with a value several times greater than the magnitude of the capacitive reactance at the lowest frequency of interest, in series with the capacitor, to form an essentially constant-current circuit. The output of a variable-frequency signal source is applied across this series circuit and maintained at a constant amplitude. The output voltage of the signal source will divide between the resistor and capacitor in proportion to the ratio of capacitive reactance to resistance. Since the noninductive resistor is not frequency-dependent, the voltage measured across the capacitor, as the frequency of the signal source is varied, provides an indication of capacitor impedance versus frequency.

At relatively low frequencies, where the magnitude of the series inductive reactance is small compared with the magnitude of the series capacitive reactance, the voltage variation across the capacitor will be inversely proportional to frequency. At relatively high frequencies, where the magnitude of the series inductive reactance becomes large compared with the magnitude of the series capacitive reactance, the voltage variation across the capacitor will be proportional to frequency. At some intermediate frequency, the two curves with opposing slopes cross, indicating a series resonance in the form of a broad negative peak.

The value of series impedance measured at and above this fundamental series resonant frequency cannot be reduced by increasing the value of capacitance used, because the series inductive reactance tends to increase with capacitance in a given capacitor configuration, lowering the fundamental series resonance, and dominating an even larger portion of the frequency spectrum. As the signal-source frequency is increased above the fundamental series resonant frequency, the capacitor impedance will alternate between a series of low-impedance series resonances and high-impedance parallel resonances that are a function of the capacitor configuration.

The capacitor fails to function effectively in this portion of the frequency spectrum and is ordinarily replaced or supplemented with an improved capacitor configuration or supplemented with external inductance to form a multiple-element filter. Some capacitor manufacturers have curves and other information describing the impedance of specific capacitor values and configurations versus frequency. Since the distributed parameters of capacitors are not ordinarily specified, large, uncontrolled variations in these values may be expected.

Conventional foil-wound capacitors, having terminations of the inserted tab type, have the lowest fundamental resonant frequencies. A very high-value, foil-wound, tantalytic capacitor might be resonant at audio frequencies. The same basic capacitors, having terminations of the extended foil type, have significantly higher fundamental resonant frequencies, but high-frequency performance is still severely limited by associated wiring. This same capacitor in a feedthru configuration has a much higher fundamental resonant frequency, and performance is essentially independent of associated wiring but imposes mounting limitations. The feedthru capacitor is a three-terminal device, similar to a filter, that is oridnarily mounted directly on the ground-plane structure to function properly, usually in a bulkhead type mount through a metallic panel to provide the improved input-output isolation necessary to take full advantage of the superior performance available from this configuration.

3.2.10.1.5.4.2 Inductors. The distributed shunt capacitance of inductors can be measured using the same techniques described for capacitors if the resistor has a value several times greater than the magnitude of the inductive reactant at the highest frequency of interest at relatively low frequency where the magnitude of the shunt capacitive reactance is relatively high compared with the magnitude of inductive reactance, the shunt capacitive current flow will be negligible and the voltage across the inductor will be proportional to frequency. At relatively high frequencies, where the magnitude of the shunt capacitive reactance becomes low compared with the magnitude of the inductive reactance, the shunt capacitive current flow will dominate the inductive current flow and the voltage variation across the inductor will be inversely proportional to frequency. At some intermediate frequency, the two curves with opposing slopes cross, indicating parallel resonance in the form of a broad peak.

Above this fundamental parallel resonance, the inductor impedance will alternate between a series of high-impedance parallel resonances and low-impedance series resonances that are a function of inductor configuration. The inductor fails to function effectively in this portion of the frequency spectrum and is ordinarily replaced or supplemented with an improved inductor configuration or supplemented with external capacitance to form a multiple element filter. Some inductor manufacturers supply shunt capacitance values or impedance/reactance curves and other information describing the impedance of specific inductor values and configurations versus frequency. Since the distributed parameters of inductors are not ordinarily specified, large uncontrolled variations in these values may be expected.

3.2.10.1.5.5 Impedance. The vector sum of the resistance, inductive reactance, and capacitive reactance provides the net low-frequency complex impedance of the terminating circuit but does not adequately describe the high-frequency response of the termination near and above the fundamental resonances produced by distributed parameters. The equivalent high-frequency circuit configuration, including all distributed parameters, is required for a meaningful circuit analysis.

3.2.10.1.5.6 Nonlinear Devices. The presence of nonlinear devices may result in several unusual effects. The impedance, both resistive and reactive, of circuitry associated with nonlinear devices becomes amplitude sensitive. Nonlinear devices produce distortion products not present in the original function. When severe nonlinearity occurs, alternating currents are rectified producing direct-current offset voltages and low-frequency modulation products that alter the characteristics of the original function.

3.2.10.1.5.7 Frequency Discrimination in Terminating Circuitry. The amplitude of interference coupled through a terminating circuit is determined by the amplitude of the source of interference at the input of the terminating device and the ratio of interference division between components of the function transmission path internal to the terminating device. When these components are reactive, the transmission path internal to the terminating device becomes frequency selective, often providing useful discrimination that supplements the shielding and transmission characteristics of the external interconnection cabling and intentional filtering.

3.2.10.2 Conductor Zoning Fundamentals

3.2.10.2.1 Introduction to Electrical Zoning of System Wiring. A major source of electromagnetic incompatibilities in any electrical/electronic system is the system interconnection wiring. Paragraph 3.2.10.1 explains spurious-coupling mechanisms, describes a method of determining the magnitude of extraneous energy tolerated by a circuit without impairment of function, and the degree of isolation required between circuits. A method is described for determining the actual degree of isolation provided by specific cable and conductor configurations transmitting specific interfering and susceptible functions, and terminated in a specific manner.

Comparing the degree of isolation required with the degree of isolation actually existing provides an indication of the safety margin either available or required for satisfactory system operation. This section describes a method of design that reduces the effort required to achieve an initial wiring configuration with optimum conductor-to-conductor isolation, and a high probability of obtaining the required electromagnetic safety margin. The application of this method of wiring design also ensures that differences between the characteristics of FCC and conventional RWC are adequately considered by personnel with minimal FCC experience.

3.2.10.2.2 Conductor Relationships. Every conductor is related electromagnetically to every other conductor in the wiring system. Some functions are natural sources of interference. Other functions are generally susceptible to interference. It is quite possible for one group of functions to be susceptible to interference from another group of functions, and simultaneously be a source of interference to a third group of functions.

Experience has shown that certain levels of interference and susceptibility are typical of the average electrical/electronic system, and that these levels can be extrapolated for use in more specialized types of systems. Because of the extremely broad spectrum of hardware involved, these levels are subject to wide variations and are utilized only as a preliminary design goal until more specific hardware design and test information become available. As confidence in system performance increases, arbitrarily specified, initial levels should be superseded or refined with analyses of actual system performance.

This section provides gross methods for the initial evaluation of wiring performance and a general approach for the refinement of this information as more specific information becomes available. The user must modify the assigned units of coupling and generalized approaches for improved compatibility with the particular system involved, as experience is accumulated, so that useful degrees of performance-prediction accuracy will be achieved.

3.2.10.2.3 Spurious-Coupling Circuit Configuration. A schematic of the interference circuit, the susceptible circuit, and the spurious-coupling circuit must be generated. The interference circuit should show the electrical configuration of the interference-carrying conductor and the associated return conductor, or other path, including any shield terminations. Conductor-termination circuitry at both ends should be shown in detail up to the input or output element of the first isolating device, such as a transistor. The susceptible circuit should be shown in the same detail. When large, reactive terminations and/or radio frequencies are involved, the distributed parameters of the terminating circuits must be considered.

The lengths of conductors, conductor breakouts, and shield terminations must be detailed. When conductors follow separate routes for part of the total path length, the common and separate path lengths must be dimensioned. Reasonable approximations are usually satisfactory. The cable assembly cross-sectional geometry and composite dielectric constant or generic materials description will be required so that the cable-distributed parameters can be either taken from the prepared tables or calculated. When interaction between conductors in separate strips of the cable assembly is being evaluated, the cable-stack geometry and the effect of air gaps, dielectric space strips, metallic spacer strips, and intervening shielded cables over all or part of the transmission path length must be considered.

The resultant spurious-coupling circuit schematic will resemble one of the basic sketches shown in Figures 3-91 through 3-96. The evolutionary process, from distributed parameters to equivalent lumped constant values, is described in Paragraph 3.2.3.2.2. This selection of electric- or magnetic-field configurations is determined primarily by the relationship existing between the conductor characteristic impedance and the termination impedances of the interference-generating and susceptible circuits. The conductor characteristic impedance can be obtained from Paragraph 3.2.3.1.

3.2.10.2.4 Termination Impedance Dependence of Spurious-Coupling Modes. Electric (capacitive) coupling is a voltage-related phenomenon that is independent of current flow. When the terminating impedances of a transmission line are high compared with the characteristic impedance of that particular conductor configuration, a predominantly electric field is generated or sensed. Magnetic (inductive) coupling is a current-related phenomenon that is independent of voltage level. When the terminating impedance of a transmission line is low compared with the characteristic impedance of that particular conductor configuration, a predominantly magnetic field is generated or sensed.

Both electric- and magnetic-field coupling occur when the terminating impedances of a transmission line are equal to the characteristic impedance of that particular conductor configuration; however, the magnitude of the total electromagnetic coupling is minimized. Additional advantages of a matched-impedance transmission system are highly efficient power transfer, minimum waveform distortion, insensitivity to frequency, insensitivity to cable length, resistive reflected impedances. minimum circuit loading, and a high degree of performance predictability.

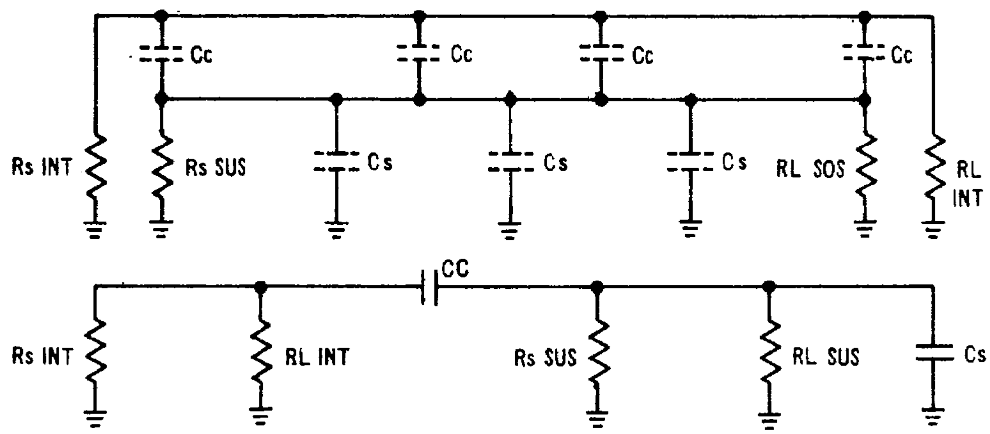


FIGURE 3-91. Electrical coupling - unshielded.

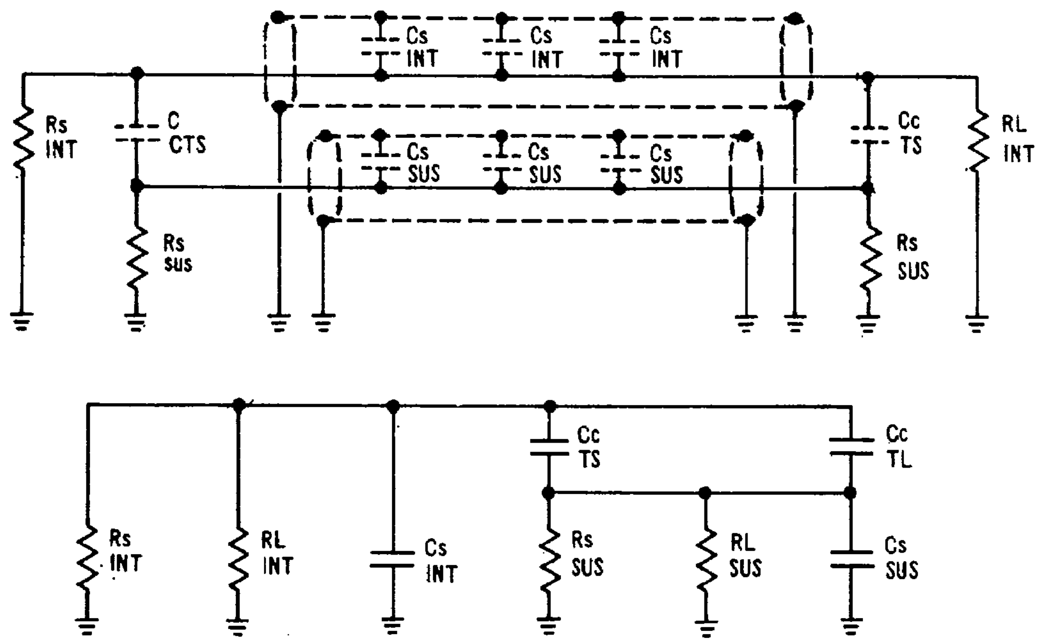


FIGURE 3-92. Electrical coupling - shielded.

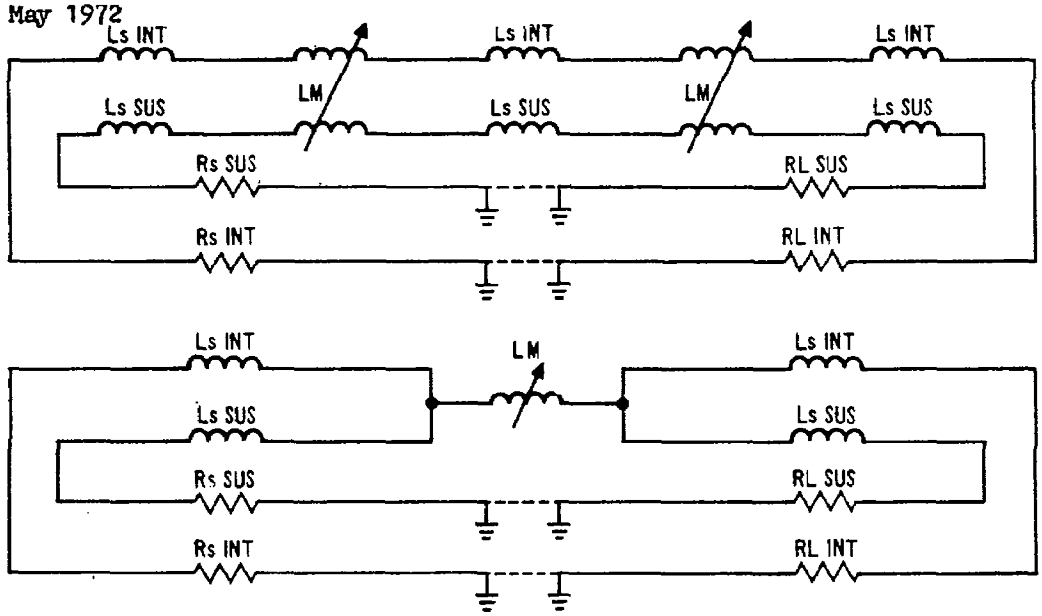


FIGURE 3-93. Magnetic coupling - unshielded.

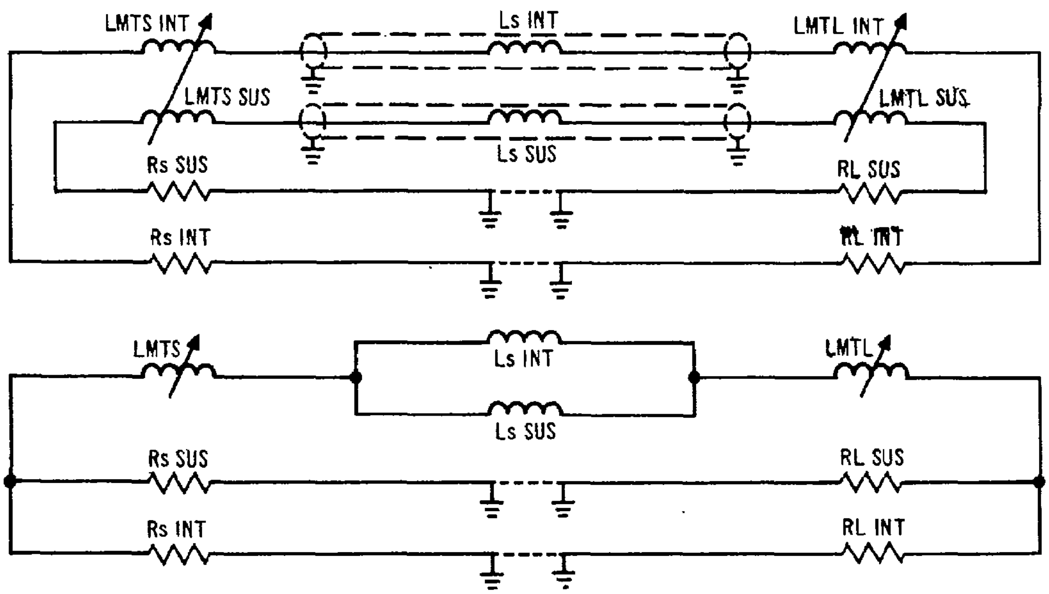


FIGURE 3-94. Magnetic coupling - shielded.

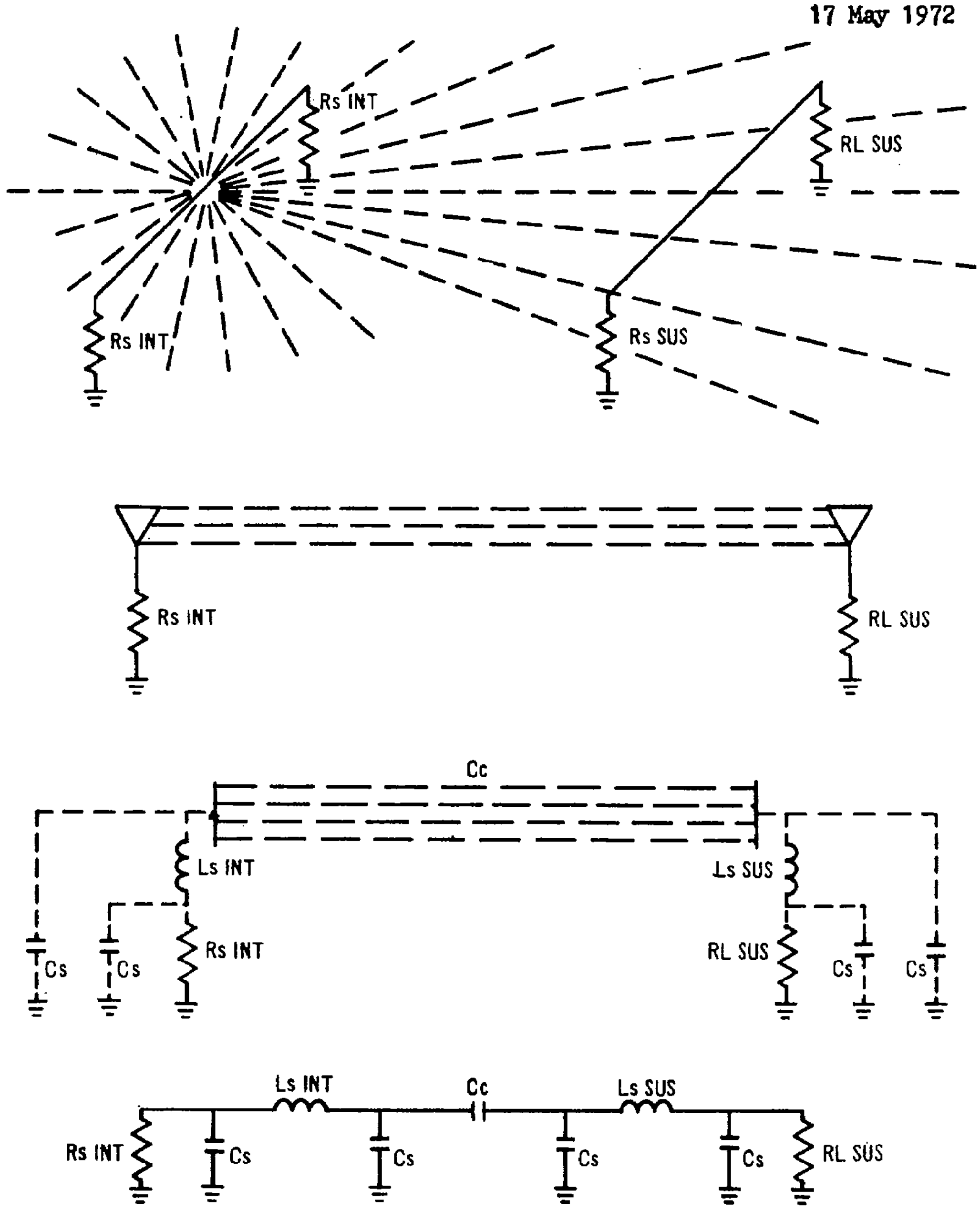


FIGURE 3-95. Radiated field coupling - electric field.

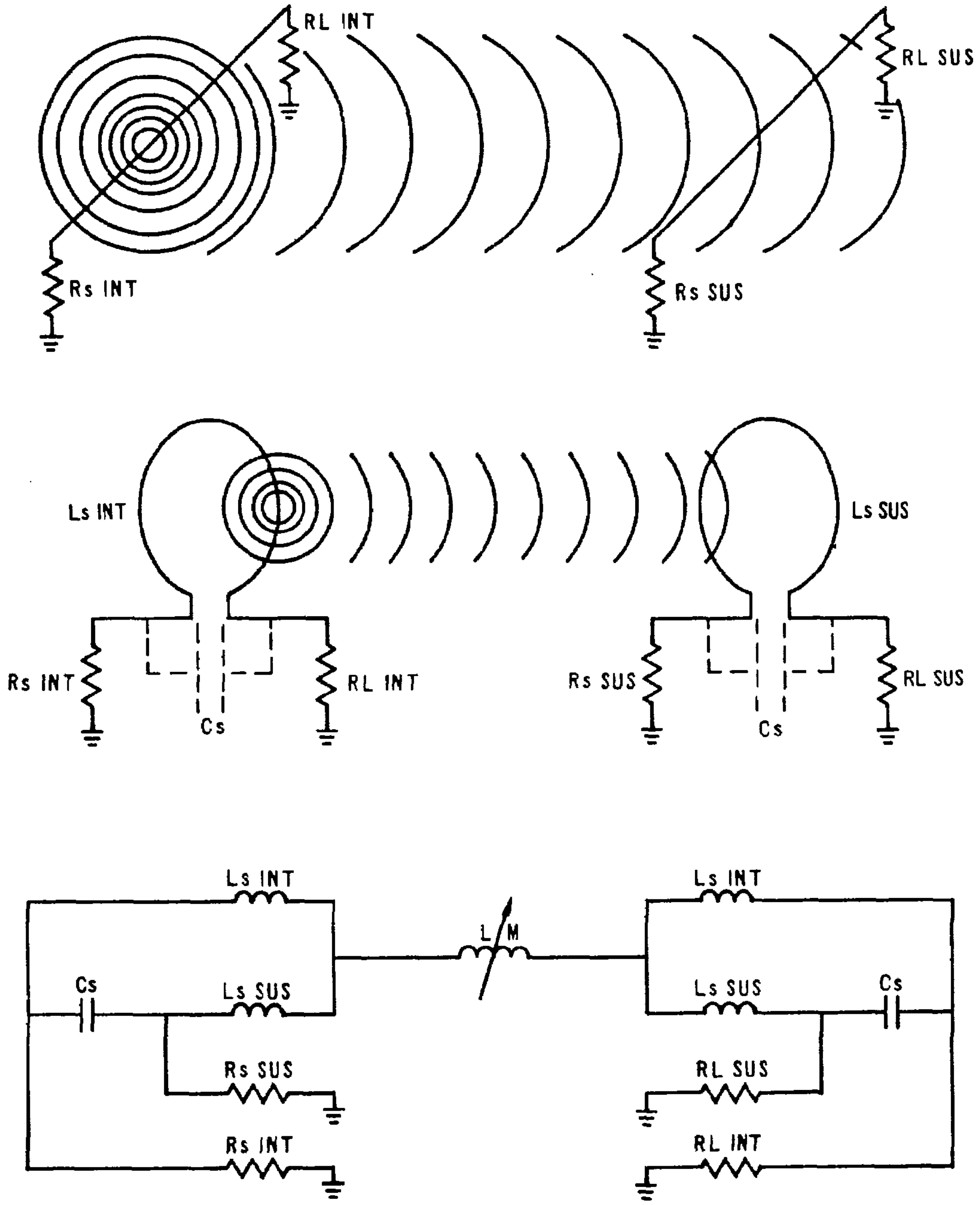


FIGURE 3-96. Radiated field coupling — magnetic field.

Both electric- and magnetic-field coupling also occur when the source and load terminating impedances have opposite magnitudes and differ greatly from the characteristic impedance of that particular conductor configuration. The magnitude of the total electromagnetic coupling is minimized when the geometric mean of the terminating impedances is equal to the characteristic impedance of that particular conductor configuration and when the terminating impedances differ from the characteristic impedance by the greatest possible magnitude. The low-impedance termination reduces the capacitively coupled voltage available while the high impedance termination limits the inductively coupled current available.

When the use of an impedance-mismatched transmission system is inevitable, this configuration minimizes spurious coupling but has the serious disadvantages of being the ultimate in inefficient power transfer, maximizing waveform distortion, extreme sensitivity to frequency, extreme sensitivity to cable length, reactive reflected impedances, reactive circuit loading, and poor performance predictability at medium and high frequencies. Low-frequency, low-level signal-type functions are not ordinarily affected by these limitations.

Minimum coupling will also occur between conductors when one conductor is terminated in low impedances and the other conductor is terminated in high impedances because the dominant generated field and dominant sensed field are incompatible and an inefficient transfer of spuriously coupled power occurs.

3.2.10.2.5 Determining Termination Impedances and Sensitivity to Spurious Coupling. Typical FCC configurations have characteristic impedances of a few tens of ohms for unshielded over-and-under or single conductors with nonferrous shields, to a few hundreds of ohms for unshielded, side-by-side or single conductors with structural returns. Ferrous shields increase these characteristic impedances from 10 times for low-grade steels to 100 times for high-permeability alloys that are not magnetically saturated.

When the termination is reactive instead of resistive, the equivalent reactance at the interference frequency is substituted for the resistance value. The values of capacitance and inductance, having similar reactive magnitudes at a variety of common power frequencies, is shown for each range of resistance/reactance levels.

If the shunt reactance is higher than the terminating resistance, use the resistance value. If the shunt reactance is lower than the terminating resistance, use the reactance value. If the series reactance is lower than the terminating resistance, use the resistance value. If the series reactance is higher than the terminating resistance, use the reactance value.

A high-impedance parallel resonance will occur at a frequency where the reactances of parallel-connected capacitances and inductances are equal. A low-impedance series resonance will occur at a frequency where the reactances of series-connected capacitances and inductances are equal. The increase or degrease in impedance, relative to the termination resistance, is a function of the resonant circuit "Q." Since the capacitor Q is normally high compared with the inductor Q, the circuit Q is limited by the inductor Q. Low-frequency inductors normally have a Q of less than 10. High-frequency inductors normally have a Q of between 10 and 100.

When the two ends of the conductor are terminated in widely differing values of impedance, the electric coupling will be determined by the two terminating impedances in parallel, and the magnetic coupling will be determined by the two terminating impedances in series. The geometric mean of the two terminating impedances will indicate which coupling mode is dominant and the extent to which that mode is dominant.

3.2.10.2.6 Frequency Dependence Spurious Coupling. The following tabulation indicates the degree of magnetic or electric coupling (on a logarithmic scale) that occurs at various frequencies for a given coupling circuit configuration:

Units of Coupling	Frequency	Equivalent Pulse Width
0	Under 3 Hz	Over 100 ms
1	3 to 30 Hz	10 to 100 ms
2	30 to 300 Hz	1 to 10 ms
3	300 Hz to 3 kHz	100 μs to 1 ms
4	3 to 30 kHz	10 to 100 μs
5	30 to 300 kHz	1 to 10 μs
6	300 kHz to 3 MHz	100 ns to 1 μs
7	3 to 30 MHz	10 to 100 ns
8	30 to 300 MHz	1 to 10 ns
9	Above 300 MHz	Under 1 ns

Basically, the frequency factor is a multiplier for the other variables involved. Frequencies and pulse widths in category zero a negligible spurious-coupling problem. Circuits with one unit or less of coupling rarely present a problem. Two units of coupling provide a problem only when extremely sensitive hardware is involved.

Three units of coupling may be a problem where sensitive hardware is used. Four units present a serious, spurious-coupling problem and may require special wiring practices. Five units will produce near-unity coupling in typical unshielded conductors, special wiring practices are required, and wiring resonances will occur where moderately long cable lengths of the order of 300 feet are involved. For six units of coupling, the same conditions apply except that resonance will occur in shorter cable lengths of the order of 30 feet, and for seven units of coupling, resonance occurs with cables of the order of 3 feet in length. Circuits with eight or nine units produce near-unity coupling in unshielded conductors, require special wiring practices, and will exhibit wiring resonances for all cable lengths.

It is essential that the transmission losses of shielded cable, regardless of shielding material and any unshielded conductors containing or coated with ferrous materials, be evaluated because both the undesired, spuriously coupled energy and the desired function may be attenuated significantly, even in the audio- and power-frequency spectrums. If unshielded cable is in intimate contact with a metallic structure, adjacent-shielded cables or adjacent-metallic spacer strips, a pseudosingle- or double-shielded flat cable is created, and the resulting transmission losses must be evaluated.

3.2.10.2.7 Length Dependence of Spurious Coupling. The degree of magnetic or electric coupling (on a logarithmic scale) that occurs at various lengths of unshielded conductors for a given coupling circuit configuration is tabulated below:

Units of Spurious Coupling	Unshielded Length of Conductors
0	Under 1 mm
1	1 to 10 mm
2	10 to 100 mm
3	100 mm to 1 m
4	1 to 10 m
5	10 to 100 m
6	100 m to 1 km
7	1 to 10 km
8	10 to 100 km
9	Over 100 km

Basically, the factor for the unshielded length of conductors is a multiplier for the other variables involved. Conductors that are shielded, or otherwise isolated from each other, have some length of unshielded conductors in the terminating hardware at distributors, junction boxes, and connector interfaces. The accumulated total of these shield breakouts is equivalent to an unshielded cable of the same length. When this accumulated length is less than the total circuit length divided by the shielding effectiveness ratio, relative to unshielded cable, the spurious coupling becomes dependent on the shielding effectiveness ratio instead of the accumulated total unshielded lengths of conductors. This condition will normally occur only in the extremely long cables associated with large land-based installations and large-wired communications systems unless sophisticated shielding techniques are utilized.

3.2.10.2.8 Amplitude Dependence of Electromagnetic Compatibility (Time-Varying Component). The degree of susceptibility or interference (on a logarithmic scale) associated with a conductor carrying various voltages and currents is tabulated below:

Units of Susceptibility	Voltage	Current
S4	Under 10 μV	Under 0.1 μA
S3	10 to 100 μV	0.1 to 1 μA
S2	100 μV to 1 mV	1 to 10 μA
S1	1 to 10 mV	10 to 100 μA
S0	10 to 100 mV	100 μA to 1 mA

Units of Interference	Voltage	Current
I0	100 mV to 1 V	1 to 10 mA
I1	1 to 10 V	10 to 100 mA
I2	10 to 100 V	100 mA to 1 A
I3	100 V to 1 kV	1 to 10 A
I4	Above 1 kV	Above 10 A

Experience has shown that certain levels of interference and susceptibility are typical of the average electrical/electronic system, and that these levels can be extrapolated for use in more specialized types of system. Because of the extremely broad spectrum of hardware involved, these levels are subject to wide variations and should only be utilized as a preliminary design goal until more specific hardware design and test information become available. As confidence in system performance increases, arbitrarily specified initial levels should be refined with the aid of measurement and analyses of actual system performance.

3.2.10.2.9 Resolution/Accuracy Dependence of Electromagnetic Compatibility. The degree of susceptibility or interference (on a logarithmic scale) associated with a conductor function having various resolution and/or accuracy requirements is tabulated below:

Units of Susceptibility	Resolution or Accuracy Required (%)
S4	Better than 0.1
S3	0.1 to 1
S2	1 to 10
S1	10 to 100
S0	On-off or other bilevel functions

Units of Interference	
I2	Average value for interference

Basically, the resolution/accuracy factor is a divider for the susceptible-conductor-function amplitude to provide a threshold amplitude of undesired signal above which the system will malfunction or exhibit an unacceptable error. The selection of a resolution/accuracy value for a component or subsystem must provide for both the division of the allowable tolerance between the components of the system chain and a division of tolerances between spurious coupling and other sources of error.

3.2.10.2.10 Functional Dependence of Electromagnetic Compatibility. Wiring-design personnel should consider the secondary characteristics of the function being analyzed when electrical wire zoning is in process. These secondary characteristics often dominate the primary characteristics of the function during an evaluation of system electromagnetic compatibility.

Direct-current power wiring would not be a source of interference if a truly pure source of direct current were available. Experience shows that many practical direct-current power distribution systems used to supply electrical/electronic hardware are modulated by a complex noise waveform having a peak-to-peak amplitude equal to 3 percent of the power supply voltage, and may have long-duration transient peaks equal to 30 percent of the power supply voltage when large electrical loads are applied or removed intermittently.

The complex noise waveform consists of both random noise and repetitive waveform created by the flow of instantaneously variable current demands through the common impedance of the power distribution wiring in response to functions generated in the connected hardware. The long-duration transients occur when high current demands on the power distribution system are made by large electrical devices and secondary power conversion hardware for these devices. The durations of these instantaneous current demands exceed the time constants of energy storage elements in practical passive-interference filters.

Based on the primary functional characteristics of a direct-current power distribution system, significant interference levels would not be anticipated. A close look at the secondary characteristics of this same direct-current power distribution system reveals the existence of a very significant interference source. Many other electrical/electronic functions have similarly significant secondary characteristics.

A repetitive pulse might appear harmless if the repetition rate is evaluated in sine-wave terms. An examination of the pulse rate-of-rise and rate-of-fall, or of pulse width, would reveal a much higher equivalent sine-wave frequency with a proportionate increase in coupling.

A nonrepetitive pulse, because of the actuation of a switching function, might appear significant on the basis of waveform or rate-of-rise and rate-of-fall when evaluated in repetitive pulse terms. An examination of the energy content of the single pulse and the time of occurrence relative to other functions in the system might well indicate that this same nonrepetitive pulse is harmless.

A pure sine-wave is normally considered the least offensive waveform, because the energy content is restricted to a single frequency and harmonics are not present. At low to mid-audio frequencies, spurious coupling of sine-wave energy is normally not a problem in typical interconnection wiring. Above the midaudio frequency range, even sine-wave energy may produce serious spurious-coupling problems in typical cabling. In the supersonic and radio-frequency spectrums, near-unity coupling often occurs. Even at low frequencies, a small amount of sine-wave energy, offset slightly from the frequency of an alternating current power or reference source, might appear as a false error signal in a servo system.

Because of the extremely broad spectrum of hardware involved, specific recommendations for the evaluation of conductor function cannot be made. The users must become thoroughly familiar with the system theory of operation and with hardware design details so that they will be aware of secondary considerations that may affect the functional separation of conductors. The previous examples are intended to point out the inconsistencies that may occur if the primary function is taken at face value without an adequate evaluation of secondary considerations.

3.2.10.2.11 Frequency Dependence of Conductor Transmission Losses. The series inductance and shunt capacitance of a conductor form a distributed low-pass filter that limits the bandwidth of the conductor. Reactive terminations will interact with the distributed parameters of the conductor and alter the inherent cable bandwidth. A match-impedance transmission system, with terminating impedances equal to the conductor characteristic impedance, will have a -3-decibel (50-percent power loss or 29-percent voltage or current loss) upper frequency limit approximately equal to the frequency at which the reactance of the conductor series inductance becomes equal to the reactance of the conductor shunt capacitance. Above this frequency, the transmitted function will exhibit a transmission loss of 12 decibels per octave (94-percent power loss or 75-percent voltage or current loss as frequency is doubled) or 40 decibels per decade (10,000 times power loss or 100 times voltage or current loss as frequency is increased 10 times).

A typical, matched-impedance, nonferrous, shielded transmission line would have a -3-decibel bandwidth of approximately 5 megahertz for a 1-meter length, approximately 500 kilohertz for a 10-meter length, and approximately 50 kilohertz for a 100-meter length. The -3-decibel frequency is inversely proportional to cable length.

A ferrous-shield material would lower these -3-decibel frequencies by an additional factor of approximately 100 for high-permeability alloys such as 4-79 Permalloy or a factor of approximately 10 for commercial steels if the shield is magnetically unsaturated.

3.2.10.2.12 Termination Impedance Dependence of Conductor Transmission Losses. The series inductance and shunt capacitance of a conductor form a distributed low-pass filter that limits the bandwidth of the conductor. When a matched impedance transmission line condition exists, with the terminating impedances equal to the characteristic impedance of the conductor, the reactances of the conductor series inductance and shunt capacitance vary symmetrically about the terminating impedance value, as frequency changes, and make equal contributions to the transmission losses experienced by the transmitted functions.

When the transmission line is mismatched, one of the reactive elements in this distributed low-pass filter becomes relatively ineffective as a frequency discriminating device; therefore, the -3-decibel (50-percent power loss or 29-percent voltage or current loss) upper frequency limit is approximately equal to the frequency at which the reactance of the effective reactive element becomes equal to the composite terminating impedance. Above this frequency, the transmitted function will exhibit a transmission loss of 6 decibels per octave (75-percent power loss or 50-percent current or voltage loss as frequency is doubled) or 20 decibels per decade (100 times power loss or 10 times voltage or current loss as frequency is increased 10 times).

In the electrostatic-coupling mode, where the paralleled terminating impedances are high compared with the characteristic impedance of the conductor, the frequency at which the series inductive reactance exceeds the paralleled terminating impedances is considerably higher than the frequency at which the shunt-capacitive reactance falls below the paralleled terminating impedances. Therefore, the shunt capacitance dominates the high-frequency transmission losses. The conductor is relatively useless as a transmission line at the still higher frequencies where the series inductive reactance becomes significant.

In the magnetic-coupling mode, where the seriesed terminating impedances are low compared with the characteristic impedance of the conductor, the frequency at which the shunt-capacitive reactance falls below the terminating impedances is considerably higher than the frequency at which the series-inductive reactance exceeds the seriesed terminating impedances. Therefore, the series inductance dominates the high-frequency transmission losses. The conductor is relatively useless as a transmission line at the frequencies where the shunt-capacitive reactance becomes significant.

A deliberately impedance-mismatched transmission system, in which one terminating impedance is selected lower than the conductor characteristic impedance, and the other terminating impedance is selected higher than the conductor characteristic impedance by similar ratios, has the conductor characteristic impedance at the geometric mean of the terminating impedances. The bandwidth characteristics will be determined by the series-inductive reactance and shunt-capacitive reactance of the conductor as elements of a distributed low-pass filter.

The bandwidth of this transmission system will be similar to that of a matched-impedance transmission system; however, this system has all the disadvantages of mismatched transmission systems, including inefficient power transfer, waveform distortion, sensitivity to frequency, sensitivity to cable length, reactive reflected impedances, reactive circuit loading, and poor performance predictability at medium and high frequencies.

3.2.10.2.13 Analyzing the Electromagnetic Compatibility of Two Conductors. The following steps define the method for analyzing the electronic compatibility of two conductors:

a. Determine the allowable level of undesired energy that may be spuriously coupled into the susceptible circuit without causing the system to malfunction or produce an unacceptable error. Error analyses made by the cognizant design engineer during mandatory design analyses performed in accordance with the requirements of good engineering practice and the system specification will provide the necessary basic information for the derivation of the allowable susceptibility level. The allowable susceptibility level will be some fractional part of the total allowable malfunction or unacceptable error level, because spuriously coupled, undesired energy is only one of several noise sources that may be present simultaneously in the system.

   The allowable susceptibility level may vary with frequency if the susceptible circuit provides frequency discrimination in the spectrum of interest. The effects of direct-current shift and modulation detection should be considered. Beat-frequency generation, in carrier-type amplifiers, including two-phase servos, in the presence of harmonically related, spuriously coupled energy, should be considered. An adequate safety margin should be included to allow for performance-prediction uncertainties. Good engineering practive and most specifications require a minimum safety margin of 6 decibels, or one-half the voltage or current threshold, and one-fourth of the power threshold. Safety margins in excess of 6 decibels should be value engineered because of the extra effort that may be required to achieve this increased confidence level.

b. Determine the ratio by which the interference source amplitude must be reduced to achieve the acceptable level of spuriously coupled, undesired energy at the susceptible circuit. This is the required isolation loss ratio. If the source of interference has an amplitude that varies with frequency and/or the susceptible circuit has a threshold level that varies with frequency, the required isolation ratio may vary with frequency.

c. Determine the ratio by which the interference source amplitude is actually reduced at the susceptible circuit. This is the actual spurious-coupling loss. The actual spurious-coupling loss may be expected to vary with frequency.

   1. Generate a schematic of the interference source circuit, the susceptible circuit, and the spurious-coupling circuit, including all source and load termination circuitry up to the input or output element of an isolation device such as a transistor.

   2. Determine which coupling modes exist and become dominant in various parts of the frequency spectrum. Both coupling modes may be significant simultaneously, if the matched and the deliberately mismatched-impedance transmission-line conditions exist.

   3. Calculate the losses that occur when energy, at a variety of frequencies, passes through the spurious-coupling network. Be sure to include all critical frequencies related to both the interference function and the susceptible function. This spurious-coupling network is merely a frequency-sensitive voltage, current, or power divider.

      If the network appears to be too complex for convenient manipulation, break the circuit down into several subsections that are easier to analyze. When analyzing the network, look for any interactions that may occur between isolated subsections of the circuitry when these subsections are combined to form a complete circuit. The reactance chart is a convenient tool that simplifies this analytical process considerably.

d. Determine the magnitude of the existing safety margin or the degree of additional isolation required to produce an acceptable safety margin.

   1. If the actual spurious-coupling loss has a greater magnitude than the required isolation ratio, divide the actual spurious-coupling loss ratio by the required isolation ratio to determine the existing safety-margin ratio.

   2. If the required isolation ratio has a greater magnitude than the actual spurious-coupling loss ratio, divide the required isolation ratio by the actual spurious-coupling loss ratio to determine how much the spurious-coupling loss ratio must be increased.

e. Determine what method will be used to increase the actual spurious-coupling loss ratio.

   1. Increasing the separation distance between two conductors will reduce the mutual capacitance and mutual inductance of the conductors and increase the spurious-coupling loss.

   2. Grounding guard conductors between the two conductors will reduce the mutual capacitance and mutual inductance by the creation of a pseudoshield and increase the spurious-coupling loss. Guard conductors, grounded at one end only, provide electric-field isolation only. Guard conductors, grounded at both ends, provide both electric- and magnetic-field isolation.

   3. Dielectric isolation-spacer strips can be used to increase the separation distance between layers of stacked cables when moderately susceptible and moderately interfering conductors are not available to create a buffer zone, a relatively small improvement is required, and schedule limitations preclude the rearrangement of cabling.

4. Metallic isolation-spacer strips increase the isolation between layers of stacked cables, with performance similar to electrostatically shielded cables, but have the disadvantage of incomplete isolation in the connector region; therefore, the potential shielding effectiveness of the cable shield is degraded significantly. Moderate increases in electric-field isolation will be achieved with long cables, and very little improvement will occur when used with short cables. Magnetic-field isolation will be negligible except at radio frequencies where high transmission losses through the cable tend to limit the usefulness of shielded cable. A shielded cable placed between unshielded cables is equivalent to a metallic-isolation spacer strip.

5. Nonferrous-shielded cable greatly increases the electric-field isolation between stacked layers of cable but produces a negligible magnetic-field improvement except at radio frequencies where high transmission losses through the cable tend to limit the usefulness of shielded cable. Shielded cable also serves as a pseudometallic, isolation spacer strip when placed between layers of unshielded cable.

6. Ferrous-shielded cable greatly increases both the electric- and magnetic-field isolation between stacked layers throughout the frequency spectrum. The ferrous-shielded cable has a limited audiofrequency bandwidth that is inversely proportional to length and the square root of the effective shield-permeability. A ferrous-shielded cable serves as a pseudometallic, isolation spacer strip when placed between layers of unshielded cable but does not provide magnetic-field isolation throughout the frequency spectrum in this application.

7. Adjacent conductors in a cable used as "hot" and return conductors, a conductor pair, either floating or balanced, or conductor sets in a multiple-phase circuit, sense or radiate almost equal induced-interference levels that tend to cancel each other at the susceptible circuit.

   This is virtually the same effect produced by twisting conductors. The resultant pseudotwist greatly increases the spurious-coupling loss. This conductor configuration supplements and complements, but is not a complete substitute for the shielded cable.

   The increase in the spurious-coupling loss, when compared with widely separated conductors, is equal to the average amplitude of the induced interference in the individual conductors, divided by the difference in amplitude between conductors in the circuit. Over-and-under conductors, separated by the thinnest practical layer of dielectric, are superior to side-by-side conductors on conventional centerline spacings.

8. Unshielded conductors that contain any ferrous materials, either alloyed or deposited, exhibit the high-frequency transmission-loss characteristics of the equivalent ferrous-shielded conductors. Ferrous or ferrous-coated, unshielded conductors form a distributed low-pass filter capable of rejecting radio-frequency energy, without the complications introduced by shielding, if the ferrous material is maintained in a magnetically unsaturated state.

   The ferrous-coated configuration would saturate at relatively low levels. Since the transmission loss of this conductor configuration is amplitude-sensitive, it would be feasible to produce a cable that had limited bandwidth when used to carry low-amplitude functions, and a relatively unlimited bandwidth when used to carry high-amplitude functions, provided that the surrounding environment was free of high-current conductors and other sources of strong magnetic fields.

f. Using the new cable configuration, recalculate the actual spurious-coupling loss ratio and redetermine the existence of an adequate safety margin.

Repeat the foregoing process, as required, until an optimal wiring design for all the circuit combinations involved is achieved for the system.

3.2.10.3 Shielding Fundamentals. Shielding effectiveness is the reduction in spurious coupling of energy from one conductor to another, compared to equivalent unshielded conductors, that occurs when the electromagnetic environments of the two conductors are isolated by the insertion of a shielding medium between the conductors. Shielding effectiveness is usually measured in decibels.

3.2.10.3.1 Theory of Shields (Types of Fields Encountered). Three interrelated types of fields must be considered during any shield design. The plane wave or far field exists when the shield intercepts energy at a point distant from the source of energy in terms of wavelengths, and the resultant wavefront has a negligible curvature. The plane wave contains both electric- and magnetic-field components in a known relationship. The plane wave is not normally considered at low frequencies because the large separation distances required to produce low-frequency plane waves generally attenuate the received energy to acceptable low levels.

The near field, or induction field, exists when the shield intercepts energy at a point near the source of energy in terms of wavelengths, and the resultant wavefront has a significant curvature. The near field contains both electric- and magnetic-field components, but these components lack the relatively fixed relationship that exists between them in the far field; therefore, they are considered separately. The near field and its components, the electric and magnetic fields, are not normally considered at relatively high radio frequencies because the extremely small separation distances required to produce relatively high frequency near fields rarely exist in practical systems and hardware.

The electric field is created by the existence of a potential between two conductive objects isolated by a dielectric and is the mechanism by which a capacitor functions. Transducers such as the monopole and dipole antenna, used to generate and sense electric fields, are basically capacitor plates separated by the propagation distance as a dielectric. Since the mutual capacitance of these capacitor plates is extremely small at any reasonable separation distance and the capacitively coupled current in the circuit loop is negligible, a virtual open circuit exists. Therefore, the electric field is dependent on the existence of a voltage between objects, is not significantly dependent on the flow of current in either the transmitting or receiving circuits, and, as a result, is a high-impedance phenomenon.

The magnetic field is created by the existence of a current flow through a conductive object, which in turn generates a reciprocal current flow in conductive objects and is the mechanism by which a transformer functions. Transducers, such as the loop antenna and current probe used to generate and sense magnetic fields, are basically transformer windings separated by the propagation distance as a transformer core. Since the reactance of the mutual capacitance between windings is extremely high compared with the inductive reactance of the transformer windings, the capacitively coupled voltage across the secondary circuit and the capacitively coupled current through the secondary circuit are limited to relatively low values at any reasonable separation distance, and a near short circuit exists at the secondary winding. Therefore, the magnetic field is dependent on the flow of current through conductive objects and produces reciprocal current flows in conductive objects, is not significantly dependent on the existence of a voltage between objects, and, as a result, is a low-impedance phenomenon.

3.2.10.3.2 Type of Losses Contributing to Shielding Effectiveness. Shielding effectiveness for electric, magnetic, and plane-wave fields is the sum of absorption and reflection losses.

3.2.10.3.2.1 Absorption Loss. When a conductive object is immersed in a magnetic field, a current flow is produced in the object which, in turn, generates a mirror image of the original magnetic field and, in effect, cancels the original magnetic field. Since the object is not a perfect conductor, the secondary field generated is not a perfect replica of the original field, and the existence of this unbalance produces magnetic-field attenuation, rather than perfect magnetic field cancellation, in the practical case. When an object having a high-magnetic permeability is immersed in a magnetic field, the magnetic field tends to detour through, or be concentrated in, the high-permeability material, since high-permeability materials have a low-magnetic resistance or reluctance. If the high-permeability material surrounds another object, the magnetic field detours through the low reluctance of the high-permeability material in preference to flowing through the high-reluctance path of a nonferrous material. Diverting the magnetic field from the interior of the shielded object is equivalent to eliminating the magnetic field. Since the degree of diversion is proportional to the permeability of the ferrous material, and infinitely high permeabilities are not available in practice, a small, residual magnetic field continues to exist, and the magnetic field is attenuated rather than eliminated.

Both of these effects contribute to the absorption loss through the shielding material to a degree dependent on the conductivity and permeability of the materials used.

3.2.10.3.2.2 Reflection Loss. A basic requirement for the efficient transfer of power from one circuit or medium to another is that the source and load impedances be equal or matched. When the impedance of the shield, considered as an inadvertent antenna, does not match the impedance of the electric, magnetic, or plane-wave field, the energy is reflected rather than transferred from one circuit or medium to the other, and the efficiency of the antenna as a transducer is decreased significantly. This decrease of energy transfer or conversion efficiency is known as the reflection loss. The reflection loss is actually the sum of the interface mismatch losses or both side of the shield. The shield is a receiving antenna on one side and a transmitting antenna on the other side.

3.2.10.3.2.3 Total Shielding Effectiveness. The total shielding effectiveness of a shielded layer is the sum of the absorption and reflection losses for the type of field under consideration. When the shield comprises multiple layers, either individual laminated, or coated sheets, the total shielding effectiveness of the composite assembly is equal to the sums of the individual shielding layers.

The shielding effectiveness of any given shield configuration is a function of the shielding material used, the thickness of shielding material, frequency, the type of field being shielded against, the geometry of the interference source, shield assembly and susceptible item, and the configuration of any perforations or discontinuities in the shield.

3.2.10.3.3 Loss Characteristics of Shielding Materials. The two basic types of materials used for shielding are the nonferrous materials such as copper and aluminum that cannot be magnetized and the ferrous materials such as iron, steel, and nickel-iron alloys that are magnetic. The ferrites have electrical properties similar to the ferrous metals, but generally lack the mechanical properties required of a shield, and are limited to applications such as cup cores for self-shielding, high-frequency transformers, and other usages not related to shielding.

3.2.10.3.3.1 Reflection Losses. Any metal of any thickness will provide reflection losses that are a function of the material used, frequency, the geometry of the source of interference, shield assembly and susceptible item, and the type of field being shielded against. Electric-field reflection losses vary inversely with frequency at the rate of 30 decibels per decade or 9 decibels per octave. Plane-wave reflection losses vary inversely with frequency at the rate of 10 decibels per decade, or 3 decibels per octave and are not dependent on geometry. Magnetic-field reflection losses vary at the rate of 10 decibels per decade or 3 decibels per octave at the extremes of the frequency range but have a nonlinear characteristic in the midportion of the frequency spectrum with the losses varying proportionately with frequency at the higher frequencies and inversely with frequency at the lower frequencies. The transition points are dependent on geometry and shield material.

High-conductivity, nonferrous metals provide the highest reflection losses in an electric field because the shield has a low impedance that is mismatched to the high-impedance electric field and relatively little power is transferred between the electric field and the shield. High-resistivity materials provide a better impedance match to the electric field; therefore, the reflection losses are lower. As frequency increases, the inductive reactance of the shield increases providing a better impedance match to the electric field; therefore, the reflection losses vary inversely with frequency. Ferrous materials have an inductance that is considerably higher than nonferrous materials because of the inductance multiplication provided by the magnetic permeability of these materials. Since the inductive reactance of a ferrous shield is considerably higher than that of a nonferrous shield, the ferrous shield provides a better impedance match to the electric field; therefore, the reflection losses are lower.

Plane-wave reflection losses have a different rate of change with frequency and are not geometry dependent but behave like electric-field reflection losses in most other respects.

Magnetic-field reflection losses have a complex relationship to frequency and geometry that is material dependent. High-conductivity, nonferrous metals do not exhibit useful magnetic reflection losses in the power and audiofrequency spectrum with the normally encountered interference source-to-shield separation distances. At frequencies above the audio spectrum, useful reflection losses are obtained. High-permeability ferrous metals do not exhibit useful magnetic reflection losses in the audio and low video frequency spectrum with the normally encountered interference source-to-shield separation distances. At subsonic frequencies and frequencies above the medium video spectrum, useful reflection losses are obtained. At frequencies where useful losses are achieved, the magnetic reflection losses vary proportionately with frequency at the rate of 10 decibels per decade or 3 decibels per octave, except for the case of subsonic frequencies. At subsonic frequencies, where useful losses are achieved, the magnetic reflection losses vary inversely with frequency at the rate of 10 decibels per decade or 3 decibels per octave.

3.2.10.3.3.2 Absorption Losses. Any metal will provide absorption losses that are a function of the material used, material thickness, and frequency. Absorption losses are proportional to the thickness of the material used. Absorption losses, in decibels, increase with the square root of frequency.

Nonferrous metals, in the commonly used thicknesses, do not have useful absorption losses in the power and audiofrequency spectrum. Absorption losses become significant at approximately 10 megahertz and increase rapidly to extremely high values beyond that point.

Ferrous metals of modest permeability, such as cold-rolled steel, in the commonly used thicknesses, do not have useful absorption losses in the power and low-to-medium audiofrequency spectrum. Absorption losses become significant at approximately 1 megahertz and increase rapidly to extremely high values beyond that point.

Ferrous metals of high permeability, such as 4-79 Permalloy in the commonly used thickness, do not have useful absorption losses in the power and audiofrequency spectrum. Absorption losses become significant at supersonic frequencies and increase rapidly to extremely high values beyond that point.

3.2.10.3.3.3 Secondary Reflections. Secondary reflections occurring within the metallic-shielding structure introduce minor errors when neglected if the shield has a low attenuation factor. Most shields are designed for medium-to-high attenuation factors that make the calculation of secondary reflections unnecessary.

3.2.10.4 Electromagnetic Compatibility Tests, Analyses, and Curves. Electrostatic Crosstalk, Magnetic Crosstalk, and Transmission Loss tests were made on various types of unshielded and shielded FCC.

3.2.10.4.1 Electrostatic Crosstalk. The electrostatic crosstalk tests were made on unshielded and shielded cables with the electrical test conditions as follows:

a. Excited conductor

   1. Source impedance - 50 ohms (all cases)
   2. Load impedance - open circuit

b. Sensing conductor

   1. Source impedance - open circuit
   2. Load impedance - 20 Hz to 10 kHz, nominal 100 K ohm receiver input

      - 20 to 200 kHz, Tektronix 1A7 plug-in preamplifier and Tektronix 545 oscilloscope (nominal 1-megohm input shunted by 47 plus 50 pF of cable capacity).

      - 50 kHz to 400 MHz, nominal 50 ohm receiver input.

When two conductors are in close proximity to each other, a small but finite capacitance exists. The conductors are capacitor electrodes and the conductor insulation and other nonconductive materials form the capacitor dielectric. Any varying voltage on one conductor is capacitively coupled onto the other conductor as an induced voltage. The induced voltage appears across the parallel-connected combination of terminating impedances connected to the ends of the second conductor.

The capacitance between the second conductor and objects other than the first conductor also appears in parallel with the terminating impedances unless balanced circuitry is used. This shunt capacitance is a function of the total circuit length while the series coupling capacitance between the two conductors is a function of the shared path length. The series and shunt capacitances form a capacitive voltage divider. The shunt capacitance in the lower leg of the voltage divider is in parallel with the terminating impedances connected across the ends of the conductor.

At low frequencies, the induced voltage is inversely proportional to the reactance of the conductor-to-conductor capacitance. The conductor-to-conductor capacitive reactance is extremely high compared with the value of the parallel-connected terminating impedances connected across the ends of the conductor and the shunt capacitance between the conductor and structural ground plane. The voltage at the interfering conductor is divided between the two legs of this voltage divider in proportion to the impedances in the upper and lower legs of the divider.

As frequency increases, the reactance of the conductor-to-conductor capacitance decreases while the terminating impedances remain relatively constant because of the resistive component usually present. Therefore, the induced voltage that appears between the susceptible conductor and the structural ground plane increases with frequency at the rate of 6 decibels per octave or 20 decibels per decade at low frequencies.

At high frequencies, the induced voltage at the susceptible conductor remains relatively constant as frequency changes. The reactance of the conductor-to-conductor capacitance becomes insignificantly low compared to the relatively constant, resistive component of the conductor terminations, and essentially the entire interfering voltage appears on the susceptible conductor.

If the resistive component of the terminating impedances is dominated by the lower reactance of the parallel capacitance in the terminating hardware and/or the distributed shunt capacitance of the conductor, the resultant capacitive voltage divider has a division ratio that is relatively independent of frequency.

The reactance of this capacitive divider is inversely proportional to frequency, and will load the interference generator at relatively high frequencies if the reactance of the capacitive voltage divider is significantly lower than the output impedance of the interference generator. Under these conditions, the induced voltage will decrease at the rate of 6 decibels per octave or 20 decibels per decade.

If the terminating hardware is dominantly inductive, the reduction in loading on the interference generator would increase the induced voltage at the rate of 6 decibels per octave or 20 decibels per decade.

The measured data are significantly affected by the instrumentation and by the interconnection wiring and test configuration used. Physical limitations reduced the coupled length of the conductors to 4 feet out of a total conductor length of 6 feet. A short-shielded conductor, used to connect the susceptible conductor to the input of the instrumentation, had significant capacitance to the structural ground plane. This shunt reactance formed a capacitive voltage divider in conjunction with the conductor-to-conductor capacitance, preventing the full interference voltage from appearing at the input of the instrumentation.

Because of this pseudoreduction in induced voltage, the coupling loss, even at the high frequencies, does not approach zero decibels. In actual system wiring, this reduction in induced voltage would be considerably smaller except where large capacitive terminations were encountered.

The data break appearing between 200 and 500 kilohertz occurred because available high-input impedance instrumentation was limited to frequencies below 200 kilohertz. Above 500 kilohertz, commercially available instrumentation with the necessary sensitivity was limited to an input impedance of 50 ohms, causing an artifical change in induced voltage.

The distributed electrical parameters of the 6-foot-long test specimens produced conductor resonance at approximately 5 megahertz and a series of harmonically related frequencies above this point. Data above this fundamental resonance in the 2- to 10-megahertz region are dominated by the conductor impedance characteristics and do not reflect the conductor-coupling characteristics.

3.2.10.4.1.1 Electrostatic Crosstalk, Unshielded FCC. Electrostatic crosstalk tests were run on four configurations of unshielded cable setups. Analyses of the resulting information and curves are as given in the following paragraphs.

Figure 3-29 (Curve 1) shows the magnitude of induced voltage appearing across the high-impedance susceptible load referenced to the magnitude of the disturbing voltage on the interfering conductor. Note the perturbation because of resonance near 10 megahertz.

Figure 3-31 (Curve 1) shows the magnitude of induced voltage appearing across the susceptible high-impedance load referenced to the magnitude of the distrubing voltage on the interfering conductor. Note the perturbation because of resonance near 10 megahertz. A lower-frequency perturbation between 200 and 500 kilohertz was because of a reduction of instrumentation input impedance.

Figure 3-39 (Curve 3, referenced to the right-hand vertical scale) shows the change in induced voltage appearing across the susceptible high-impedance load that occurs when various thicknesses of dielectric spacer strips are inserted between stacked unshielded cables.

The dielectric spacer strips produce a relatively small reduction in electric crosstalk when inserted between stacked unshielded cables. Excessive dielectric thicknesses would be required to achieve generally useful degrees of isolation for typical electronic systems. The use of dielectric spacer strips appears to be limited to applications, such as digital systems, where a marginally unsatisfactory condition can be made marginally satisfactory with an extremely small reduction in crosstalk. The dielectric spacer has the advantage of not increasing the capacitance between the conductor and the structural ground plane.

Figure 3-49 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced voltage appearing across the susceptible high-impedance load when one grounded, nonferrous, metallic-shielding foil is inserted between unshielded cables. The nonferrous foil provided an excellent reduction in electric coupling between adjacent stacked cables below 2 megahertz, provided a generally useful reduction in electric coupling between 2 and 5 megahertz, and produced some reduction in electric coupling between adjacent stacked cables between 5 and 400 megahertz.

The electric-shielding effectiveness exceeded 76 decibels between 20 and 50 hertz, was approximately a measured 77 decibels between 50 hertz and 1 kilohertz, gradually increasing to 88 decibels between 10 and 20 kilohertz, gradually decreasing to 80 decibels at 200 kilohertz, decreasing sharply to 55 decibels between 500 kilohertz and 2 megahertz, decreasing to approximately 10 decibels between 100 and 200 megahertz, and increasing to 18 decibels at 400 megahertz. The measured data are of questionable validity above 5 megahertz because of conductor resonances. The low-frequency electric-shielding effectiveness greatly exceeded the values shown but could not be measured because of the state-of-the-art limitations of commercially available monitoring instrumentation.

3.2.10.4.1.2 Electrostatic Crosstalk, Shielded FCC. Electrostatic crosstalk tests were run on seven configurations of shielded cable setups. Analyses of the resulting information and curves are as given in the following paragraphs.

Figure 3-33 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced voltage appearing across the susceptible high-impedance load that occurs when a nonferrous solid-shielded cable with open edges is substituted for an unshielded cable. The nonferrous solid shield with open edges produces some reduction in electric-field crosstalk throughout the measured frequency spectrum, but does not achieve really useful degrees of electric crosstalk reduction. Electric crosstalk reduction is 22 decibels at 1 kilohertz, rising slowly to 36 decibels between 10 and 200 kilohertz, dropping to 22 decibels between 500 kilohertz and 2 megahertz, and gradually rising to 29 decibels at 5 megahertz. A rise to a peak of 48 decibels at 20 megahertz and decrease to 25 decibels at 400 megahertz is a questionable validity because of conductor resonances.

Figure 3-35 (Curve 3, referenced to the right-hand vertical scale) shows that reduction in induced voltage appearing across the susceptible high-impedance load that occurs when a nonferrous solid-shielded cable with joined edges is substituted for an unshielded cable. The nonferrous solid shield with joined edges produces some reduction in electric-field crosstalk throughout the measured frequency spectrum, but does not achieve really useful degrees of electric crosstalk reduction. Electric crosstalk reduction is 23 decibels, rising slowly to 38 decibels between 10 and 200 kilohertz, dropping to 22 decibels at 500 kilohertz, and rising irregularly to 40 decibels at 5 megahertz. A rise to a peak of 64 decibels at 20 megahertz and 72 decibels at 100 megahertz and decrease to 40 decibels at 400 megahertz is of questionable validity because of conductor resonances.

Figure 3-37 (Curve 3, referenced to the right-hand vertical scale) shows the change in induced voltage appearing across the susceptible, high-impedance load that occurs when a woven, nonferrous-shielded, twisted-pair conductor is substituted for unshielded cable. The woven, nonferrous shield produces a moderate increase in electric crosstalk below 200 kilohertz, a small reduction in electric crosstalk between 200 kilohertz and 2 megahertz, indifferent performance above 2 megahertz, and does not achieve really useful degrees of electric crosstalk reduction. A spurious peak occurs at 5 megahertz because of conductor resonance. Electric crosstalk is approximately 10 decibels worse than unshielded flat cable below 200 kilohertz and approximately 6 decibels worse between 200 kilohertz and 2 megahertz. A long rise to a large peak of 108 decibels of electric crosstalk reduction at 5 megahertz, decreasing to zero decibel reduction at 70 megahertz, and a degradation rising to 5 decibels at 400 megahertz is of questionable validity because of conductor resonances. The large peak in Curve 3, near 5 megahertz, is characteristic of the higher "Q" resonance exhibited by RWC. The existence of these higher "Q" resonances was discussed in DAC-56440, "Flat Cable Applications Study," final report.

The increase in electric crosstalk below 2 megahertz is because of the higher conductor-to-conductor capacitance of round conductors. The smaller edge-to-edge surface area of flat conductors in the same cable-layer results in a lower coupling capacitance between flat conductors. Even though the round conductor-to-shield capacitance, plus the instrumentation capacitance, is approximately twice the instrumentation capacitance associated with the unshielded flat conductor and tends to reduce the electric crosstalk, and the much higher conductor-to-conductor capacitance of the shielded round conductor pair more than offsets this trend and increases electric crosstalk by a factor of three times (9 dB) compared to unshielded flat cable below 2 megahertz.

Above 2 megahertz, the higher capacitance to the structural ground plane of the shielded round conductors produces a higher degree of unintentional magnetic coupling, not electric coupling, than the unshielded flat cable test configuration. Capacitance between the conductor and ground plate completes a capacitively coupled, magnetically efficient loop at both the interfering and susceptible conductors. This problem is made even more difficult by the use of monitoring instrumentation with an input impedance of 50 ohms at the higher frequencies. Sensitive high-frequency monitoring instrumentation is universally low-impedance because of physical limitations imposed by high-frequency transmissions systems. The existence of this spuriously coupled, high-frequency magnetic component must be recognized and properly interpreted since it cannot be eliminated at the present state-of-the-measurement art.

Figure 3-43 (Curve 3, referenced to the left-hand vertical scale) shows the reduction in the induced voltage appearing across the susceptible high-impedance load when a nonferrous, solid-shielded cable with open edges is substituted for unshielded cable. The nonferrous, solid shield with open edges provided an excellent reduction in electric coupling between adjacent stacked cables below 5 megahertz and provided a generally useful reduction in electric coupling between adjacent-stacked flat cables between 5 and 400 megahertz.

The electric-shielding effectiveness exceeded 78 decibels at 20 hertz, rising to a value exceeding 122 decibels at 1 kilohertz, decreased to a value exceeding 108 decibels at 2 kilohertz, and decreasing gradually to approximately 40 decibels between 10 and 400 megahertz. The measured data were of questionable validity above 5 megahertz because of conductor resonances. The low-frequency electric-shielding effectiveness greatly exceeded the values shown, but could not be measured because of state-of-the-art limitations of commercially available monitoring instrumentation.

Figure 3-45 (Curve 3, referenced to the left-hand vertical scale) shows the reduction in the induced voltage appearing across the susceptible high-impedance load when a nonferrous, solid-shielded cable with joined edges is substituted for unshielded cable. The nonferrous shield with joined edges provided an excellent reduction in electric coupling between adjacent-stacked cables below 500 kilohertz and a generally useful reduction in electric coupling between adjacent-stacked cables between 500 kilohertz and 400 megahertz. The electric-shielding effectiveness exceeded 78 decibels at 20 hertz, rising to a value exceeding 118 decibels at 500 hertz, decreased to a value exceeding 116 decibels at 1 kilohertz, was measured as approximately 116 decibels between 1 and 5 kilohertz, decreased sharply to 85 decibels at 20 kilohertz, decreased gradually to 78 decibels at 200 kilohertz, and decreased sharply to approximately 46 decibels between 500 kilohertz and 400 megahertz. The measured data were of questionable validity above 5 megahertz because of conductor resonances. The low-frequency electric-shielding effectiveness greatly exceeded the values shown, but could not be measured because of state-of-the-art limitations of commercially available monitoring instrumentation.

Figure 3-47 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced voltage appearing across the susceptible high-impedance load when a woven, nonferrous-shielded cable is substituted for unshielded cable. The woven, nonferrous shield provided an excellent reduction in electric coupling between adjacent-stacked cables below 7 megahertz, decreasing to a negligible effect on the electric coupling between 10 and 100 megahertz, and produced some increase in electric coupling between adjacent-stacked cables between 100 and 400 megahertz.

The electric-shielding effectiveness exceeded 76 decibels at 20 hertz, increasing to a measured 89 decibels at 50 hertz, decreasing to 82 decibels between 100 hertz and 10 kilohertz, decreasing to approximately 66 decibels between 20 and 200 kilohertz, decreasing to approximately 45 decibels between 1 and 2 megahertz, rising to a large peak of 117 decibels at 5 megahertz, decreasing to approximately zero decibels between 10 and 100 megahertz, and increased the electric coupling between adjacent-stacked cables by 19 decibels at 400 megahertz. The measured data were of questionable validity above 2 megahertz because of conductor resonances. The low-frequency electric-shielding effectiveness greatly exceeded the values shown, but could not be measured because of state-of-the-art limitations of commercially available monitoring instrumentation.

Figure 3-51 (Curve 3, referenced to the left-hand vertical scale) shows the reduction in induced voltage appearing across the susceptible high-impedance load when a high-permeability-ferrous solid shield with open edges and NASA/DAC aluminum connectors is substituted for unshielded cable. The Chromerics shielding gaskets in the aluminum connector were removed and short, copper jumper strips were substituted between the shield foils and the structural ground plane, while the aluminum connector shell was grounded through existing mounting clips. The high-permeability-ferrous solid shield and aluminum connectors provided an excellent reduction in electric coupling between adjacent stacked cables below 3 megahertz, provided a generally useful reduction in electric coupling between 3 and 6 megahertz, and produced some reduction in electric coupling between adjacent stacked cables between 6 and 400 megahertz.

The electric-shielding effectiveness exceeded 78 decibels at 20 hertz, increasing to a value exceeding approximately 112 decibels between 50 hertz and 10 kilohertz, decreasing to 12 decibels at 10 megahertz, increasing to a peak of 40 decibels at 20 megahertz, and decreasing to 10 decibels at 400 megahertz. The measured data are of questionable validity above 5 megahertz because of conductor resonances. The low-frequency electric-shielding effectiveness greatly exceeded the values shown, but could not be measured because of state-of-the-art limitations of commercially available monitoring instrumentation.

3.2.10.4.2 Magnetic Crosstalk. The magnetic crosstalk tests were made on unshielded and shielded cables with the electrical test conditions as follows:

a. Excited conductor

1. Source impedance - 50 ohms (all cases)
2. Load impedance - Short to ground-plane return

b. Sensing conductor

1. Source impedance - Short to ground-plane return
2. Load impedance - Nominal 50-ohm receiver input

The mere existence of a longitudinal conductor creates a small but finite inductance. When two conductors are in close proximity to each other, a transformer is created because of the mutual inductance of, or magnetic coupling between, the inductances. Any varying current flow in one conductor is inductively coupled into the other conductor as an induced voltage because of the transformer action. The induced voltage appears across the winding-load impedance and causes a current flow through the load impedance that is a function of the varying current amplitude in the first conductor, the coupling coefficient of the conductors, the output winding impedance, and the impedance of the load.

Turns ratio is ordinarly fixed at 1 to 1 by the geometry of the procured cable. The coupling coefficient and mutual inductance are based on a uniform geometry between conductors over the entire lengths of the conductors. Extensions of the conductor lengths beyond the points of common geometry increase the total series inductance of the conductors without increasing the total mutual inductance of the conductors and, therefore, reduces the effective mutual inductance and effective coupling coefficient of the conductors.

At low frequencies, the induced voltage is proportional to the impedance of the susceptible conductor. The conductor-source impedance is extremely low compared with the value of the series-connected terminating impedances at the ends of the conductor. The unloaded induced-output voltage appears across the series-connected terminating impedances.

The current through the terminating impedances is a function of the unloaded induced-output voltage of the susceptible conductor and the value of the series-connected terminating impedances at the ends of the conductor. As frequency increases, the source impedance of the susceptible conductor increases proportionately; therefore, the impedance match between the conductor and the series-connected load impedances improves as frequency increases, and the induced current through the series-connected load impedances increases at the rate of 6 decibels per octave or 20 decibels per decade at low frequencies.

At high frequencies, the induced voltage is inversely proportional to the impedance of the susceptible conductor. The conductor-source impedance is extremely high compared with the value of the series connected at the ends of the conductor. The induced-output voltage is heavily loaded by the series-connected terminating impedances.

If the two ends of the conductor were connected together, a short-circuit current would flow. This short-circuit current has twice the amplitude of a current flowing from the conductor through a load impedance that matches the conductor-source impedance.

The short-circuit current is a function of the unloaded induced voltage and the conductor-source impedance. When the relatively low, series-connected terminating impedances are inserted in series with the source impedance of the conductor, the induced current through the terminating impedances is reduced proportionately.

As frequency increases, the source impedance of the susceptible conductor increases proportionately; therefore, the impedance match between the conductor and the series-connected load impedances gets worse as frequency increases, and the induced current through the series-connected load impedances decreases at the rate of 6 decibels per octave or 20 decibels per decade at high frequencies.

At some intermediate frequency, where the two curves with opposing slopes meet, optimum coupling between the conductors occurs. At and near this frequency, the current flowing through the series-connected terminating impedances is equal to the current flowing through the interfering conductor multiplied by the coupling coefficient of the conductors. Since the coupling coefficient of most adjacent conductors approaches unity, the induced current through the terminating impedances almost equals the disturbing current through the interfering conductor near this optimum-coupling frequency.

The measured data are affected by the characteristics of the instrumentation and interconnection wiring and the test configuration used. The effective coupling coefficient of the two conductors was reduced significantly because of the relatively short length of the available test specimens. Physical limitations reduced the coupled length of the conductors to 4 feet out of a total conductor length of 6 feet. Since this additional uncoupled inductance is in series with both the interfering and susceptible conductors, the coupling coefficient is reduced in proportion to the square of this ratio. Interconnection wiring at the ends of the test specimen also contributed to the reduction in effective-coupling coefficient.

Because of this pseudoreduction in the coupling coefficient of the test specimens, the coupling loss, even at the optimum coupling frequency, does not approach zero decibel. In actual system wiring, this reduction in effective-coupling coefficient would not occur except for isolated cases.

3.2.10.4.2.1 Magnetic Crosstalk, Unshielded FCC. Magnetic crosstalk tests were run on four configurations of unshielded cable setups. Analyses of the resulting information and curves are as given in the following paragraphs.

Figure 3-28 (Curve 1) shows the magnitude of induced current flowing through the susceptible 50-ohm load referenced to the magnitude of the disturbing current flowing in the interfering conductor. Note the perturbations because of resonances near 10 megahertz and 20 megahertz.

Figure 3-30 (Curve 1) shows the magnitude of induced current flowing through the susceptible 50-ohm load referenced to the magnitude of the disturbing current flowing in the interfering conductor. Note the perturbations because of resonances between 5 and 10 megahertz and near 20 megahertz. A lower-frequency perturbation of approximately 6 decibels near 100 kilohertz is probably nonexistent. Speculation indicates that personnel operating the signal sources may have supplied incorrect disturbing-current amplitude information during measurements made at this frequency.

Figure 3-38 (Curve 3, referenced to the right-hand vertical scale) shows the change in induced current flowing through the susceptible 50-ohm load that occurs when various thicknesses of dielectric spacer strips are inserted between stacked unshielded cables. The dielectric spacer strips produce a relatively small reduction in magnetic crosstalk when inserted between stacked unshielded cables. Excessive dielectric thicknesses would be required to achieve generally useful degrees of isolation for typical electronic systems. The use of dielectric spacer strips appears to be limited to applications such as digital systems where a marginally unsatisfactory condition can be made marginally satisfactory with an extremely small reduction in crosstalk. The dielectric spacer has the advantage of not increasing the capacitance between the conductor and the structural ground plane.

Figure 3-48 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load when one grounded, nonferrous, metallic-shielding foil is inserted between unshielded cables. The nonferrous foil had a negligible effect on the magnetic coupling between adjacent stacked conductors below 5 kilohertz and produced some reduction in magnetic coupling between 5 kilohertz and produced some reduction in magnetic coupling between 5 kilohertz and 400 megahertz but did not provide a generally useful reduction in magnetic coupling at any point in the entire measured frequency spectrum. Above approximately 100 kilohertz, over most of the frequency range where some reduction in magnetic coupling occurs, the transmission losses of this cable configuration become so high that the cable becomes useless as a medium for the transmission of information in electronic systems.

The magnetic-shielding effectiveness was actually zero decibel below 5 kilohertz. The low negative values shown are because of small, long-term drifts in the monitoring instrumentation. The magnetic-shielding effectiveness gradually increased above 5 kilohertz to approximately 32 decibels between 500 kilohertz and 5 megahertz, dipped to 4 decibels at 10 megahertz, went through zero decibels at 250 megahertz, and dropped to a negative value of 10 decibels at 400 megahertz. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

3.2.10.4.2.2 Magnetic Crosstalk, Shielded FCC. Magnetic crosstalk tests were run on seven configurations of shielded cable setups. Analyses of the resulting information and curves are as given in the following paragraphs.

Figure 3-32 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load that occurs when a nonferrous solid-shielded cable with open edges is substituted for an unshielded cable. The nonferrous solid shield with open edges has no effect on adjacent conductor magnetic crosstalk within the shield below 10 kilohertz, produces some magnetic crosstalk reduction above 10 kilohertz, and only provides a useful magnetic crosstalk reduction at one point near 1 megahertz, at which frequencies high transmission losses tend to make the cable relatively useless as a medium for the transmission of system information. Note the perturbations because of the reference cable resonance between 5 and 10 megahertz and near 20 megahertz, and the shielded cable resonance near 50 megahertz.

Figure 3-34 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load that occurs when a nonferrous solid-shielded cable with joined edges is substituted for an unshielded cable. The nonferrous solid shield with joined edges has no effect on adjacent-conductor magnetic crosstalk within the shield below 5 kilohertz, produces some magnetic crosstalk reduction between 5 and 200 kilohertz, and provides a useful magnetic crosstalk reduction above 200 kilohertz, at which frequencies high transmission losses tend to make the cable relatively useless as a medium for the transmission of system information. Note the perturbations because of shielded-cable resonance near 10, 20, 100, and 200 megahertz.

The distributed electrical parameters of the 6-foot-long test specimens produced conductor resonance at approximately 5 megahertz and a series of harmonically related frequencies above this point. Data above this fundamental resonance in the 2- to 10-megahertz region are dominated by the conductor impedance characteristics and do not accurately reflect the conductor coupling characteristics.

Figure 3-36 (Curve 3, referenced to the right-hand vertical scale) shown the change in induced current flowing through the susceptible 50-ohm load that occurs when a woven, nonferrous-shielded, twisted-pair conductor is substituted for unshielded cable. The woven nonferrous shield has no effect on adjacent conductor magnetic crosstalk within the shield over the entire frequency spectrum measured. The low-frequency end of Curve 3 is actually on the zero-decibel line, but is shown as approximately -3 decibels because of small long-term drifts in the instrumentation. The large peak in curve 3 near 5 megahertz is characteristic of the higher "Q" resonances exhibited by RWC.

Figure 3-42 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load when a nonferrous solid-shielded cable with open edges is substituted for unshielded cable. The nonferrous solid shield had a negligible effect on the magnetic coupling between adjacent stacked conductors below 5 kilohertz, produced some reduction in magnetic coupling between 5 and 500 kilohertz, provided a generally useful reduction in magnetic coupling between 500 kilohertz and 150 megahertz, and produced some reduction in magnetic coupling between 150 and 400 megahertz. Above approximately 100 kilohertz, at the frequencies where a useful reduction in magnetic coupling occurs, the transmission losses through the cable become so high that the cable is useless as a medium for the transmission of information in electronic systems.

The magnetic-shielding effectiveness was actually zero decibel below 5 kilohertz. The low-negative value shown is the result of small, long-term drifts in the monitoring instrumentation. The magnetic-shielding effectiveness gradually increased from zero decibel at 5 kilohertz to an irregular 34 decibels between 500 kilohertz and 10 megahertz, increased to a peak of 58 decibels at 50 megahertz, and dropped to 4 decibels at 400 kilohertz. The measured data have questionable validity above approximately 5 megahertz because of conductor resonances.

Figure 3-44 (Curve 3, referenced to right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load when a nonferrous solid-shielded cable with joined edges is substituted for unshielded cable. The nonferrous solid shield had a negligible effect on the magnetic coupling between adjacent stacked conductors below 2 kilohertz, produced some reduction in magnetic coupling between 2 and 500 kilohertz, provided a generally useful reduction in magnetic coupling between 500 kilohertz and 250 megahertz, and produced some reduction in magnetic coupling between 250 and 400 megahertz. Above approximately 100 kilohertz, at the frequencies where a useful reduction in magnetic coupling occurs, the transmission losses through the cable become so high that the cable is useless as a medium for the transmission of information in electronic systems.

The magnetic-shielding effectiveness was actually zero decibels below 2 kilohertz. The low-negative value shown is the result of small, long-term drifts in the monitoring instrumentation. The magnetic-shielding effectiveness gradually increased from zero decibel at 2 kilohertz to 36 decibels between 500 kilohertz and 2 megahertz, increased to a peak of 80 decibels at 20 megahertz, and dropped to 14 decibels at 400 megahertz. The measured data have questionable validity above approximately 5 megahertz because of conductor resonances.

Figure 3-46 (Curve 3, referenced to the right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load when a woven nonferrous-shielded round-conductor cable is substituted for an unshielded cable. The woven nonferrous shield had a negligible effect on the magnetic coupling between adjacent round conductors throughout the entire measured frequency spectrum. The magnetic-shielding effectiveness was actually zero decibel below 2 megahertz. The low values shown are because of small long-term drifts in the monitoring instrumentation.

The peaks at 5 megahertz, between 20 and 50 megahertz, at 200 megahertz, and the dips at 10, 100, and 400 megahertz are because of conductor resonances. The measured data have questionable validity above approximately 2 megahertz because of conductor resonances. The large peaks and dips in curve 3, above 2 megahertz, are characteristic of the high "Q" resonances exhibited by round conductors.

Figure 3-50 (Curve 3, referenced to right-hand vertical scale) shows the reduction in induced current flowing through the susceptible 50-ohm load when a high-permeability-ferrous, solid shield with open edges and NASA/DAC aluminum connectors is substituted for unshielded cable. The Chromeric shielding gaskets in the aluminum connector were removed, and short, copper jumper strips were substituted between the shield foils and the structural ground plane, while the aluminum connector shell was grounded through existing mounting clips. The high-permeability-ferrous solid shield and aluminum connectors had a negligible effect on the magnetic coupling between adjacent stacked cables below 20 kilohertz, produced some reduction in magnetic coupling between adjacent-stacked cables between 20 kilohertz and 200 megahertz, and produced some increase in magnetic coupling between adjacent stacked cables between 200 and 400 megahertz, at which frequencies the transmission losses through the cable become so high that the cable is useless as a medium for the transmission of information in electronic systems.

The magnetic-shielding effectiveness was actually zero decibel below 20 kilohertz. The low-negative value shown is the result of small, long-term drifts in the monitoring instrumentation. The magnetic-shielding effectiveness gradually increased to approximately 16 decibels between 500 kilohertz and 2 megahertz, decreasing to 2 decibels at 10 megahertz, increasing to a peak of approximately 20 decibels between 20 and 50 megahertz, decreasing to 4 decibels between 100 and 200 megahertz, goes through zero decibel at 260 megahertz, and increases the magnetic coupling by 6 decibels at 400 megahertz. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

3.2.10.4.3 Transmission Loss. The transmission-loss test was made on unshielded and shielded cables with both 1 ohm and 100 k ohm terminations which were matched to the test setup instrumentation.

The distributed-series inductance and shunt capacitance of a conductor form a distributed low-pass filter. This low-pass filter has negligible losses at low frequencies, has a rapidly increasing rate of losses over a relatively narrow band of transition frequencies determined by the distributed electrical constants of the conductor, and has a relatively constant-rate loss with a high, absolute value at high frequencies. The conductor is a useful medium for the transmission of information in electronic systems at low frequencies where the reactive losses of the conductor do not greatly exceed the resistance losses of the conductor. At the high frequencies, the reactive losses become prohibitive and make the conductor useless for the transmission of information in electronic systems.

The unshielded conductor bandwidth is extended for digital systems by utilizing impedance-matched, unshielded conductor pairs, but this application for bulk cable will decrease sharply as integrated circuitry reduces computer size. This bandwidth extension is limited by high-frequency copper losses. At these higher frequencies, only a very limited number of communications systems are capable of accommodating the large conductor losses. The percent of conductor feet utilized for interconnection wiring in future digital and communications systems is expected to be insignificant.

3.2.10.4.3.1 Transmission Loss, Unshielded FCC. Transmission-loss tests were run on one configuration of unshielded cable. Analyses of the resulting information and curves are as given in the following paragraphs.

With 1-ohm terminating impedances (Curve 1, Figure 3-87) at the ends of the 6-foot unshielded cable, the transmission loss down a centrally located conductor is negligible below 50 kilohertz, increases gradually to 40 decibels at 5 megahertz, dips to an irregular 33 decibels between 10 and 150 megahertz, and increases to 38 decibels at 200 megahertz and 42 decibels at 400 megahertz. This relatively short cable would be generally useful below 50 kilohertz, of limited usefulness between 40 and 100 kilohertz, and relatively useless above 100 kilohertz.

With 100,000-ohm terminations (Curve 2, Figure 3-87), the transmission loss is negligible below 500 hertz, increases gradually to a peak of 49 decibels at 2 megahertz, dips slightly to 43 decibels at 5 megahertz, drops to 4 decibels between 10 and 20 megahertz, dips to a negative value (transmission gain) of 20 decibels at 100 megahertz, and dips to a negative value (transmission gain) of 5 decibels at 400 megahertz. The transmission gains are probably false indications because of conductor resonances. This relatively short cable would be generally useful below 500 hertz, of limited usefulness between 500 hertz and 3 kilohertz, and relatively useless above 3 kilohertz.

The transmission losses are proportional to length, and the useful frequency limit is inversely proportional to length. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

3.2.10.4.3.2 Transmission Loss, Shielded FCC. Transmission-loss tests were run on three configurations of shielded cables. Analyses of the resulting information and curves are as given in the following paragraphs.

With 1-ohm terminating impedances (Curve 1, Figure 3-88) at the ends of the 6-foot length of mesh-shielded cable, the transmission loss down a centrally located conductor is negligible below 60 kilohertz, increases gradually to 34 decibels at 5 megahertz, continues irregularly at approximately 30 decibels to 200 megahertz, and increases sharply to 65 decibels at 400 megahertz. This relatively short cable would be generally useful below 60 kilohertz, of limited usefulness between 60 and 130 kilohertz, and relatively useless above 130 kilohertz.

With 100, 000-ohm terminations (Curve 2, Figure 3-88), the transmission loss is negligible below 1 kilohertz, increasing to 58 decibels at 5 megahertz, dropping sharply to a negative value (transmission gain) of 13 decibels at 10 megahertz, decreasing through zero decibels at 84 megahertz, and increasing to 19 decibels at 400 megahertz. The transmission gain is a false indication, probably because of conductor resonance. This relatively short cable would be generally useful below 1 kilohertz, of limited usefulness between 1 and 2. 5 kilohertz, and relatively useless above 2. 5 kilohertz.

The transmission losses are proportional to length, and the useful frequency limit is inversely proportional to length. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

With 1-ohm terminating impedances (Curve 1, Figure 3-89) at the ends of the 6-foot solid 4-79 Permalloy shielded cable with open edges, the transmission loss down a centrally located conductor is negligible below 9 kilohertz, increases gradually to approximately 25 decibels between 2 and 5 megahertz, increases sharply to approximately 73 decibels between 10 and 100 megahertz, and decreases to 35 decibels at 400 megahertz. This relatively short cable would be generally useful below 9 kilohertz, of limited usefulness between 9 kilohertz and 30 kilohertz, and relatively useless above 30 kilohertz.

With 100, 000-ohm terminations (Curve 2, Figure 3-89), the transmission loss is negligible below 1 kilohertz, increases gradually to approximately 55 decibels between 3 and 5 megahertz, dropping sharply to approximately 2 decibels between 9 and 50 megahertz, increasing rapidly to a peak of 56 decibels at 200 megahertz and decreasing to 45 decibels at 400 megahertz. This relatively short cable would be generally useful below 1 kilohertz, of limited usefulness between 1 and 2. 5 kilohertz, and relatively useless above 2. 5 kilohertz.

The transmission losses are proportional to length, and the useful frequency limit is inversely proportional to length. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

With 1-ohm terminating impedances (Curve 1, Figure 3-90) at the ends of the 6-foot length of woven, copper-shielded, round-conductor cable, the transmission loss down the conductor is negligible below 25 kilohertz, gradually increases to approximately 30 decibels between 2 and 50 megahertz, dips to 12 decibels at 100 megahertz, increases to a peak of 32 decibels at 200 megahertz, and decreases to 23 decibels at 400 megahertz. This relatively short cable would be generally useful below 25 kilohertz, of limited usefulness between 25 and 65 kilohertz, and relatively useless above 65 kilohertz.

With 100, 000-ohm terminations (Curve 2, Figure 3-90), the transmission loss is negligible below 700 hertz, gradually increasing to 63 decibels at 5 megahertz, drops sharply to 2 decibels at 10 megahertz, increases to a peak of 12 decibels at 20 megahertz, decreases through zero decibel at 38 megahertz to negative values (transmission gains) of 18 decibels at 100 megahertz, 7 decibels at 200 megahertz, and 20 decibels at 400 megahertz. The transmission gains are probably false indications, because of conductor resonances. This relatively short cable would be generally useful below 700 hertz, of limited usefulness between 700 hertz and 2. 5 kilohertz, and relatively useless above 2. 5 kilohertz.

The transmission losses are proportional to length, and the useful frequency limit is inversely proportional to length. The measured data are of questionable validity above 5 megahertz because of conductor resonances.

SECTION IV. WIRING CHANGES

4.1 Introduction

This section discusses various methods for accomplishing wiring changes in FCC interconnecting harness systems.

Harnesses can be reworked temporarily by cutting existing conductors and splicing in new conductor segments or by using special splicing devices. These techniques are explained further in Paragraph 4.2.2. Normally, neither of these methods would be considered acceptable for high-reliability production units.

The transition to RWC and the use of the distribution unit system permits multiple pin-assignment changes.

4.2 Wiring-Change Categories

4.2.1 Production. Production change methods can be described as those which would normally be acceptable for end-item use. As such, these change techniques should be economical, be capable of clean documentation, and should have high reliability.

4.2.1.1 Distribution Units. Distribution units will provide the production means for accomplishing the initial interconnection, and for making subsequent pin-assignment changes. These could be either separate units or incorporated into existing interconnecting or distribution electronic packages. Distribution units for use on programs with intricate electronic systems are of such importance that they are covered in detail in Paragraph 4.3.

4.2.1.2 Terminating to Round Connectors. These are two basic methods for terminating FCC into RWC connectors; the first involves terminating the FCC conductors to the connector pins through a solid wire or other device. All terminations can be made in a very limited space; the terminating area is usually potted to provide sealing and strain relief; and there are no provisions for making specific pin-assignment design changes.

The second method (Fig. 4-1) involves making a transition from FCC to RWC in the area dajacent to the round connector, or in the FCC harness run in the vicinity of the round connector. This method will see much general use for the interim period while many electronic units have round-wire connectors. In addition to providing the transition to the RWC connectors, it also provides a production means of accommodating pin-assignment changes in the rear of the round-wire connectors. If removable crimp contacts are used, the harness can be easily reworked; if solder and/or potting are utilized at the RWC connector, then only design revisions can be made for pin-assignment changes in new harness fabrication.

The transition from FCC to RWC for the second method can be made in several ways. NASA/MSFC has completely developed, tooled, and tested a method for lap soldering the stripped RWC to the bared FCC. A prepared assembly, prior to molding, is shown in Figure 4-2. Section VI of this report contains detailed instructions for the manufacturing of this NASA/MSFC transition. Figure 3-83 shows an assembly of many such transitions proposed for use on the ATM program.

Other methods for making this transition, which have been successfully prototyped, include crimping, welding, and soldering. Figure 4-3 shows a crimping technique developed by Picatinny Arsenal. Figure 4-4 shows a miniature, tungsten inert-gas (TIG) weld by the Dynatech Corporation that can be easily tooled for high production. Figure 4-5 shows a ganged soldering technique accomplished with Raytheon solder sleeves. In each method shown, the transition area would be covered with a minimum molded cross section for sealing and strain relief. The transition area could be supported by a connector adapter bracket or be located a distance from the connector and separately supported.

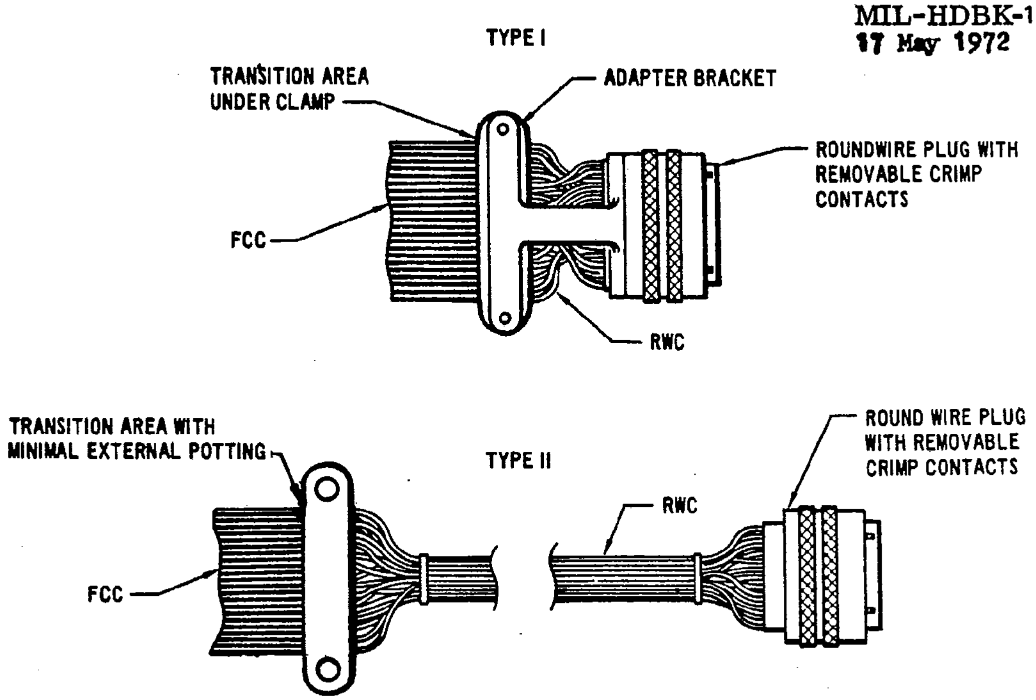


FIGURE 4-1. Transition from round-wire plug termination (NASA/MSFC).

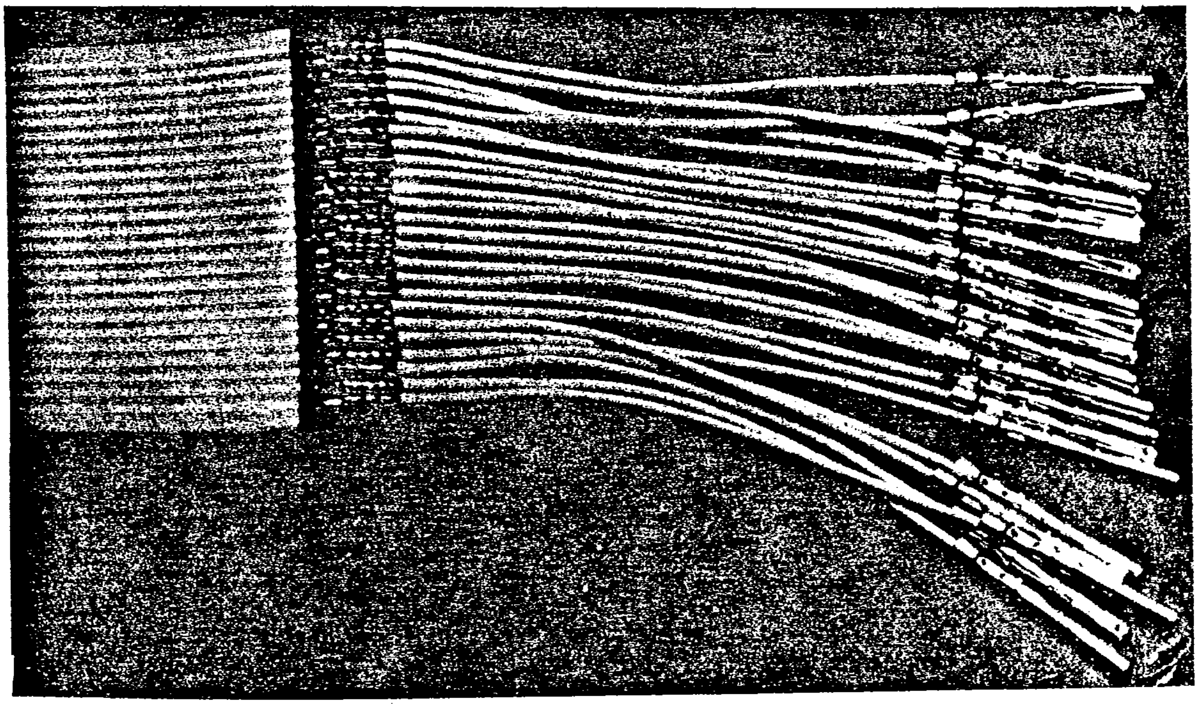


FIGURE 4-2. NASA/MSFC transition - FCC to RWC (potting omitted for clarity).

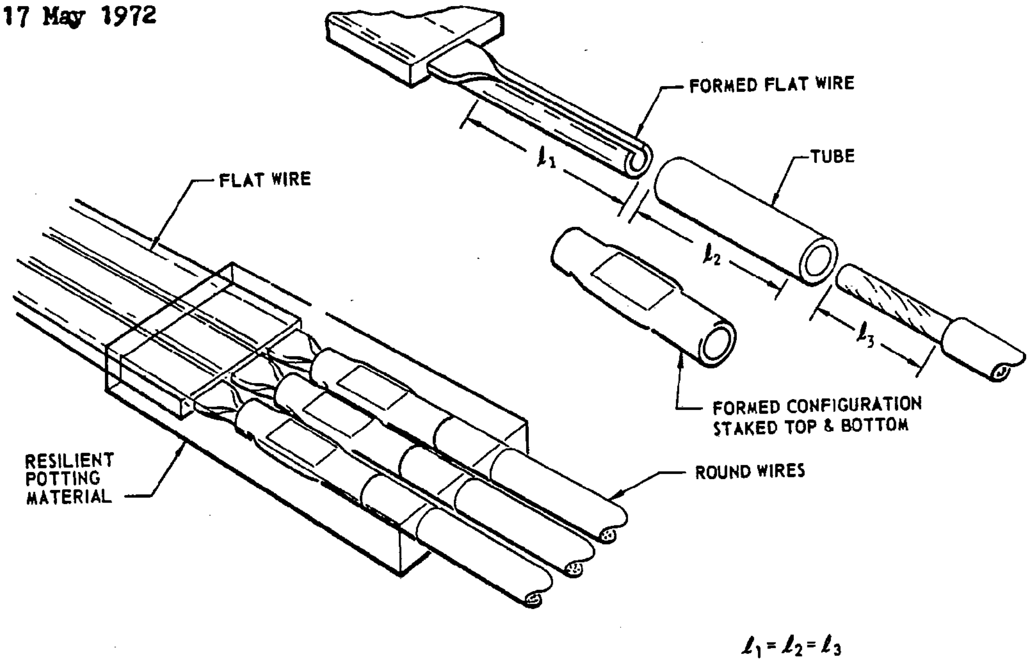


FIGURE 4-3. Crimp transition - FCC to RWC (Picatinny Arsenal).

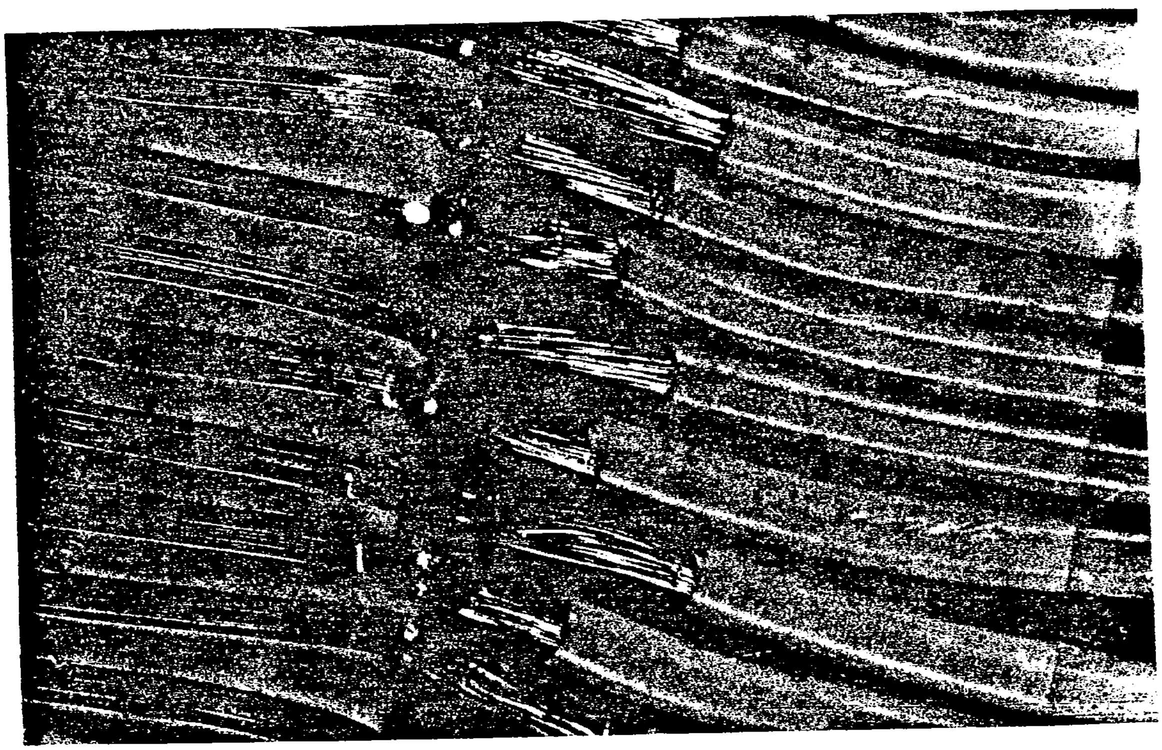


FIGURE 4-4. TIG welding transition - FCC to RWC (Dynatech Corp.).

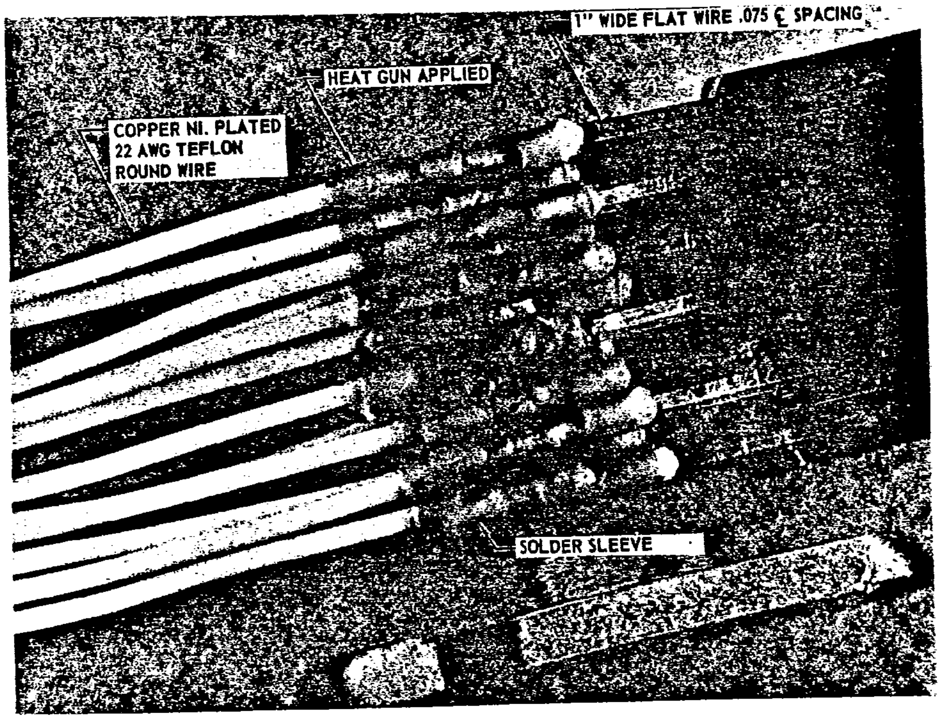


FIGURE 4-5. Ganged solder transition - FCC to RWC (Raytheon).

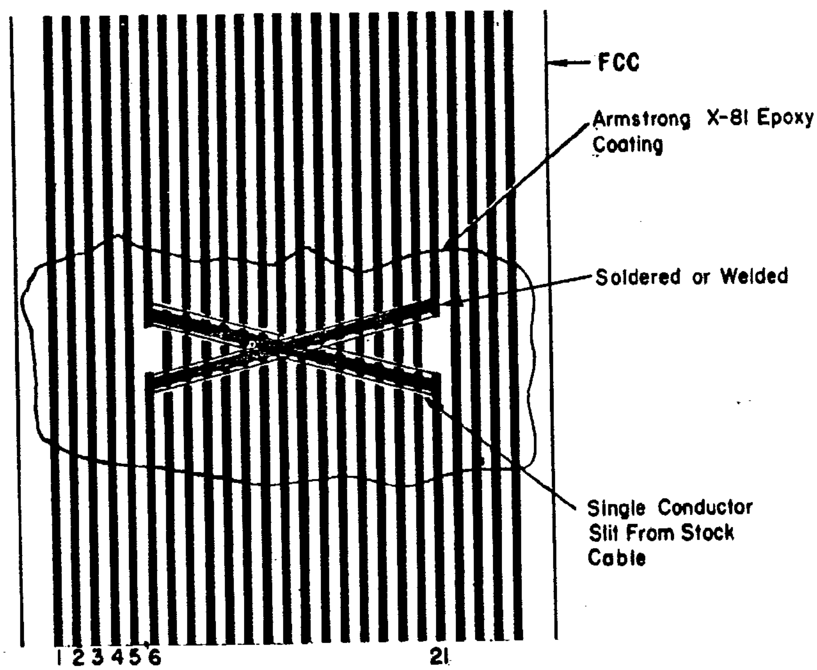


FIGURE 4-6. Rerouting conductors within an FCC.

In general, the transition to round-wire plugs provides an efficient termination system, with RWC pin-assignment change capability; however, part of the harness-fabrication cost saving is sacrificed, and additional termination junctions are imposed in the harness system.

4.2.2 Temporary. The following FCC wiring-change techniques can generally be considered as temporary or nonproduction. For many testing and development programs for system evaluation, and other limited applications, these methods could be used; however, for production efficiency and reliability, they would not normally be acceptable.

4.2.2.1 Rerouting Within a Cable. Simple wiring-circuit changes can be accomplished by a crossing or switching of two or more conductors of an interconnecting FCC without the use of external hardware. The two conductors are interrupted, and single conductors are soldered or welded to the ends of the interrupted conductors to restore the desired continuity (Fig. 4-6). This exchange should be made at a point in the interconnecting hardware where the cable is anchored or properly supported to eliminate subsequent cable flexing in the cable joint area.

4.2.2.2 Rerouting Within the FCC Plug Area. By properly preparing the cable, simple pin-assignment changes can be made in the plug-termination area. No additional junctions are required.

An example of this method for the NASA/MSFC conductor-contact plug assembly is explained as follows: Assuming conductor Nos. 2 and 10 are to be interchanged, the cable is stripped, slit, and folded as shown in Figure 4-7. Then conductor plating and plug assembly, as explained in Section VI, can be accomplished for either the premolded or molded-on plug versions.

4.2.2.3 Cable Matrix Joints. It is possible to accomplish pin-assignment changes and parallel circuit paths in an FCC harness through the use of the matrix joint system. Figure 4-8 shows the principles involved in such a joint. Interconnections can be made by welding, either of bare conductors or through insulation. The completed joint would be coated or encapsulated for sealing and mechanical strength. The Ralph Thacker Company of Los Angeles, California, has an automated X-Y coordinate-sensitive drilling machine for removing the insulation from preselected circular areas. Although the method adds one additional joint in the harness, complete pin-assignment-change capability is provided. The matrix system has been used by Ansley West on the carrier landing equipment for Bell Aerosystems.

4.2.2.4 Auxiliary Terminating Devices. Various auxiliary terminating or splicing devices are available for connecting FCC conductors to terminals, wires, pins, and to other FCC conductors. Figure 4-9 shows a line of tape terms available from Ansley West. The FCC is slit between conductors, and the terminals crimp on and pierce the insulation to make contact. This system is not applicable where vibration, frequent bending, extreme temperature cycling, or high reliability are required.

4.3 Distribution Units

4.3.1 System Advantages. The design application of distribution units was covered in detail in Section III. The important system advantages achieved are:

a. Cable assemblies are two-ended and can be terminated in a "by layer," predetermined configuration for all program connectors.

b. The electronic unit pin assignments can be selected for optimum circuit zoning that will automatically provide optimum zoning in the FCC harnesses.

c. All circuit or pin-assignment changes can be made in the distribution units without affecting FCC harnesses or electronic units.

d. The FCC harnesses between the distributors can be designed and installed prior to the circuit-design freeze of the electrical systems. The optimum cable and connector widths and sizes can be used on these harnesses.

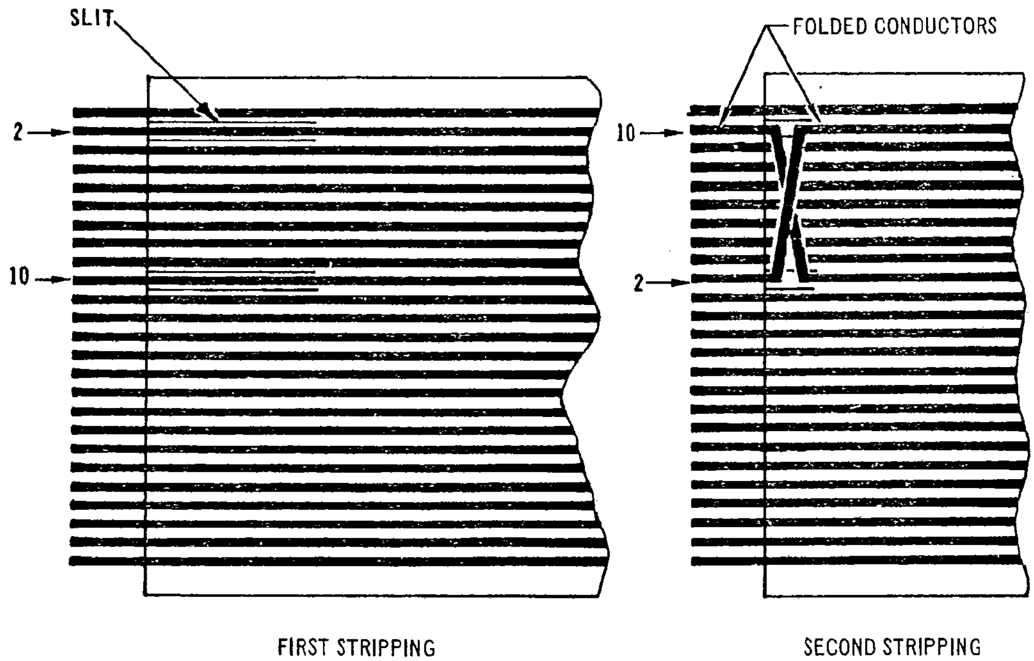


FIGURE 4-7. FCC preparation for plug rerouting.

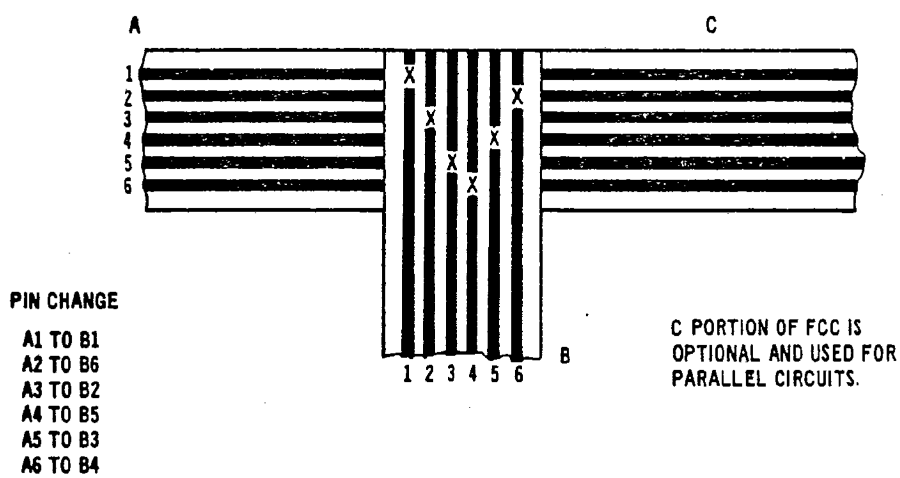


FIGURE 4-8. Cable matrix joint (Ansley West).

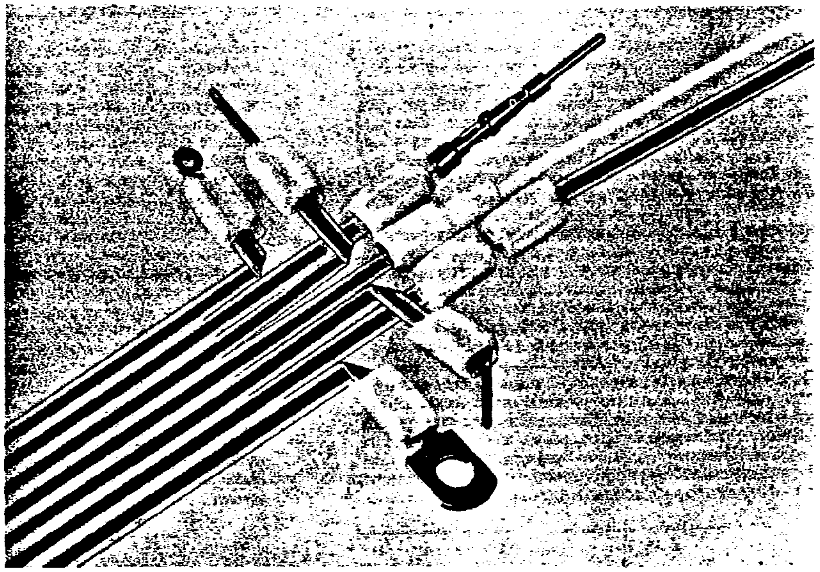


FIGURE 4-9. Tape - terms (Ansley West).

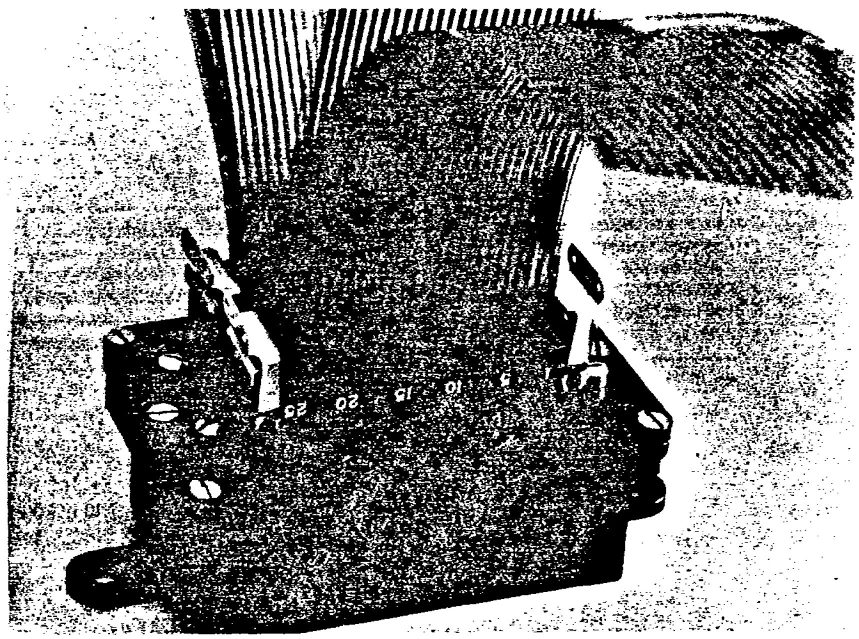


FIGURE 4-10. MSFC jumper wire distribution unit.

e. The minimum-number and smallest-size connectors can be used on each electronic unit.

f. The electronic unit pin-assignment designed for one program will automatically provide the optimum design for all other programs.

g. The number of wire-harness changes will be reduced to a minimum. It is estimated that this would be up to 95 percent reduction, depending on the complexity of the system.

4.3.2 Design Objectives. The design objectives are as follows:

a. Minimum number of circuit joints.

b. Minimum size and weight.

c. Capability of being wired or interconnected automatically for production and manufally for prototype.

d. Capability of being reworked manually with connectors mated.

e. Installation or replacement with minimum disturbance to adjacent installations and interconnecting harness system.

f. Random, nonparallel interconnections to reduce internal field interferences to a minimum.

g. Capability of accommodating various input-ouptut connectors, including both the FCC and RWC type.

h. Accommodate various conductor sizes required by the interconnecting network.

i. Provide bussing and parallel circuit paths as required.

4.3.3 Configurations. Various configurations of distribution units, suitable for use with FCC, have been proposed and a number have been developed. In general, these fall into two categories or configurations: those with a few connectors (usually two identical connectors) and those with many connectors of various types and sizes. The former would generally be used in a single-harness run to provide the pin-assignment change capability. These units could be included in initial design, but could also be added easily to harness runs requiring circuit changes after initial design. The many connector distribution units would generally be incorporated in the initial design to provide the many advantages listed above.

4.3.3.1 Distributors With Few Connectors. NASA/MSFC has developed several distribution units. They are relatively lightweight, simple, easy to install, and provide the means for unlimited pin-assignment changes. Two of these units are further discussed in the following paragraphs.

Figure 4-10 shows a simple, sealed box with two MSFC solder-type receptacles, and molded-on FCC plugs installed. The interconnections are made by soldering insulated round-wire jumpers between the receptacle solder pots that are inside the housing.

Figure 4-11 shows a disassembled view of a distributor that uses a PC board to accomplish the required pin-assignment changes. By cutting circuit conductors and adding jumper wires, all pin-assignment combinations can be accomplished. Small terminals to facilitate soldering can be easily added to the modified PC board if desired.

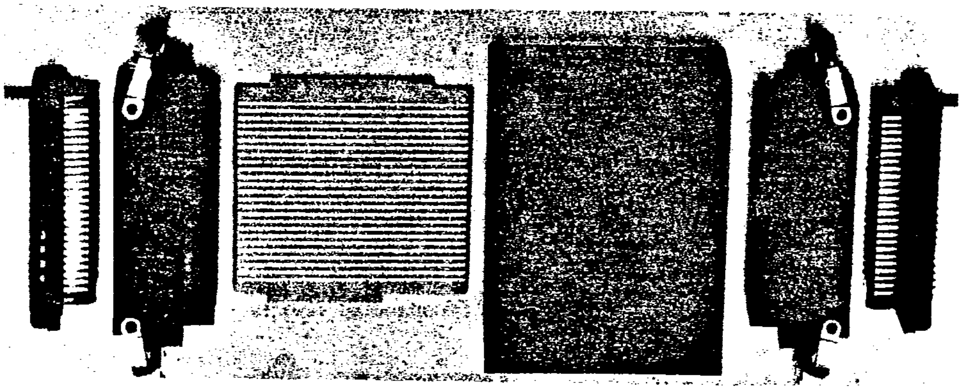


FIGURE 4-11. MSFC PC board distribution unit.

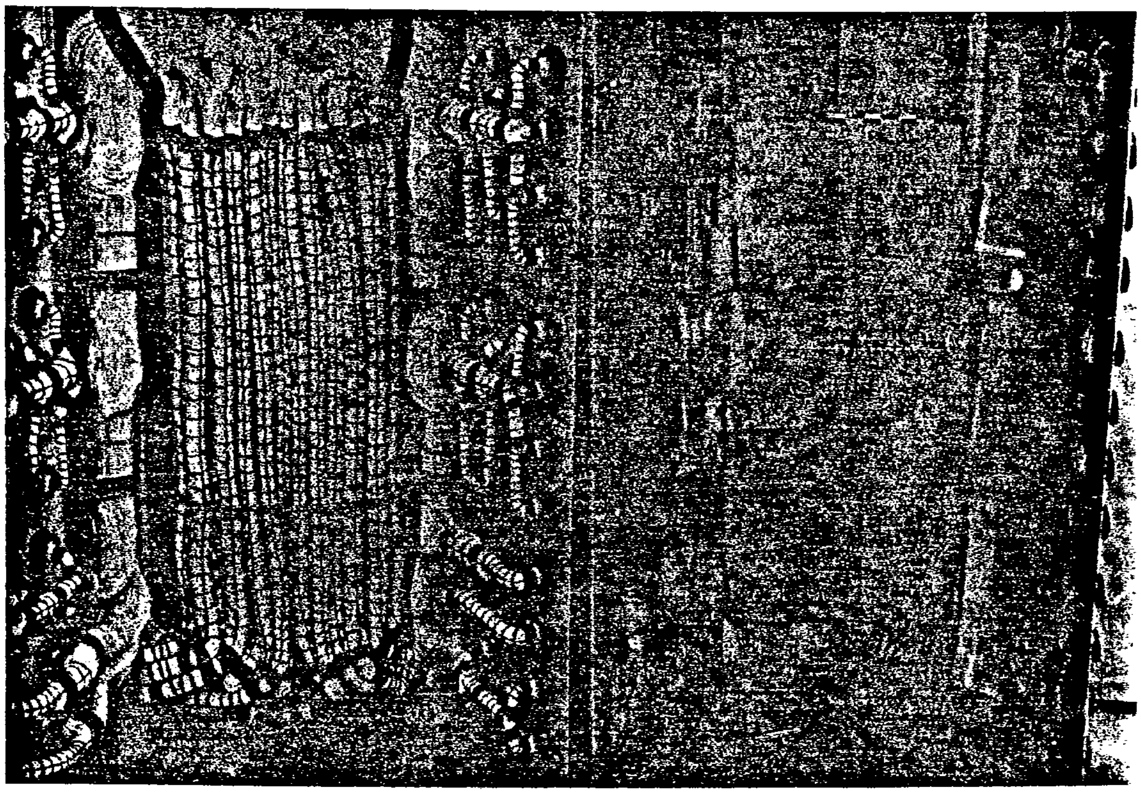


FIGURE 4-12. Saturn GSE patch-panel distributor (NASA/MSFC).

4.3.3.2 Distributors With Many Connectors. Various types of central distribution units with many input-output connectors have been considered and/or prototyped. These are described as follows:

a. GSE patch-panel distributor - Figure 4-12 shows the rear-view wiring comparison between FCC and RWC patch-panel distributor designs used by NASA/MSFC on the Saturn program. These distributors have forty 61-pin RWC input-output connectors and test points for each circuit. To avoid costly design changes, initial RWC terminations and pin assignments were retained. The use of the printed-circuit, flexible harnesses provided major cost savings, 50-percent reduction in cabinet volume, and 30-percent reduction in weight. Continuous FCC can also be incorporated into this type design through the use of the matrix interconnection described in Paragraph 4.2.2.3.

b. Wire-wrap distributor - Figure 4-13 shows a programmable distributor unit (by Ansley West) used on a research space vehicle program to provide maximum circuit change flexibility and rework capability in the instrumentation circuits. RWC input-output connectors are interconnected with a wire-wrap plane by continuous FCC. This design permits programmed, automatic production interwiring and simple hand rework for circuit changes to the instrumentation circuits after initial fabrication.

c. Termi-point distributor - A distribution unit using the Termi-Point termination system was developed and a prototype built by MDC. Figure 4-14 shows the design concept and typical installation. All interconnection wiring can be accomplished by programmed automatic equipment. Multilayer wiring will permit bussing of circuits. Rework can be accomplished with simple hand tools. Upper terminations can be moved to lower positions on the post terminals to simplify rework. The use of stranded, interconnecting wire, with the post clip securely gripping the insulation, gives added resistance to vibration and shock. This system provides the minimum number of circuit junctions by making all interconnections directly to the connector rear post. The use of this concept would require the development of connectors with Termi-Point rear posts located on a modular grid to accommodate the automatic wiring systems. In addition, the interconnecting wire sizes would be limited by the connector post sizes and centerline spacings.

d. Multiconnector distributor using PC boards and plug-in jumpers - Figure 4-15 shows the NASA/MSFC basic design and jumper-wire arrangement. The PC board is double-sided to accommodate the usual NASA/MSFC double-cable connectors. This design is very convenient for making wiring changes and the plug-in jumper concept facilitates almost unlimited rechange cycles or capability. Figure 4-15 shows a design accommodating six 1-inch, 24-pin FCC connectors. The dimensions of this particular distributor are 19 by 10 by 2.2 centimeters (7.5 by 4.5 by 0.85 inches). The bushings in the PC board are a standard type (Cambion 3704-1-03) manufactured by Cambridge Thermionic Corporation, Cambridge, Massachusetts. The pins are modified (shortened) to save space. Depending upon circuit quantity requirements, other sizes of this type distributor are feasible, practical, and manufacturable.

4.4 Conclusion

The various wiring-change methods described can be used, as applicable, to accommodate pin-assignment changes in FCC interconnecting harness systems. It is important to give proper consideration to the anticipated pin-assignment change requirements early in the program, and design the system accordingly. The addition of change devices or the use of "temporary" rerouting schemes done on an "as required" basis will result in a less-than-optimum final design.

The use of distribution units will provide system circuit changeability, permit use of simple interconnecting harnesses designed and fabricated early in the program, and will efficiently accommodate kit additions and various configuration changes between production units.

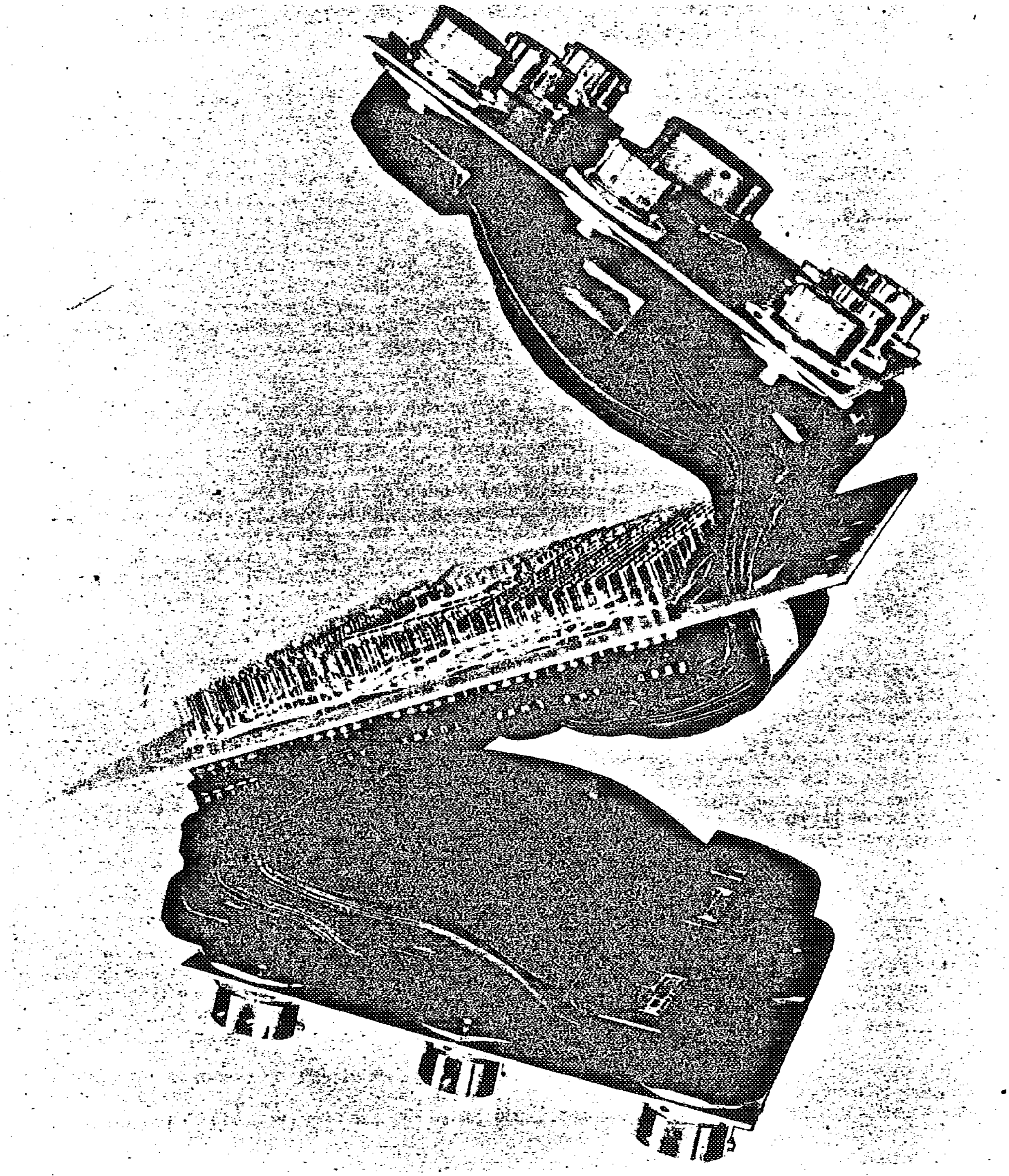
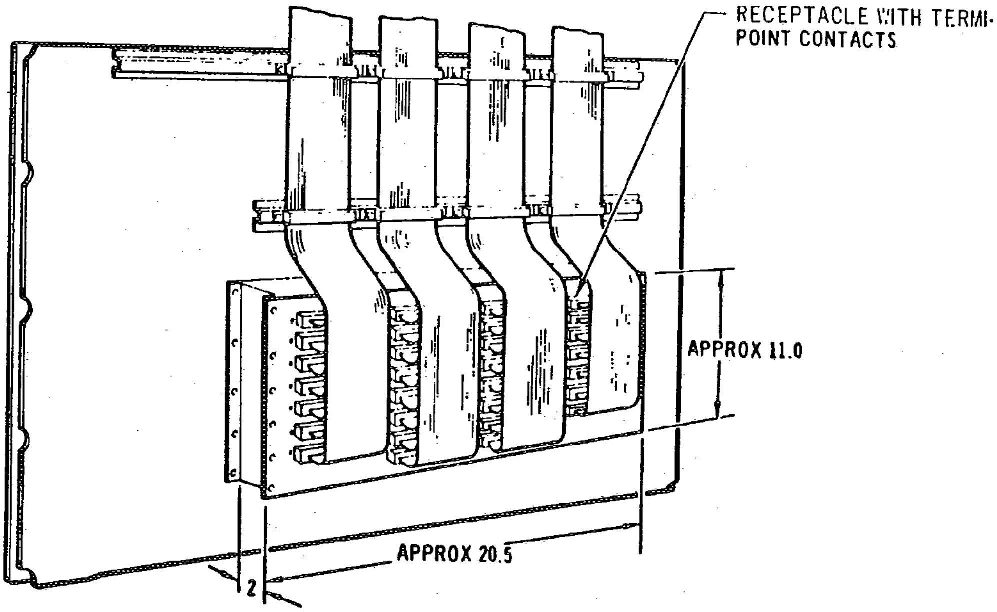
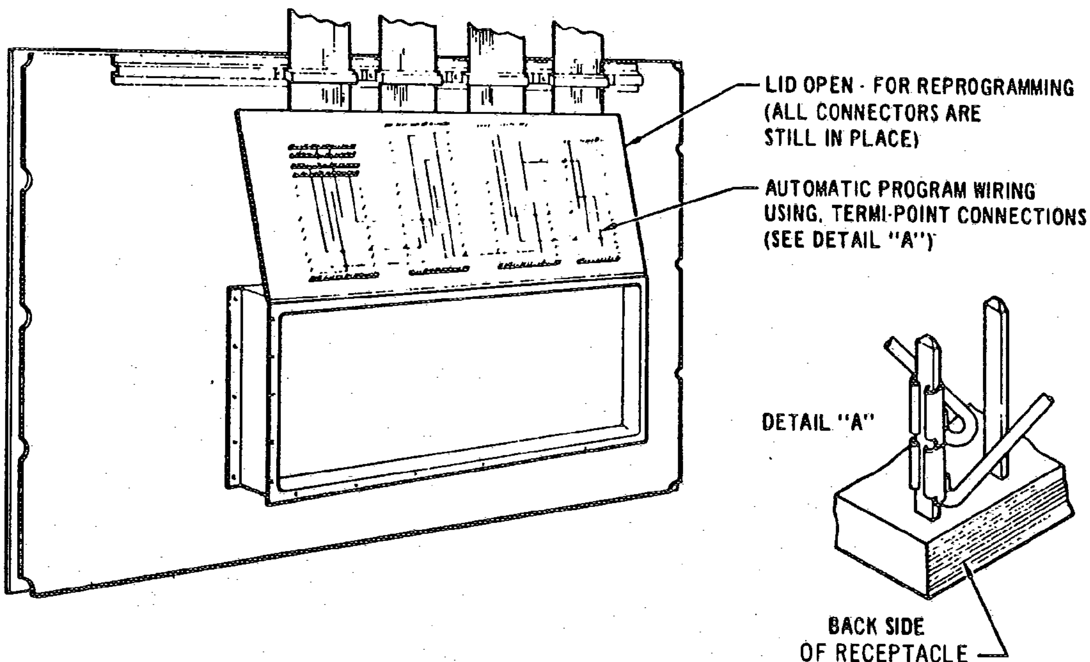


FIGURE 4-13. Wire-wrap distributor (Ansley West).



WITH LID CLOSED



WITH LID OPEN

FIGURE 4-14. Termi-Point distributor.

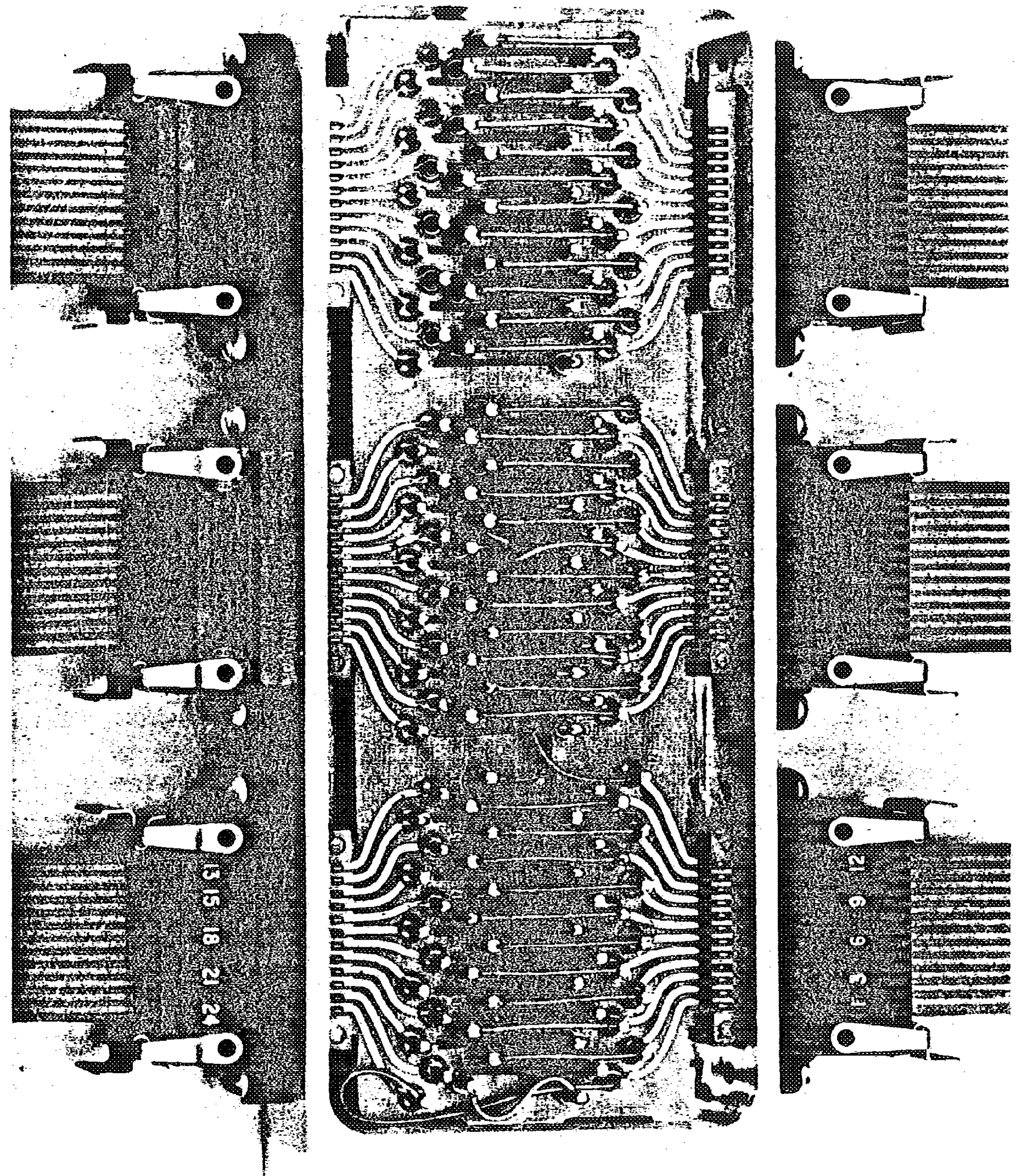


FIGURE 4-15. Multiconnector distributor with plug-in jumper pins (NASA/MSFC).

SECTION V. RELIABILITY

5.1 Introduction

The FCC interconnecting systems have not seen extensive enough use to provide statistical data on failure rates, criticality, and reliability figures for direct comparison to RWC interconnecting systems. Therefore, the reliability comparison will be made primarily from an analysis of the materials, the cable and connector constructions, the cable heat dissipation, the plug assembly methods, the harness installation, and the system technical performance. Analytical studies on quality and dependability of electrical interconnecting systems using RWC show generally current leakage, conductor breakage, and junction failure as major points of concern. All these will be analyzed in the following paragraphs.

5.2 Cable

RWC harnesses are made up of individual conductors with insulation materials extruded, or wrapped in layers, over the conductors. To facilitate wire stripping, the insulation normally has a low-shear bond strength to the conductor. This, together with the relative low-tensile strength of the RWC insulation (5,000 to 10,000 psi), limits the structural tensile strength of the individual cable to that of the conductor. The random nature of the conductor routing, and bundle tying in the RWC harness, does not provide load sharing of the individual cables. Therefore, the axial and bending stresses permitted on RWC harnesses are much less than the average for combined conductors. In many applications, such as bending or twisting, the allowable load could approach the stress allowable of the conductor in an individual cable.

In comparison, FCC insulation materials are laminated or bonded to the conductors to provide a homogeneous structure having high collective strength.

Polyester (Mylar) and polyimide (Kapton) insulations, commonly used in FCC constructions and those specified by MIL-C-55543 have tensile strengths of 25,000 and 20,000 psi, respectively. This strength, which is approximately five times that of common insulations used with RWC, is added directly to that of the conductors to provide a cable strength of many times that of an equivalent RWC harness. In addition, any stress or strain placed at a termination area having proper strain relief will be shared by all conductors.

As the conductor size requirements become smaller and smaller for future programs utilizing integrated circuit electronics, the reliability advantages of the FCC become greater and greater. This is the direct result of the mechanical load-sharing characteristics of the FCC system and the automated, multiple-termination systems used.

Numerous mechanical, environmental, and electrical tests have been performed on various FCC configurations to verify the properties which contribute to the increased reliability as described above. NASA/MSFC has conducted and contracted numerous tests on various cable configurations. The U.S. Army Electronics Command at Fort Monmouth, New Jersey, has conducted an extensive study to verify the mechanical and electrical characteristics of FCC.

The inspection of nonshielded FCC is greatly facilitated by the translucent insulation used. This permits visual inspection of all conductors and insulation layers. Many cable faults covered by the opaque insulation of most RWC systems would be readily apparent in the FCC system.

5.3 Connectors

The reliability of electrical connectors is a function of the connector design, the materials, the termination system used, and the method of connector assembly. Much experience has been gained over the years in the design and fabrication of RWC connectors in termination techniques and in connector assembly. As a result, a high degree of confidence and reliability has been established. All RWC connector experience has been applied to existing and will be applied to future FCC connector systems. In addition, the FCC connector offers certain inherent advantages over that of the RWC system.

In the NASA/MSFC conductor-contact connector system, at least one electrical joint per conductor is eliminated by using the FCC conductor as the plug contact. Furthermore, the carefully designed contact spring of the receptacle, having a spherical contact of controlled radius, spring rate, spring deflection, and contact force is a built-in warranty for reliable, continuous performance.

On all FCC connector systems designed for high reliability and production, terminations are made to the connector contacts on a "by-layer" basis; therefore, the conductors do not require individual stripping, handling, or forming. With proper design and tooling, there is no probability of individual stressing of conductors, insulations, or connector contacts.

5.4 Harness Assemblies

An increase in reliability of FCC harness assemblies is the result of several factors. First, the termination of the FCC to the FCC plug is made in an automatic or semiautomatic operation. Instead of handling hundreds of individual conductors for identification, jig-board routing, preparation for termination, termination, and assembly into connectors, as is required on the RWC system, the FCC system requires only the handling of several cables to build an equivalent harness.

FCC assemblies can be designed for much simpler interconnecting harnesses. The simpler harnesses are easier to build and inspect; thus, a reliability improvement is gained.

Very small conductors, of 26-gage equivalent or less, can easily and reliably be assembled and terminated in FCC harnesses. Extreme caution must be exercised with a major reliability degradation potential when these smaller gage conductors are used on the RWC system.

The FCC harnesses also have greatly improved abrasion resistance over RWC harnesses. This increase in reliability is the result of the improved mechanical properties of the insulation materials plus the geometric configuration of the FCC. The RWC insulation varies from 5 to 15 mils in thickness. When an RWC bundle makes physical contact with an interference or abrasion surface, only the insulation on the outside cable need be penetrated to effect an electrical short circuit. This radial surface offers relatively little abrasion resistance. With larger bundles, the forces will generally be greater and the probability of failure is even higher.

The improved insulation on the FCC is generally much thinner (about 3 mils thick). However, instead of a small-radiused area of one conductor coming in contact with the abrasion medium, a contact line, the width, of the FCC is established. As a result, the FCC harness will withstand many times the abrasion that can be tolerated by the RWC harness. The FCC insulation edge margin is approximately 0.10 inch to provide increased abrasion resistance on the cable edges where concentrated loads could be applied.

5.5 Harness Installations

A review of Figures 1-1 and 1-2 gives a clear indication of the improvement and simplification in harness installation that can be achieved with the FCC interconnecting system. The much-simpler FCC harnesses make installation and replacement more reliable. Each FCC harness can be easily routed into and supported with the major harness runs. The number and complexity of supports and attachment clamps are greatly reduced. In addition, the series of clamps developed have captivated hardware so no loose parts can be dropped or misplaced during installations. All sharp edges and protrusions were also eliminated.

The cleaner routing and support, with the major space reduction for FCC, contributes heavily to increased reliability. Installations can be made with fewer protrusions that could be used as handholds or would be subject to maintenance damage. The major space savings achievable with FCC will have the effect of making less dense installations with more room for installation and serviceability.

The FCC weight saving will result in less massive installations with a reduction of stresses in the various support areas.

FCC can be bonded directly to basic structure in many instances to provide the ultimate in installation simplification, harness protection, light-weight support, and resultant reliability. Bonding to structure is especially applicable to the longer harness runs between major distribution areas, in tunnel runs, and in airborne external installations such as those routing to transducers.

5.6 Heat Dissipation

A major reliability aspect is the verification of performance of the system being used. During the past few years there have been many claims made and curves and charts published on the current-carrying capability of FCC and its comparison with RWC. The recently completed study and testing by NASA/MSFC has resulted in an unquestionable comparison between the load carrying and thermal characteristics of FCC and RWC. Extensive comparison tests were made in air and vacuum with various directly comparable bundles. The test results indicate that the temperature rise of FCC in air is approximately: 50 percent less than RWC for a 25-conductor, one-layer FCC cable; 40 percent less than RWC for a 75-conductor, three-layer FCC cable; and 10 percent less than RWC for a 250-conductor, 10-layer FCC cable.

The temperature rise of FCC in vacuum is approximately: 60 percent less than RWC for a 25-conductor, one-layer FCC cable; 50 percent less than RWC for a 75-conductor, three-layer FCC cable; and 35 percent less than RWC for a 250-conductor, 10-layer FCC cable. All the tests were made with bundles isolated, except in their support areas. When FCC is bonded to structure, which then acts as a heat sink, even greater heat dissipation with reusltant lower temperature will be experienced.

Section III contains instructions, curves, and correction factors to predict temperature rise versus current for FCC conductor cross sections listed in MIL-C-55543. The predictability of the resultant temperature rise and the appreciable lower operating temperature of the FCC are major contributions to reliability.

5.7 System Performance

The use of FCC permits the prediciton of the specific electrical characteristics and assures the repeatability from unit to unit of the interconnecting harnesses with the resultant reliability improvement in system performance.

RWC systems, with random routing of individual conductors in the cable bundles, have no control over the placement and resultant electrical characteristics between conductors. To overcome this shortcoming, excessive shielding and numerous bundle runs have been utilized over the years to achieve the required system performance. This has resulted in an overdesign for worse-case conditions. Excessive weight and space were required for the RWC systems with the reduction of reliability previously described. Even with all these precautions, EMC tests on the required percentage of end items indicated that subsequent units, supposedly interwired identically to previous units that have successfully passed the tests, needed additional circuit isolation.

With the FCC system, each conductor location is controlled in relation to all other conductors and to the ground plane throughout the entire interconnecting harness system. This permits the proper selection of the simplest system with the most desirable electrical characteristics and assures that all units will perform identically. It further encourages, and even forces, the system designer to consider the interconnecting harness system as components of the overall electronic systems. When he thoroughly understands and applies this component concept and utilizes the available configurations of FCC, a major step in simplicity and reliability will be achieved.

The capability of FCC harnesses to act as a built-in line-filter to effectively reduce spurious electrical noise and disturbing signals is discussed in Section III. This provides an increase in reliability by eliminating a separate filter unit with its individual components and interconnections that are possible sources of failure.

5.8 Conclusions

In conclusion it can be stated that the use of the FCC system offers many potential reliability improvements over the RWC system. These include: greater collective strength and greater abrasion resistance for FCC; fewer junctions, simpler assembly and less probability of overstressing individual contacts and conductors in FCC connectors; simpler, smaller, and lighter-weight harness assemblies and installations; improved heat dissipation provides cooler operating temperatures for the same electrical loads and equivalent conductor cross sections; and improved and predictable system performance, repeatable unit after unit.

SECTION VI. MANUFACTURING AND INSTALLATION TECHNIQUES

6.1 General

This section described the flat-cable harness fabrication and installation using the NASA developed conductor-contact connector system. The NASA system used the MIL-C-55543 cable and MIL-C-55544 connector. To fully correlate the manufacturing and inspection sections, the process flow charts (Section VII) reference specific paragraphs in this section.

6.2 Mock-Up Installation

Most electrical cable and harness installations including those for FCC must be developed in three dimensions to clear structural components, plumbing, electrical equipment, and other cables. Mock-up manufacturing and installation are closely coordinated with design personnel.

This three-dimensional development is generally performed on an inexpensive wood-and-metal mockup or development fixture of the actual vehicle. An example is shown in Figure 6-1.

6.2.1 Materials. An inexpensive mock-up material, such as 10-mil-thick Mylar tape of proper width is used to simulate the flat cable. The Mylar is sufficiently flexible, yet stiff and rugged enough to withstand the rough handling during mockup development.

6.2.2 Installation Aids. Simple shop aids are used to develop the mockup (Fig. 6-2). A brief description in the use of the aids follows:

a. Masking tape is used as a temporary means to hold the Mylar harness together, and for identification of the simulated cable.

b. Plastic cable ties are used extensively throughout the mock-up development to fasten the Mylar to the supports and bundles.

c. A stapler is used:

1. To staple the folds of the Mylar.
2. To splice pieces of Mylar in branched harnesses where rerouting is necessary during mockup.
3. As a tie-wrap to hold bundles of harnesses.
4. To secure the Mylar to wooden panels and supports.

d. A wedge/lock clamp is used for temporarily clamping bundles of Mylar together to prevent them from sliding.

e. Clips with plastic fasteners are used to clamp the Mylar during final mockup installation.

6.2.3 General Procedures. The following step-by-step procedure is intended as a guide to made the user aware of the intended use of the mockup in the overall cable development and fabrication. The procedure may be changed to meet the specific requirements of a given installation. The mock-up cable installation is to be done on either the actual piece of equipment to be wired or on a mockup of the equipment when it is not feasible to use the actual equipment.

a. The 10-mil Mylar is routed between components and assemblies to be interconnected. An example is shown in Figure 6-3. To ensure that proper registration of the cable is maintained, identify each cable segment together with its index edge in accordance with the engineering drawing by rubber stamping with black ink.

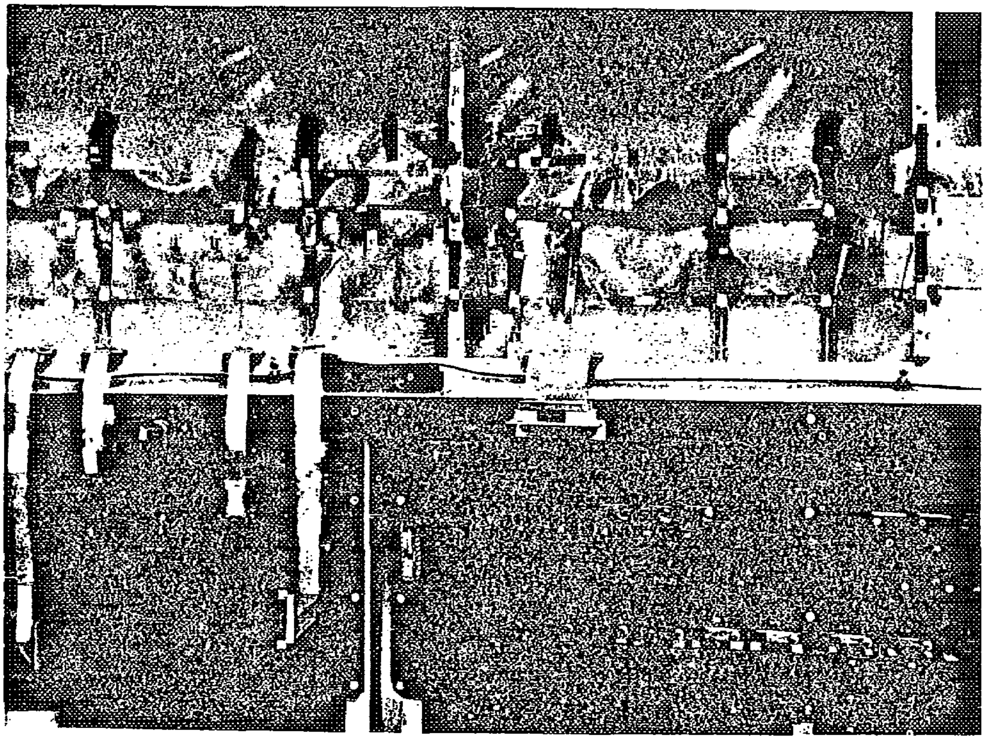


FIGURE 6-1. Mylar FCC harness mockup.

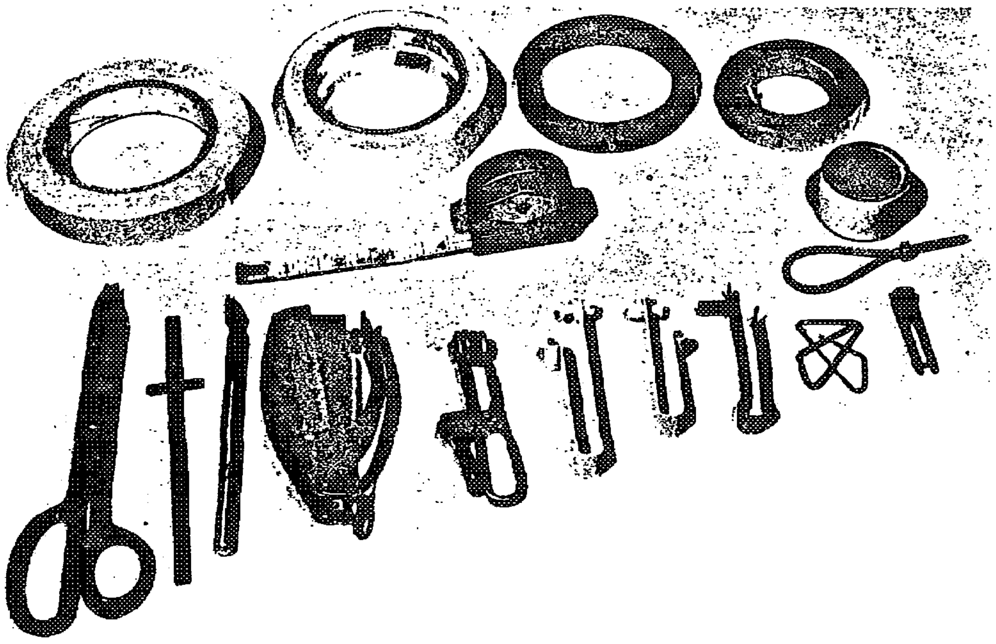


FIGURE 6-2. Tools and aids for mockup and installation.

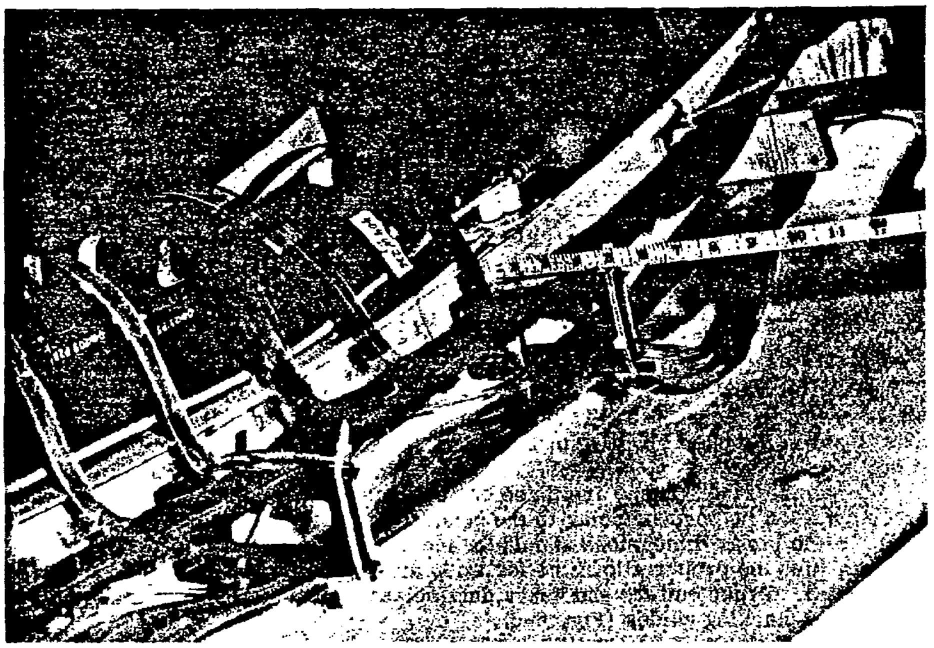


FIGURE 6-3. Mylar FCC mockup.

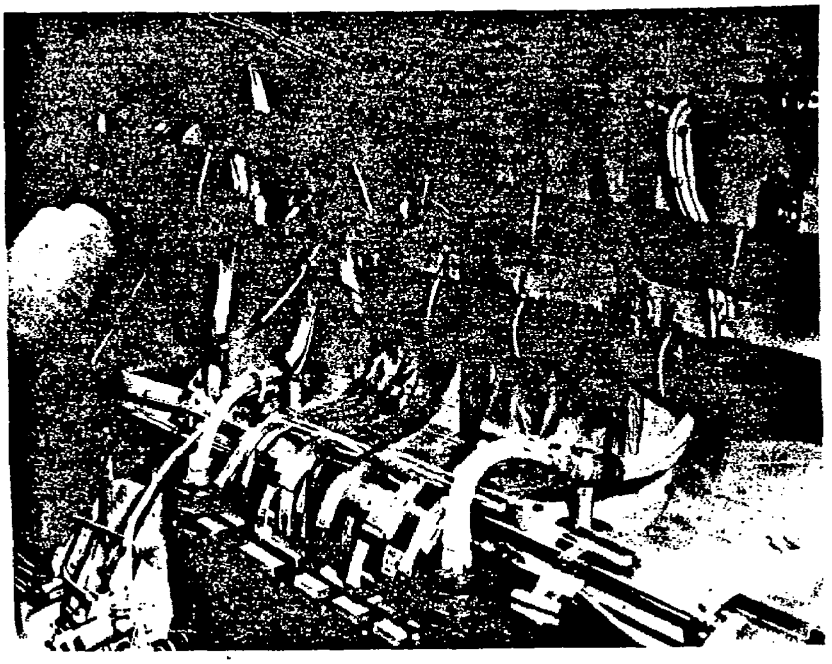


FIGURE 6-4. Basic support bracket.

b. Right-angle brackets of the appropriate length are attached as required to support the cables (Fig. 6-4).

c. The cable harness is arranged in the bundles with the branches routed in a manner to minimize interference and to simplify insertion or removal of harness assemblies.

d. When installing the Mylar mockup, bends or folds are made as required to simplify routing.

e. Upon completion, the mock-up is checked for conformity to design requirements. The mock-up cables are used as patterns in manufacturing the FCC harnesses.

6.3 Detail Manufacturing

6.3.1 Material Handling. It is advisable to package FCC lengths longer than 5 feet in the handling device shown in Figure 6-5. This system can be used during all subsequent manufacturing operations to aid in the plant handling of long runs of cable.

6.3.2 Cable Shearing. There are three basic requirements to be met in the shearing operation: (1) the cut must be perpendicular to the conductors, (2) the conductor ends must not be deformed, and (3) the linear dimensions should be accurate. The cut length shall include the mock-up cable length plus the proper allowance for strip dimensions. The precision D-Arco hand shear is commonly used. Paper cutters and heavy duty scissors provide less satisfactory results and require dimensional marking guides (Fig. 6-6).

6.3.3 Cable Stripping. The stripping lengths may be obtained from MIL-C-55544 for FCC connectors. The exposed conductors should be protected during handling by a device similar to the modified heavy duty paper clip (Fig. 6-7).

6.3.3.1 Cable Stripping Processes.

6.3.3.1.1 Chemical Stripping. All of the FCC insulating and shielding materials used, except the FEP Teflon, can be chemically stripped.

Teflon FEP Fluorocarbon film is virtually impervious to all common chenicals; therefore, any cable system containing FEP cannot be chemically stripped unless it is done in combination with some method which will remove the FEP.

The NASA termination system uses the conductor as the plug contact. Inasmuch as the flat conductor serves as the contact surface, the insulation and shield must be removed prior to terminating the cable into the plug. The actual length of stripped conductor depends on the plug being used. This is referenced in the corresponding Methode Drawing listed in MIL-C-55544.

6.3.3.1.1.1 Polyester (Mylar) Cable. A cable system employing Mylar insulation bonded with polyester adhesive can be chemically stripped. Table 6-1 presents the stripping solutions.

TABLE 6-1. SOLUTIONS FOR REMOVING MYLAR

Solution	Source	Stripping Time (min)	Stripping Temperature (°C)
DS 101 H	Methode Electronics, Inc.	3 to 8	93 to 99
Sulphuric Acid	FED 0-A-115, Class A	2 to 4	93 to 99

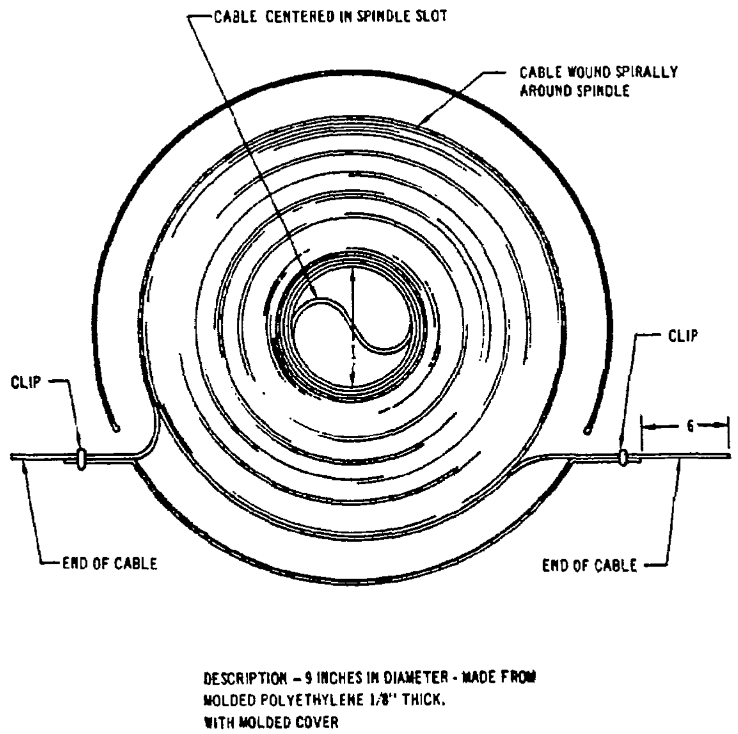


FIGURE 6-5. FCC handling device.

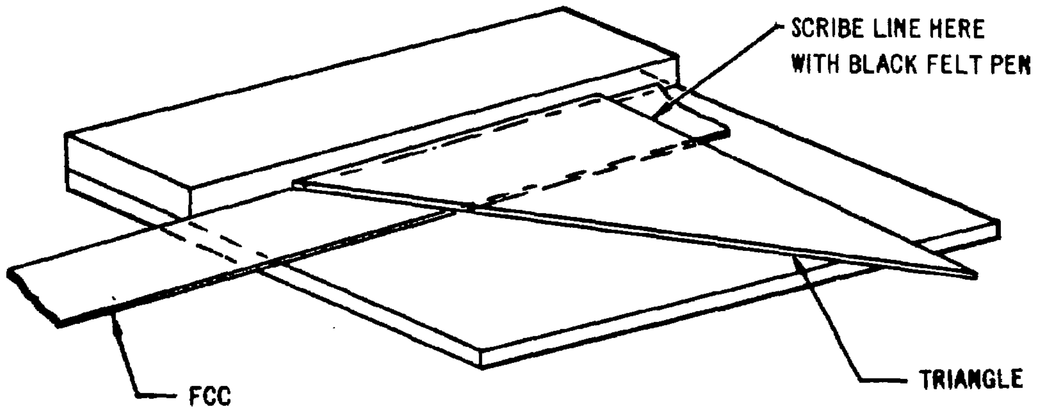


FIGURE 6-6. Right-angle marking tool (conceptual).

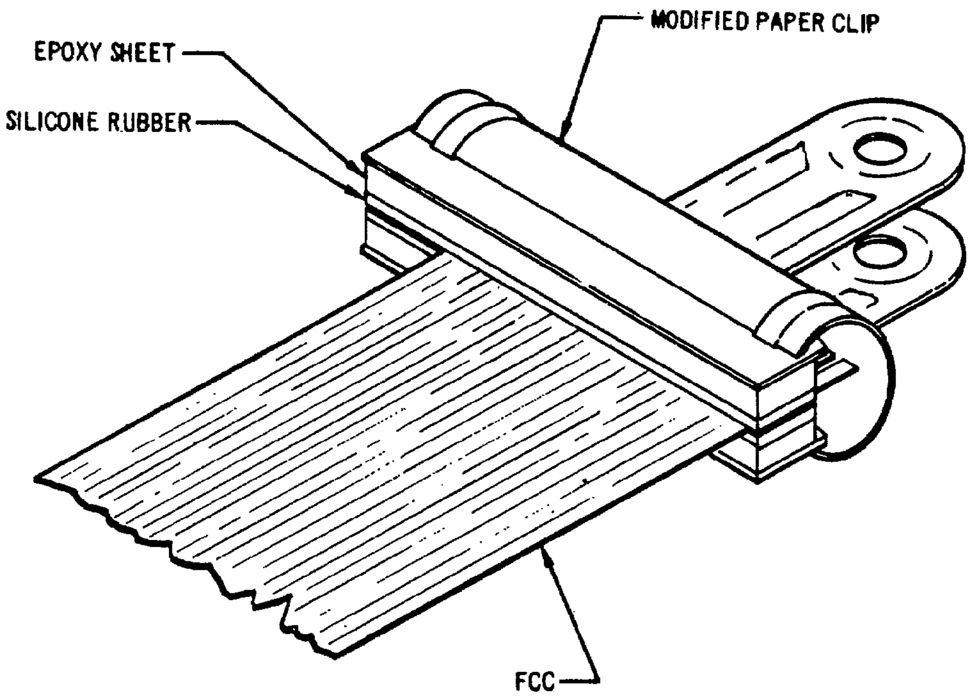


FIGURE 6-7. Conductor protecting clip.

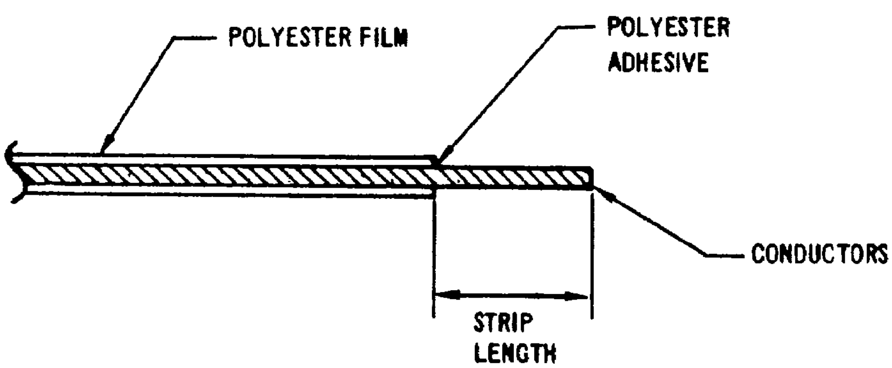


FIGURE 6-8. Unshielded polyester configuration.

The cable is masked to define the stripping area and to prevent degradation of the adjacent cable. See Table 6-2 for suitable Maskants.

TABLE 6-2. MASKANTS

Maskant	Source
Mascoat No. 2	Western Coating Company, Los Angeles, California
Maskant No. 1-2021-66	Organoceram Inc., Placentia, California
TFE Teflon Tape	3M Company, St. Paul, Minnesota
Lead Foil Tape No. 420	3M Company, St. Paul, Minnesota

6.3.3.1.1.1.1 Unshielded. The cable configuration is shown in Figure 6-8. The procedure for the stripping of the insulation to expose the conductors is as follows:

a. Apply Maskant around cabling at desired length from cut end of cable.

b. Immerse the cable in stripping solution (Table 6-1) to remove insulation.

c. Spray-rinse the stripped conductors with water to remove any residual insulation.

d. Remove Maskant. Any Maskant remaining on the cable may be removed with Toluene (TT-T-548) and a cotton swab.

e. Air-dry cable.

6.3.3.1.1.1.2 Shielded. The shielded-cable configuration consists of a polyester (Mylar) and metal-shield lamination (Fig. 6-9). The procedure for the stripping of the insulation and shielding to expose the conductors is as follows:

Removing Outer Insulation

a. See Paragraph 6.3.3.1.1.1.1.

Removing Shield

b. Apply lead tape around cabling at desired length from cut end of cable. Be sure tape is pressed firmly against cable and shield to eliminate wicking of the stripping solution.

c. Strip metal shield with ferric chloride etchant (45-degree Baume, commercially available). Etchant may be used at room temperature.

Removing Inner Insulation

d. Remove tape and apply new tape around the cabling at desired length from conductor ends.

e. Immerse the cable in stripping solution (Table 6-1) until the insulation is removed.

f. Spray-rinse the stripped conductors with water to remove any residual insulation.

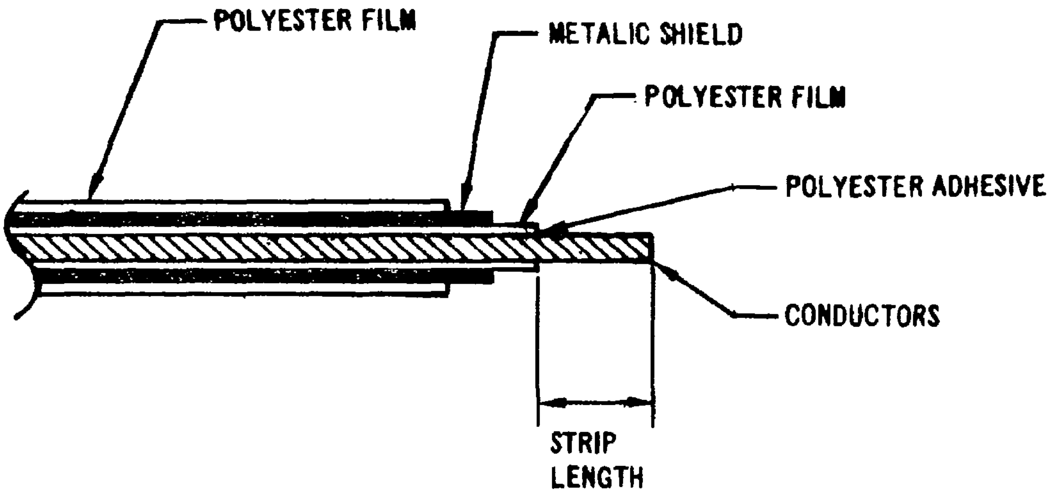


FIGURE 6-9. Shielded polyester configuration.

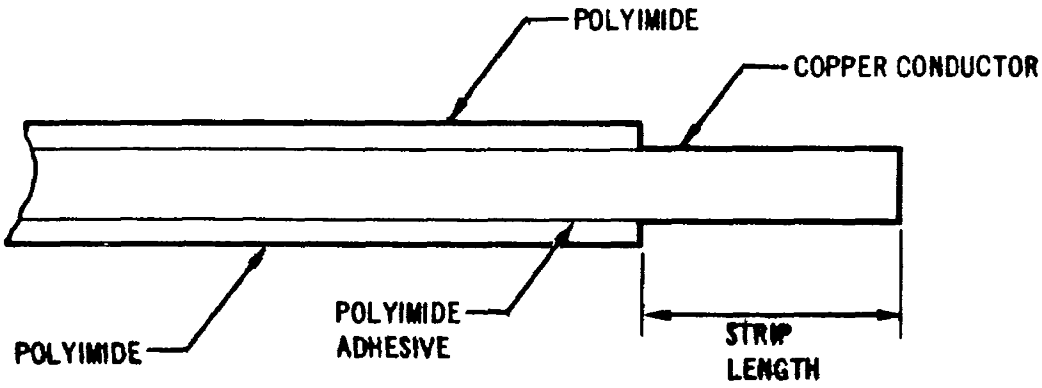


FIGURE 6-10. Unshielded polyimide cable.

g. Remove tape, and remove residual adhesive with Toluene TT-T-548 on a cotton swab and dry.

h. Protect stripped conductors (Fig. 6-7).

6.3.3.1.1.2 Polyimide Cable. An all-polyimide cable can be chemically stripped by using the step-by-step approach outlined below for both an unshielded and a shielded cable.

The cable is masked prior to stripping to prevent degradation of the insulation beyond the designated area.

The stripping solution listed in Table 6-3 can be used in insulation removal. The Maskants listed in Table 6-2 have also been applied to the cable and found to be acceptable in preventing deterioration of the insulation beyond the specified stripping area.

6.3.3.1.1.2.1 Unshielded. The unshielded cable configuration consists of polyimide and copper conductors as shown in Figure 6-10. The procedure for stripping of insulation to expose the conductors is as follows:

a. Apply Maskant (Table 6-2) around cabling at desired length from cut end of cable with the aid of the masking fixture shown in Figure 6-11, or with other suitable fixture.

b. Immerse the cable in stripping solution (Table 6-3) to remove insulation.

TABLE 6-3. STRIPPING SOLUTIONS FOR POLYIMIDE INSULATION MATERIALS

Solution	Stripping Time, 2-Mil Polyimide (min)	Stripping Temperature (°C)
(1) MER-1	3 to 6	93 to 99
(2) Lea Insolstrip	3 to 6	93 to 99
(3) PT-5-ML	5 to 8	96 to 99
(4) Endox L-76	5 to 8	99 to 110
(5) Clarcosub	5 to 10	93 to 99
(6) Sodium Hydroxide (50 parts Na OH to 50 parts H_2O	5 to 10	99 to 110

Notes:

(1) and (3) — London Chemical Company, Incorporated, Melrose Park, Illinois.

(2) — The Lea Manufacturing Company, Waterbury, Connecticut.

(4) — Ethone Incorporated, West Haven, Connecticut.

(5) — Clarkson Laboratories, Camden, New Jersey.

(6) — O-S-598 Types 1 or 2.

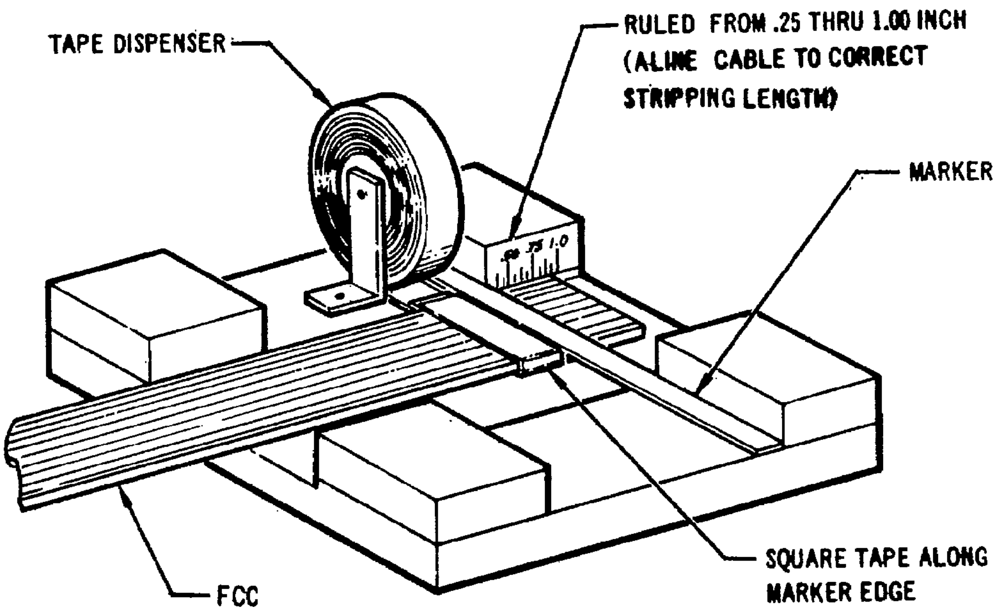


FIGURE 6-11. Masking fixture.

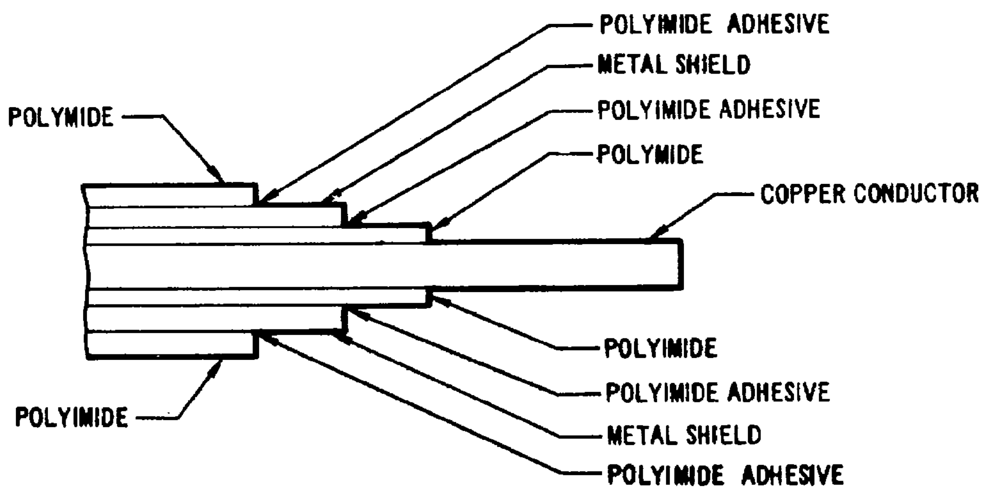


FIGURE 6-12. Shielded polyimide cable.

c. Spray-rinse the stripped conductors with water to remove any residual polyimide.

d. Remove tape. Any tape adhesive remaining on the cable may be removed with Toluene (TT-T-548).

e. Air-dry cable.

f. Protect stripped conductors (Fig. 6-7).

6.3.3.1.1.2.2 Shielded. The shielded-cable configuration consists of polyimide and a metal-shield lamination as shown in Figure 6-12.

The procedure for the stripping of the insulation and shielding to expose the conductors is as follows:

a. Remove outer insulation per paragraph 6.3.3.1.1.2.1 (a through e).

b. Apply Maskant around cabling at desired length from cut end of cable. Be sure tape is pressed firmly against cable and shield to eliminate wicking of the stripping solution.

c. Strip metal shield. Ferric chloride (45-degree Baume) etchant may be used at room temperature.

d. Remove tape, dry cable, and apply new tape around the cabling at desired length from conductor ends.

e. Immerse the cable in stripping solution (Table 6-3) until the polyimide is removed.

f. Spray-rinse the stripped conductors with water to remove any residual polyimide.

g. Remove tape. Any tape adhesive remaining on the cable may be removed with Toluene (TT-T-548).

h. Protect stripped conductors (Fig. 6-7).

i. Air-dry cable.

6.3.3.1.2 Mechanical Stripping.

6.3.3.1.2.1 Unshielded TFE Teflon Cable. The best present method for stripping this type of cable is the use of rotary abrasive-type stripping tools as described in Paragraphs 6.3.3.2.4 through 6.3.3.2.6.

6.3.3.1.2.2 Polyimide/FEP Cable.

6.3.3.1.2.2.1 Unshielded. To strip the insulation from the end of polyimide/FEP unshielded cable use the NASA-developed mechanical stripper (Fig. 6-13); also refer to Paragraph 6.3.3.2.1.

6.3.3.2 Cable-Stripping Tools.

6.3.3.2.1 NASA Cold Blade Stripper. Properly manufactured cables with FEP-bonded polyimide (Kapton) films can be stripped easily and quickly with a sharp blade stripper without applying heat (Fig. 6-13). The cutter blade must be adjusted to the thickness of the cable insulation. Additional cleaning is not needed except for routine pickling before electroplating.

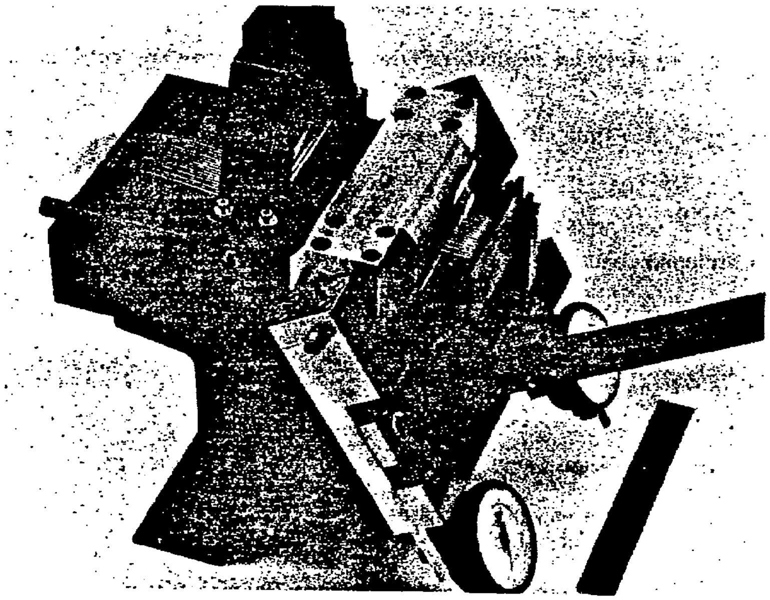


FIGURE 6-13. NASA/MSFC cold blade FCC stripper.

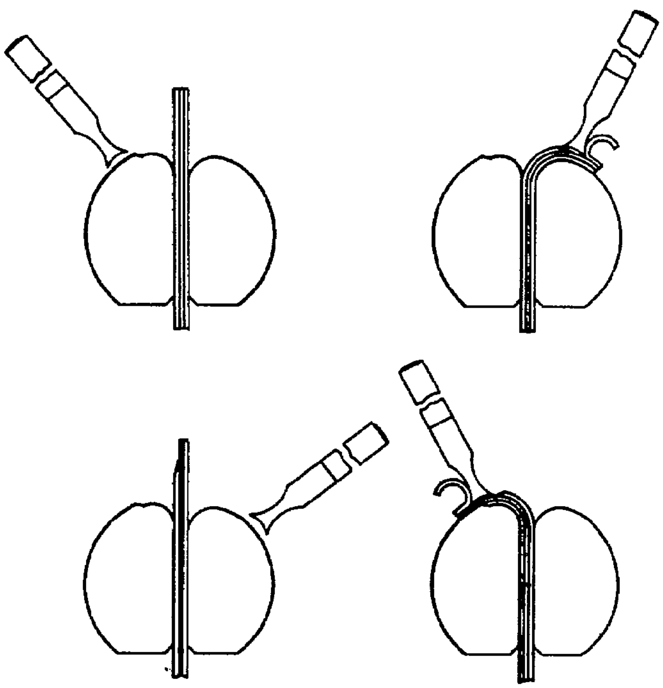


FIGURE 6-14. Stripping operations - NASA mechanical stripper.

The success of this cold blade stripper depends on the fair or poor bond of FEP to the conductors. If the bond strength is very high, then the cold blade stripper fails. A hot blade stripper may do the job superficially, leaving a thin smear of FEP that must be removed mechanically.

Briefly, the method of operating the cold stripper (Figs. 6-13 and 6-14) is as follows: The blade clearance gages are first checked to ensure that the blade is adjusted to cut through the Kapton or outer insulation but does not touch the conductors. The end of the cable is positioned in the stripper against the cable stop. The position of the cable is maintained by clamping. Rotating the blade in one direction strips one side of the cable. Moving the handle in the opposite direction strips the other side. The clamp is released and the cable is removed from the stripper.

An enlargement of a stripper blade profile for stripping Kapton FEP in the cold stripper is shown in Figure 6-15. The established dimensions will produce optimum results in the stripping operation.

6.3.3.2.2 NASA/MSFC Plane Stripper (Drawing No. PM2235).

Description.

The plane stripper (Fig. 6-16) functions on a principle similar to that of a carpenter's plane. An adjustable blade is rigidly supported by a frame that is pushed across the material to accomplish the required stripping.

With the ±0.0001-inch-depth precision required for stripping flat cables, however, it is necessary to supplement the basic "plane" with a jig for holding the cable and a guide to keep the plane square with the cable and to control the width advancement of each successive cut. The blade (Fig. 6-17) clamped between the two frames produces a shearing action at the point of the blade and a shearing action between the blade and frame, thereby producing a very clean strip.

Application.

The plane stripper can be used to strip either shielded or unshielded cables, provided the shields do not contain waves or dents and all conductors are in line with each other. The blade can be adjusted as necessary for removing insulation from the shield or conductor, as the case may be. Almost any insulating material can be removed with the plane stripper, but the stripper works best with the FEP-bonded insulations that are not fused to the conductors. The stripper is readily portable and accommodates the stripping of all cable widths without special adjustment.

Operating Procedure, Unshielded Cables.

The blade is adjusted by loosening the blade clamping screw (Fig. 6-17) and by manipulating the blade adjustment screws.

The cable is placed into the longitudinal slot of the cable jig; the plane guide is placed upon the cable with the registration pin in the hole to the extreme left. Each time the plane is pushed across the cable, the plane guide is moved one registration mark to the right. When all marks have been cleared, a shim is placed in the stripped area, the cable is turned over, and the stripping procedure is repeated. Figure 6-18 shows an unshielded cable that has been stripped and is ready to be terminated.

The insulation at the end of the cable is left to support the conductors during the stripping process, and to keep them from being bent before the cable is terminated with a plug.

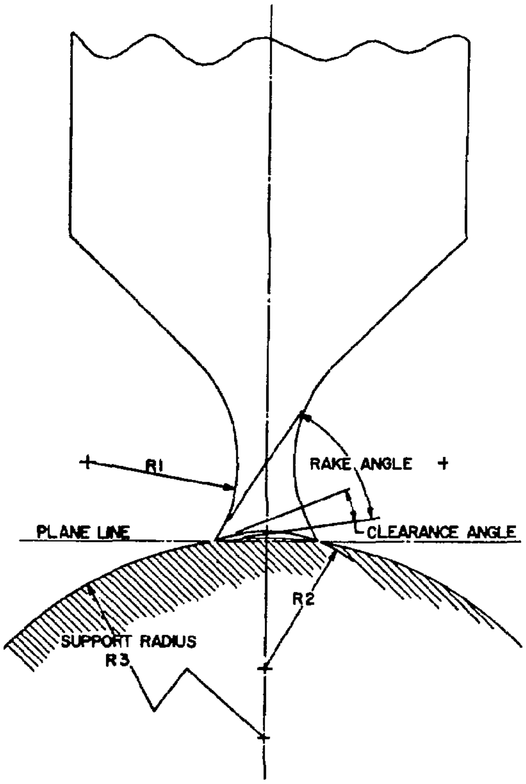


FIGURE 6-15. Stripper blade profile - NASA mechanical stripper.

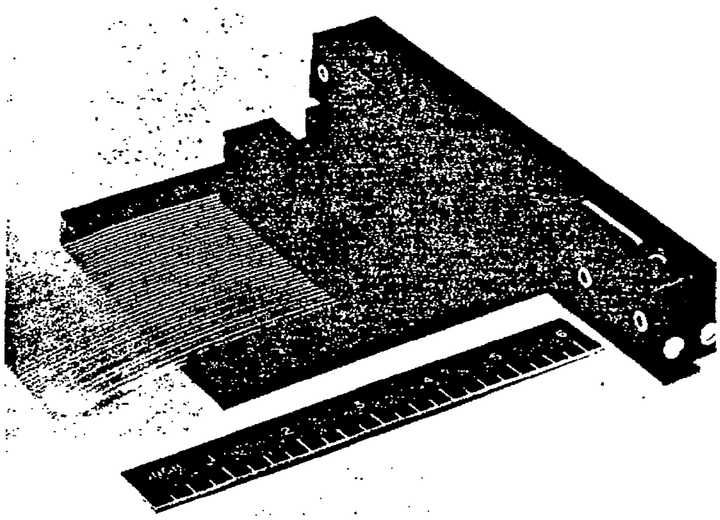


FIGURE 6-16. NASA/MSFC plane stripper (Drawing No. 2235).

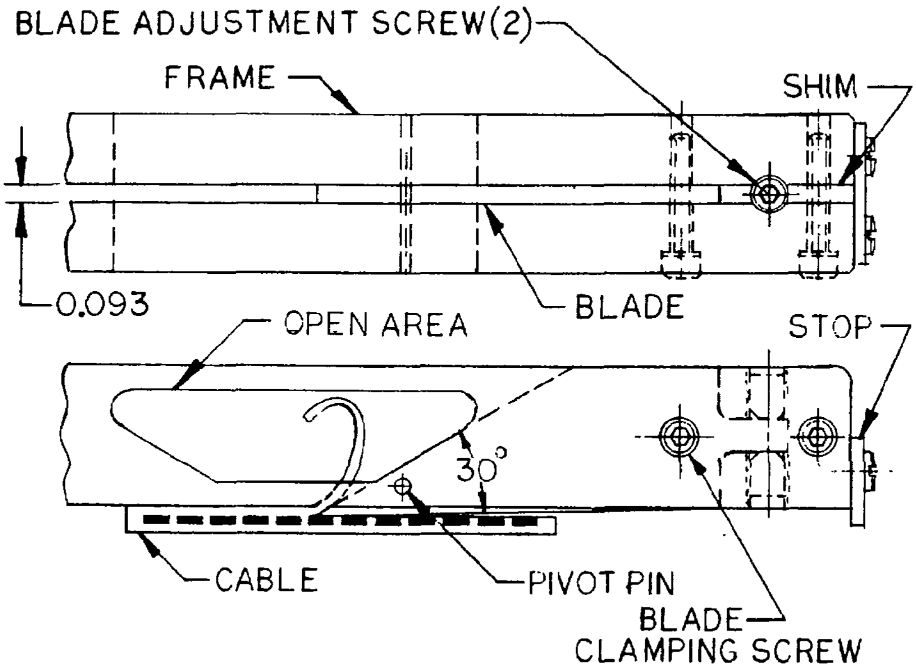


FIGURE 6-17. Blade action of the plane stripper.

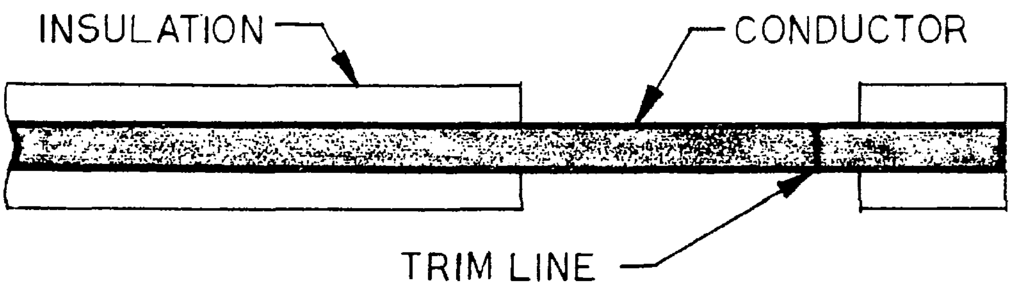


FIGURE 6-18. Unshielded cable stripped with plane stripper.

Operating Procedure, Shielded Cables.

The basic procedure for stripping shielded cables is the same as that given for stripping unshielded cables. However, more steps are involved and more than one plane should be used. The blade of a single plane may be adjusted for each of the three required depths (Fig. 6-19), but for production, the use of three planes, each having a different blade adjustment, is mandatory.

6.3.3.2.3 Gore Stripper. The Gore stripper is designed and manufactured by W. L. Gore and Associates, Newark, Delaware, for stripping Teflon-insulated FCC and round conductor ribbon cables. A pair of parallel, sharp, knife edges mounted in a sliding frame are adjusted to a distance of a little more than the conductor thickness. After the cable is clamped, the pair of knives is pushed across the cable at a distance from the cable end to be stripped. This cuts the top and bottom sides of the insulation, which is then removed by lever-arm force applied to the blade frame in the direction parallel to the conductors. Figure 6-20 shows a Gore stripper, modified by MSFC for experimental purposes. This stripper can only be applied when the insulation is not bonded to the conductors.

6.3.3.2.4 Viking FCC Stripping Machine. The Viking Industries, Inc., Canoga Park, California, manufactured (Contract NAS8-11742) a flat cable stripping machine that uses one wheel only (Fig. 6-21). Its axis of rotation is parallel to the conductor length. This means the friction force is crosswise to the conductors and has a tendency to bend the conductors. To minimize the bending, the stripping should not extend to the cable end, but should leave about a half-inch unstripped to be cut off after stripping and plating.

The wheel diameter of the Viking stripper is 2.2 inches, the width is 0.25 inch, the motor has 0.5 horsepower, and the wheel surface speed is adjustable up to 9,000 feet per minute. The table feed system is motor driven and can be regulated for various speeds.

6.3.3.2.5 Rush FCC Stripping Machine. This machine is designed by Rush Wire Stripper Division of the Eraser Company, Inc., Syracuse, New York, and has been the first friction wheel cable stripper commercially available (Fig. 6-22). The machine has two wheels, 20 inches wide and 1.25 inches in diameter, rotating in opposite directions. An 0.25-horsepower motor drives both wheels with about 300 feet per minute surface speed. To prevent grabbing of the cable, a clamp must be used to control the area of the cable to be stripped. For convenience and safety of operation, a guiding mechanism was added for the cable clamp. The older model Rush stripper has insufficient pressure and thickness control, besides having cantilevered wheel shafts that cause a tapered gap between the grinding wheels.

6.3.3.2.6 Carpenter FCC Stripping Machine. The Model 44 (Fig. 6-23) is a product of the Carpenter Manufacturing Company in Manlius, New York. It uses two wheels, 1.5 inches in diameter and 0.25-inch wide, rotating in the same direction. The axis of rotation is parallel to the FCC conductors. The 0.25-horsepower motor drives the wheels with about 800 feet per minute constant surface speed. Provision is made to adjust the gap between the wheels as well as the position of the gap with regard to the cable. The grinding force can also be selected.

Since the working surfaces of two wheels are moving in opposite directions as they touch the cable, the force acting at the conductors is nearly compensated which results in a minimum bending danger for the conductors.

6.3.4 Conductor and Shield Plating. The following procedure applies to the plating of the copper conductors and shields to be used in the FCC conductor-contact plug system. The plating serves two purposes: (1) good surface conductance, and (2) prevention of copper corrosion. The nickel plating serves as a corrosion barrier and as a receiving surface for the gold plating that provides excellent surface conductivity and resistance to contact wear.

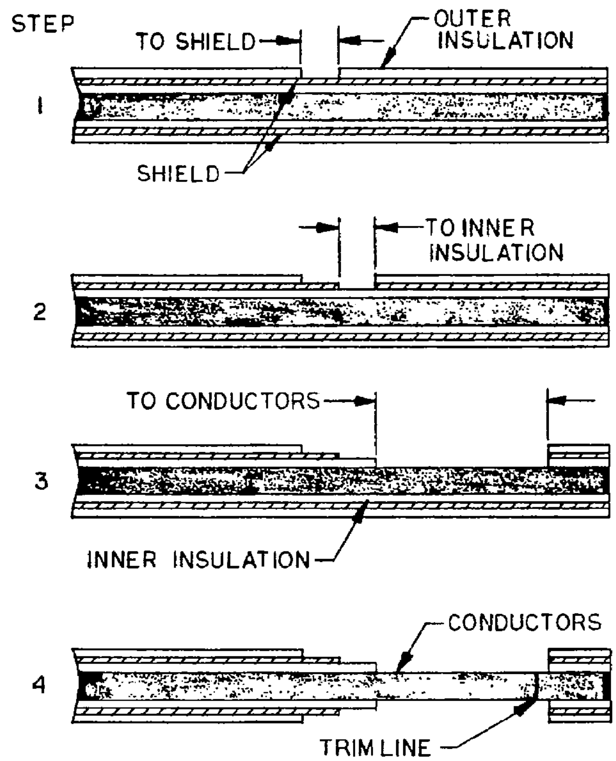


FIGURE 6-19. Shielded cable stripping with plane stripper.

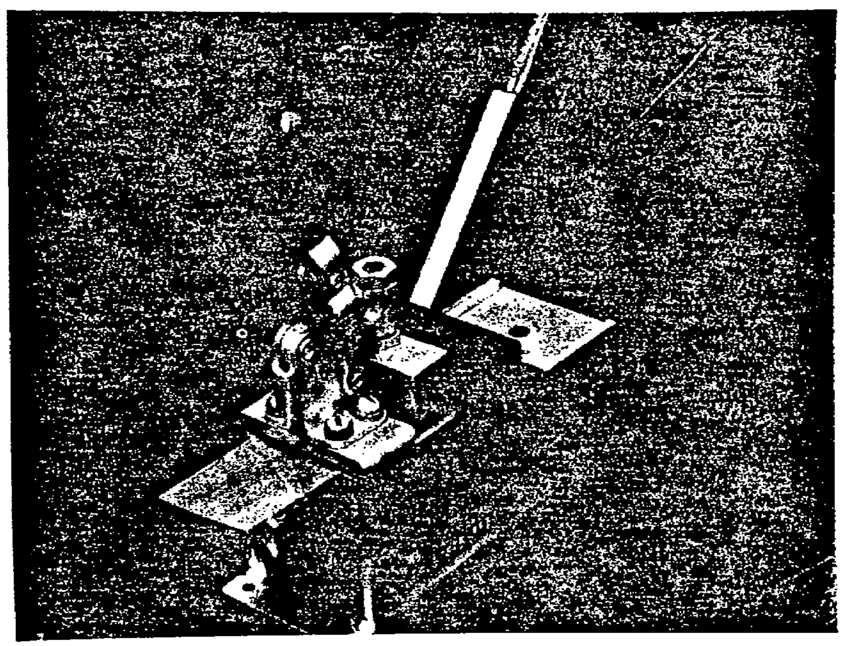


FIGURE 6-20. FCC cold blade stripper (W. L. Gore).

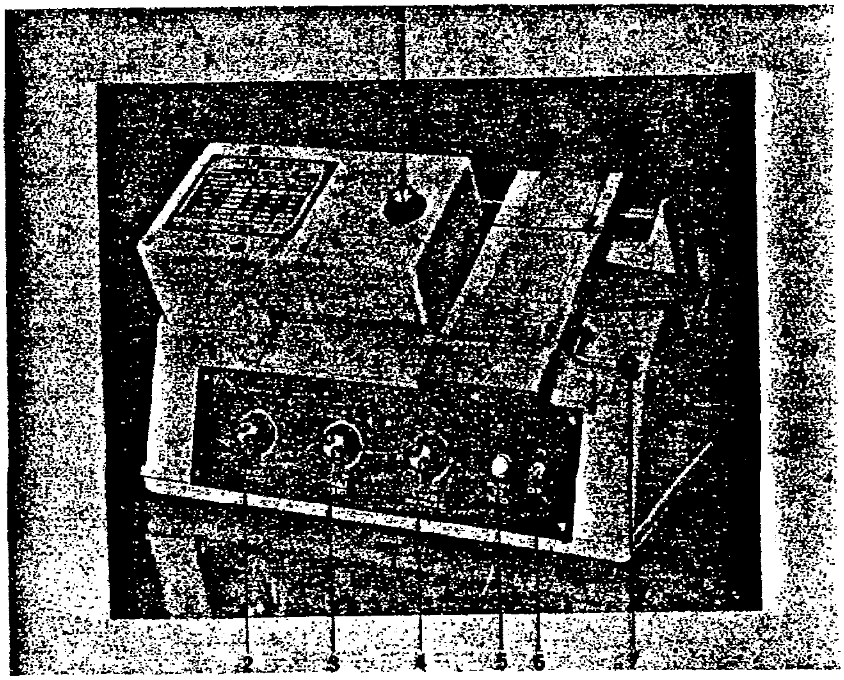


FIGURE 6-21. Abrasive wheel stripper (Viking Industries).

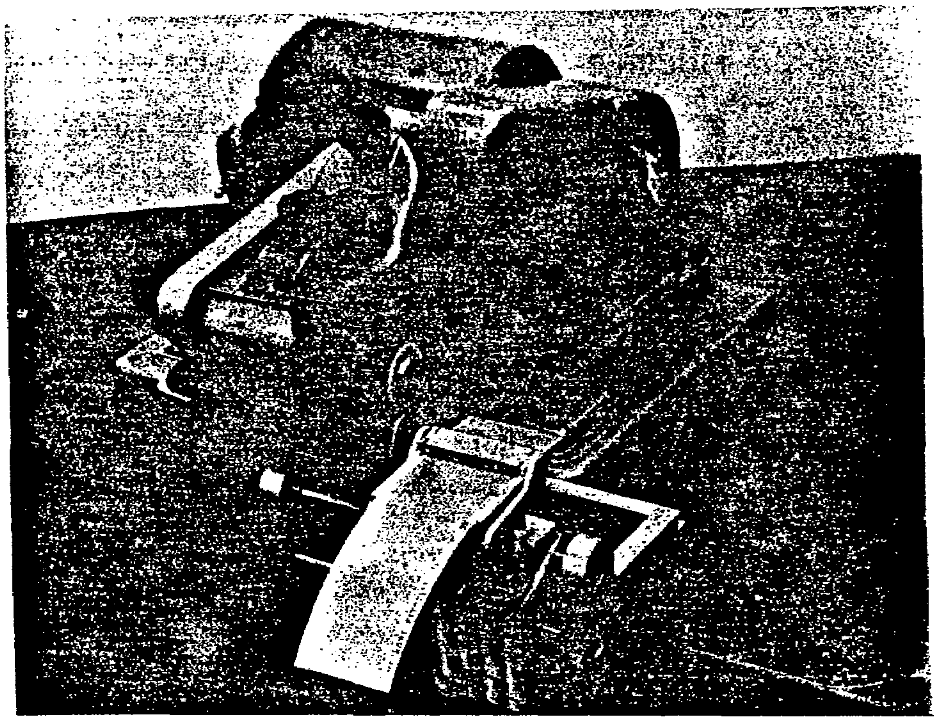


FIGURE 6-22. Abrasive wheel stripper (Rush Division of Eraser Co., Inc.).

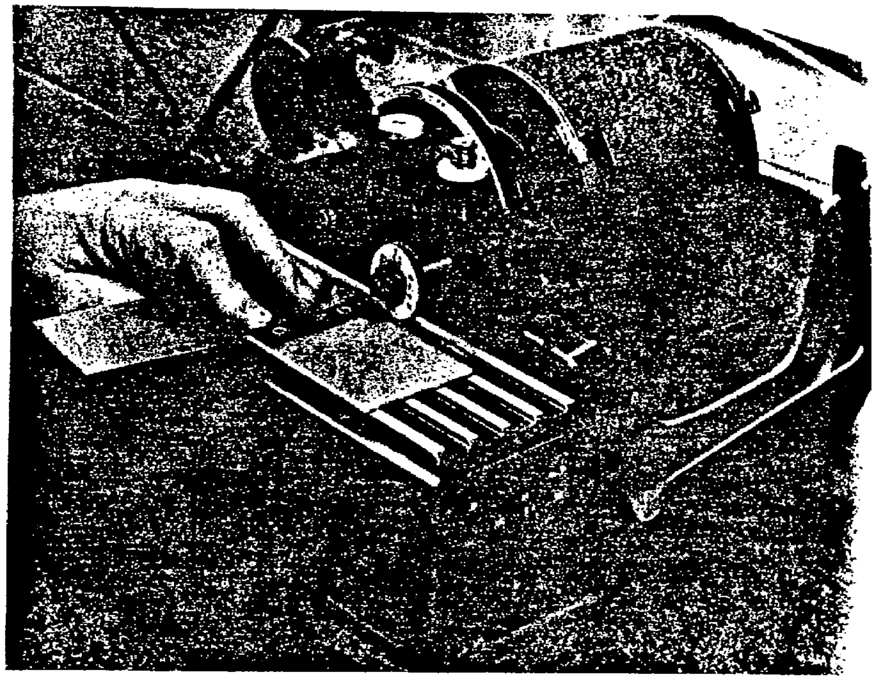


FIGURE 6-23. Abrasive wheel stripper (Carpenter Manufacturing Co.).

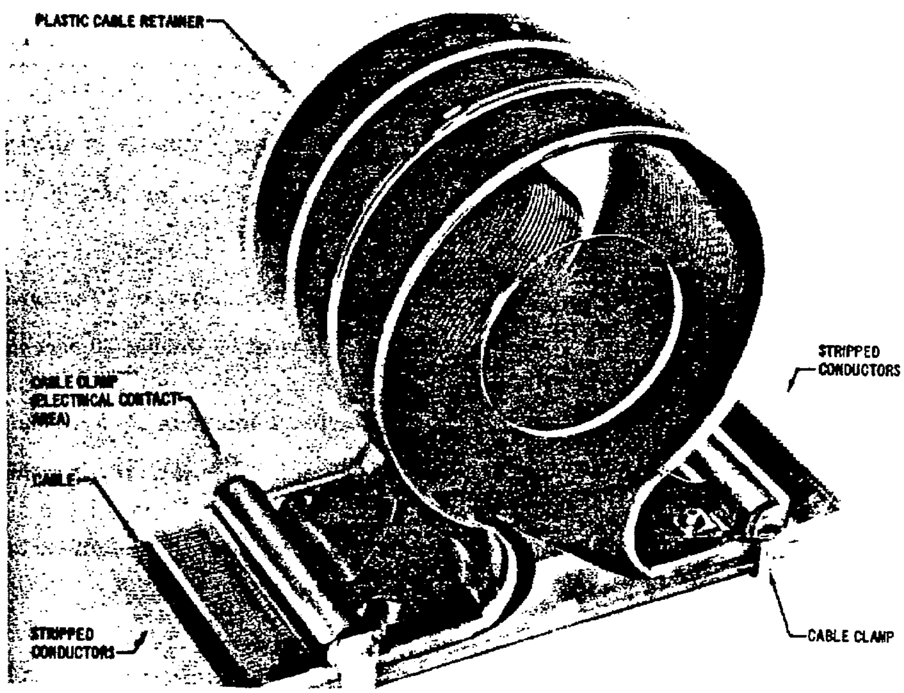


FIGURE 6-24. NASA/MSFC plating rack with cable.

CAUTION

To reduce the ionic action of dissimilar metals, the conductors are plated with nickel and gold. After the conductors have been stripped and the cleaning and plating operation has been started, do not allow more than 30 minutes to elapse between each operation until the conductors are plated. This will prevent subsequent oxidation.

Procedures for plating shall conform to the appropriate federal and military specifications as follows:

a. QQ-N-290 (Federal) - Nickel plating (Electro-deposited), Class 2

b. MIL-G-45204 (Military) - Gold plating (Electro-deposited), Type II, Class 1

The preparatory steps toward implementation of both nickel and gold plating are listed below. For detailed procedures, refer to the respective paragraph for plating (Paragraph 6.3.4.1 for nickel plating or Paragraph 6.3.4.2 for gold plating).

a. Mount cable into plating rack (Fig. 6-24). Clean conductors and attach jumper wire from cathode rod to rack.

b. Chemically clean conductors. To minimize wicking of the plating solution, do not submerge cable into the solutions beyond the stripped portion of the conductors.

c. In an emergency, if a plating rack is not available, electrical contact between the cathode rod and cable may be made by carefully applying Scotch Electrical Tape No. X-1226, 3M Company, St. Paul, Minnesota (or equal) to the exposed conductors and connect the jumper wire from the cathode rod to the tape. Plate opposite end of cable. Use extreme care in removing tape to avoid bending conductors.

6.3.4.1 Nickel Plating. If the cable has bare copper conductors, the conductor contact (stripped) areas shall be nickel plated per QQ-M-290 and the following subparagraphs (see Figure 6-25 for sequence).

6.3.4.1.1 Preparation for Plating. The preparation for plating is as follows:

a. Dip conductors in plater's cleaner (P-C-535A) for 60 to 90 seconds.

b. Rinse in overflow rinse for a minimum of 15 seconds.

c. Spray-rinse with deionized water for a minimum of 30 seconds.

d. Dip in ammonium persulfate, 10 percent by weight (90 percent H_2O), for 15 to 30 seconds.

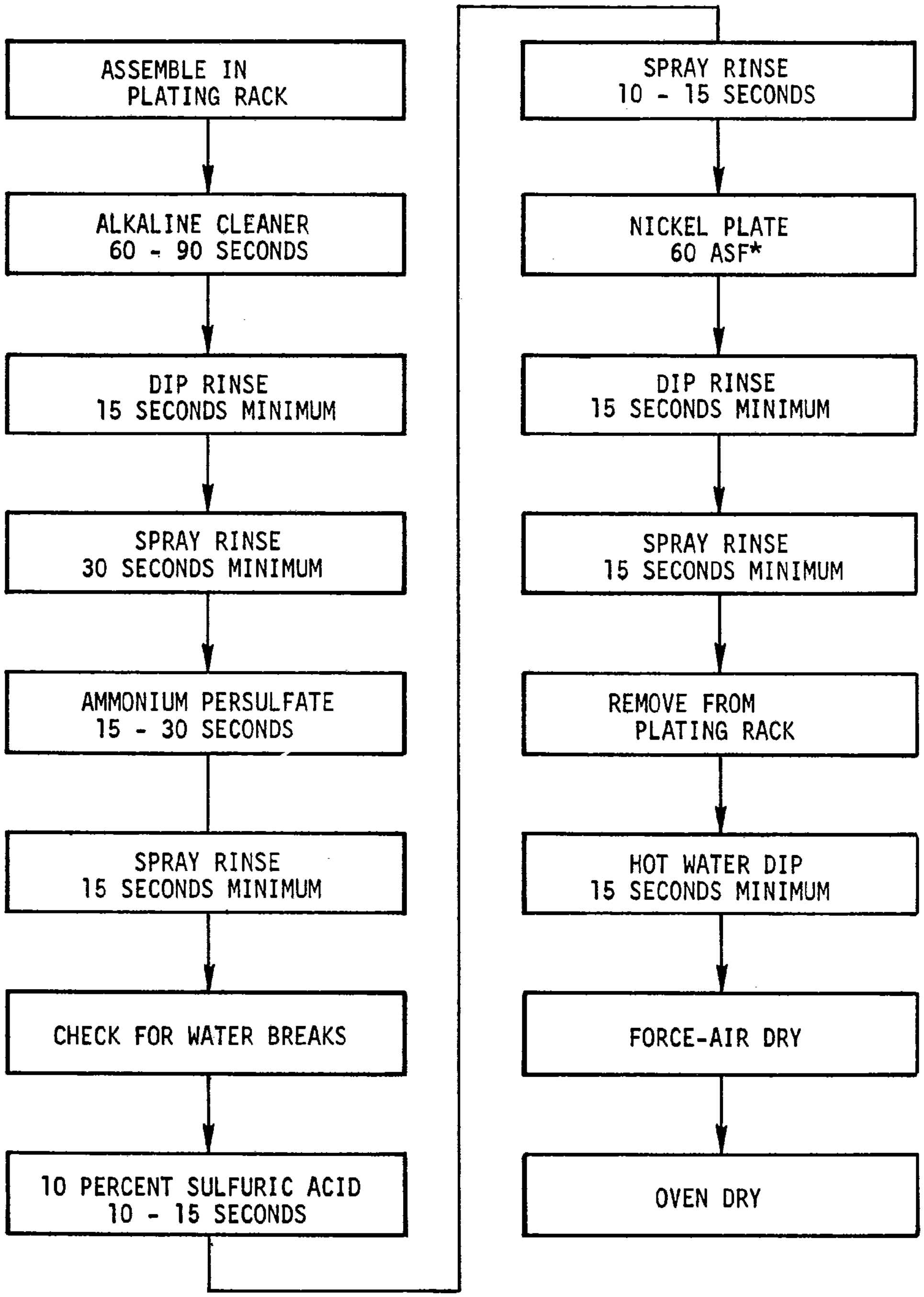
e. Spray-rinse with deionized water for a minimum of 15 seconds.

f. Check both sides of conductors for water breaks. If water breaks are present, reclean conductors per Paragraph 6.3.4.1.1, steps a through e.

g. Dip in sulfuric acid (Fed O-A-115 Class A, Grade 1) for 10 to 15 seconds.

h. Spray-rinse with deionized water for 10 to 15 seconds.

i. Nickel plate immediately.



*ASF - amperes per square foot

FIGURE 6-25. Process flow sequence for nickel plating.

6.3.4.1.2 Nickel-Plating Procedure. The nickel plating procedure is as follows:

a. Connect jumper wire from cathode rod to plating rack, before placing the conductors in the plating solution.

b. Lower conductors into the solution, making sure cable is positioned vertically.

c. Plate for a time sufficient to obtain a plate thickness of 0.000,050-inch (0.000,127-cm) minimum.

d. Dip-rinse the cable for a minimum of 15 seconds immediately upon removal from the nickel tank.

e. Spray-rinse with deionized water for a minimum of 15 seconds.

6.3.4.1.3 Post-Nickel-Plating Procedure. The post-nickel-plating procedure is as follows:

a. Soak in clean, heated, deionized or distilled water for a minimum of 15 seconds, maintaining water temperature at 150° ±30° F (66° ±17° C).

b. Force-dry with compressed, filtered air.

c. Place cable in a clean, filtered, circulating air oven for 30 minutes at 126° ±10° F (52° ±6° C).

6.3.4.2 Gold Plating. For the gold-plating sequence see Figure 6-26.

6.3.4.2.1 Cleaning Procedure. The cleaning procedure is as follows:

a. Immerse cable ends of racked cables in plater's cleaner (P-C-535A) for 60 to 90 seconds.

1. Wipe thoroughly with soft cellulose sponge.

2. Wipe only towards ends of the conductors so they will not be deformed during this process.

b. Rinse in overflow rinse for a minimum of 1 minute.

c. Spray-rinse with deionized water for a minimum of 15 seconds.

d. Check both sides of the conductor for water breaks. If water breaks are present, reclean conductor per Paragraph 6.3.4.2.1, steps a through c.

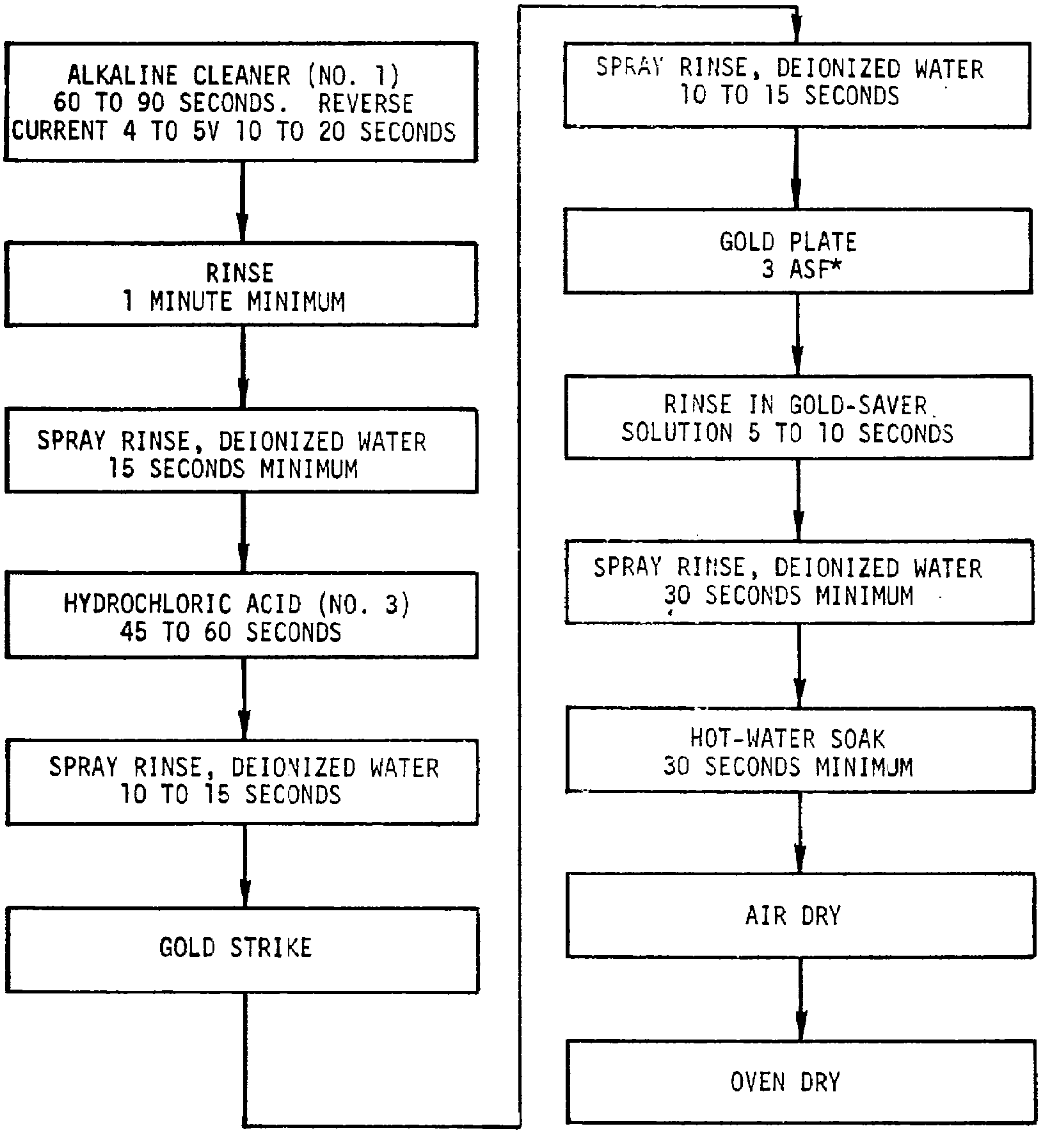
6.3.4.2.2 Gold-Strike-Plating Procedure. It is necessary to gold-strike the surface of the nickel-plated conductor before it is gold plated to enable the surface to better receive the final gold plating. The procedure for gold-strike plating is as follows:

a. Connect jumper wire from cathode rod to plating rack before placing any part of the conductors in solution, and turn current on.

b. Lower rack into solution and strike for 25 to 35 seconds at proper voltage.

c. Leave current on and jumper wire connected between cathode rod and plating rack while withdrawing conductors from solution.

d. Spray-rinse conductors with deionized water for 10 to 15 seconds.



*ASF - amperes per square foot

FIGURE 6-26. Process flow sequence for gold plating.

6.3.4.2.3 Gold-Plating Procedure. After the gold-strike plating is complete, the steps listed below are to be followed for the gold plating:

a. Connect jumper wire from cathode rod to plating rack before placing any part of the conductor in the solution.

b. Lower conductors into the plating solution, making sure conductors are positioned vertically.

c. Plate for a time sufficient to obtain a plating thickness of 0.000,050-inch (0.000,127-cm) minimum.

d. At the conclusion of the plating cycle, permit gold solution to drain from conductors back into tank.

6.3.4.2.4 Post-Gold-Plating Procedure. After the nickel-plated conductors have been gold plated, the post-plating procedure listed below shall be followed:

a. Spray-rinse with deionized water for a minimum of 15 seconds.

b. Soak in clean, heated, deionized or distilled water for a minimum of 30 seconds. Maintain water temperature at 150° ±30°F (66° ±16°C).

c. Force-dry with clean, filtered, compressed air.

d. Place cable in clean, filtered, circulating air oven for 30 minutes at 126° ±10°F (52° ±6°C).

e. Protect exposed conductors during subsequent handling.

6.3.5 FCC Plug Assembly.

6.3.5.1 Molded-On.

6.3.5.1.1 Rectangular (MIL-C-55544). The assembly procedure for molded-on plugs consists of three basic phases: (1) parts assembly, (2) molding, and (3) finishing (consisting of sprue removal, potting, and installation of the outer seal). This plug is shown in Figure 6-27.

6.3.5.1.1.1 Parts Assembly. The following is a detailed procedure for assembly of molded-on plugs:

a. Cables shall have been stripped per Paragraph 6.3.3 and plated per Paragraph 6.3.4 prior to assembly. The conductors shall have been exposed (stripped) a distance of 0.47 ±0.01 inch.

b. Make sure the registration of the cable corresponds to the requirements of the engineering drawing.

c. Thread conductors through windows of window piece.

d. Lift cam handle of seating tool (Fig. 6-28) into horizontal position, and retract the cam to provide space between the pressure plate and base.

e. Pass the conductors and window piece through the opening from the lower side of the tool.

f. Spread conductors with a suitable tool, insert cabling separator (thin one) between cabling strips, and lower the window piece almost to the base.

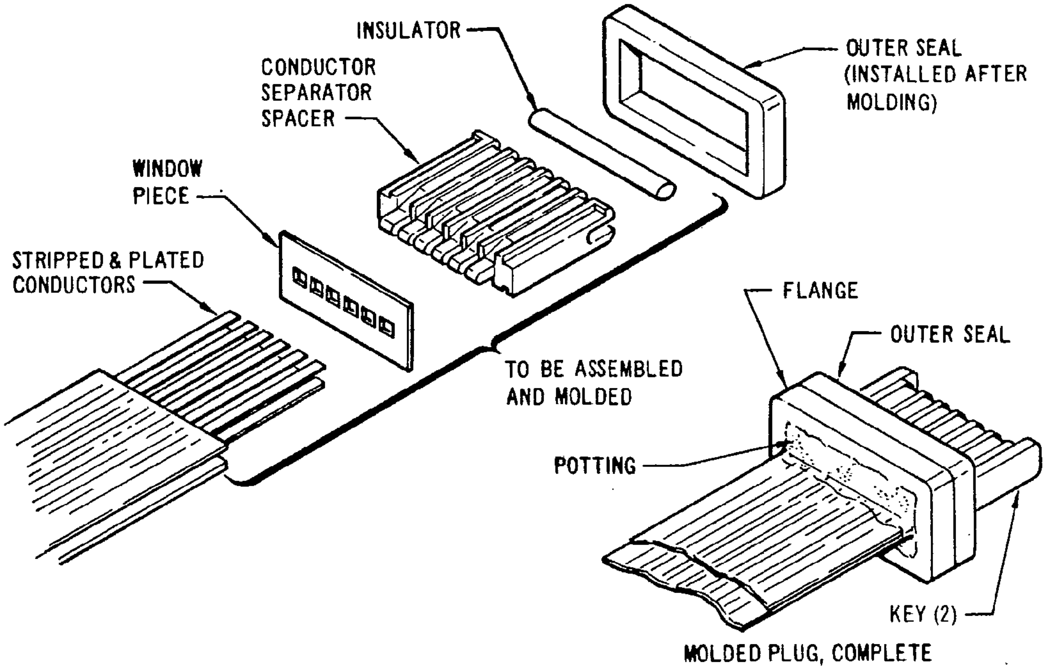


FIGURE 6-27. Molded-on plug.

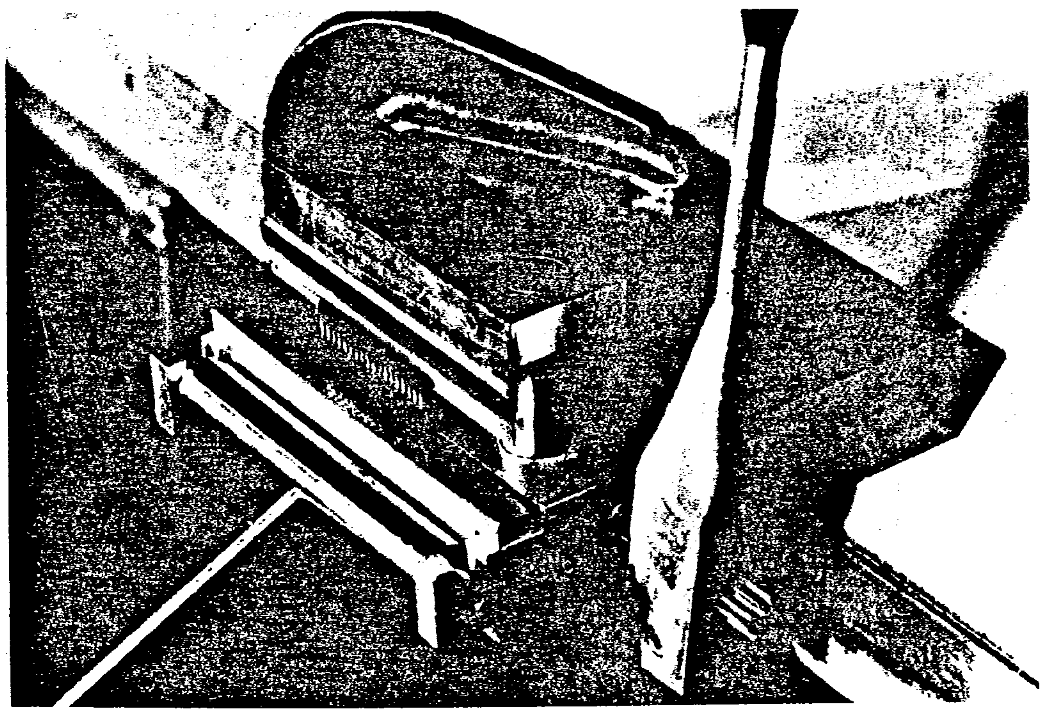


FIGURE 6-28. Seating tool - cable, window, and shuttle (spacer).

g. Move pressure plate against cabling, apply slight pressure with the cam handle, and press window piece to the base with the seater.

h. Apply full pressure to the pressure-plate lift seater and install conductor separator. (Turn small holes in conductor spacer toward cabling strip which is to be on the unkeyed side.)

i. Seat the conductor spacer, comb conductors into conductor spacer grooves, and remove cabling from the seating tool.

j. Open all jaws of the folding tool (Fig. 6-29) and insert cabling through the front opening to the adjustable stop.

k. Clamp conductor spacer with vise jaws by means of the vise jaws actuator.

l. Rotate left-horizontal jaw actuator counterclockwise to actuator stop, and return actuator stop, and return actuator to the jaw-open position.

m. Lower the vertical-fold plate actuator until the plate has folded the conductors into the conductor spacer groove.

n. Rotate the right horizontal-fold jaw actuator clockwise to actuator stop, and return actuator to the jaw-open position.

o. Repeat step m.

p. Remove cabling from folding tool, cut and install insulator (1/16-inch (0.15 cm) diameter) round, silicone-rubber rod into conductor spacer, and cut off flush at both ends using an Xacto knife.

6.3.5.1.1.2 Molding. Either molding material described below may be used if it meets the temperature requirements of the systems:

a. L-P-393 is a thermoplastic polycarbonate resin with exceptional impact strength, dimensional stability, low mold shrinkage, and a useful temperature range up to 270° F (132° C). The polycarbonate should be predried and kept dry during the melt processing. Fast injection rates are usually optimum; molding conditions and mold surface should be highly polished.

b. Polyphenylene oxide (PPO) is a high-performance thermoplastic that can be used over a wide temperature range with a brittle point of approximately 340° F (171° C) and heat distortion temperature of 374° F (190° C) at 264 psi (18.48 kg/cm^2). When molding PPO, it is desirable to have a cool mold, but it is essential to have maximum cooling in gate areas. Experience has shown that few problems are encountered with molds that can be run during production at surface temperatures between 64° F (18° C) and 100° F (38° C) in the gate area.

1. Figure 6-30 shows an example of how the inserts would look in the mold-halves for preparing plugs. To attain the assumed display, one must imagine that the mold-halves are hinged away from each other.

2. Mold halves must be partially disassembled to gain access to screws that secure the upper mold-half inserts.

3. To reduce downtime during molding operations, several runs of flat cable should be assembled.

4. With the appropriate mold die set up in the machine, all connector plugs of that size should be molded.

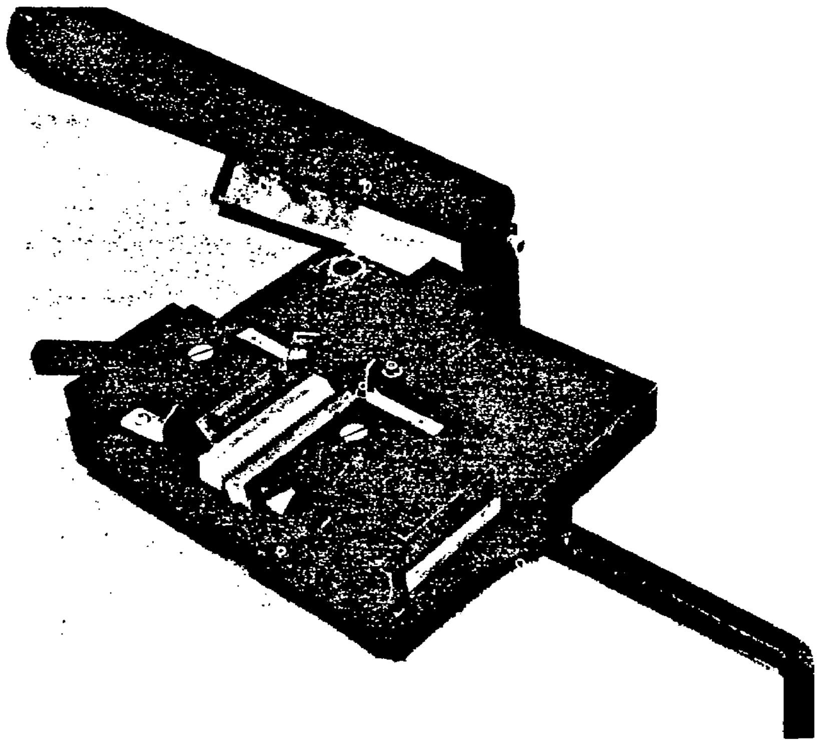


FIGURE 6-29. Conductor folding tool.

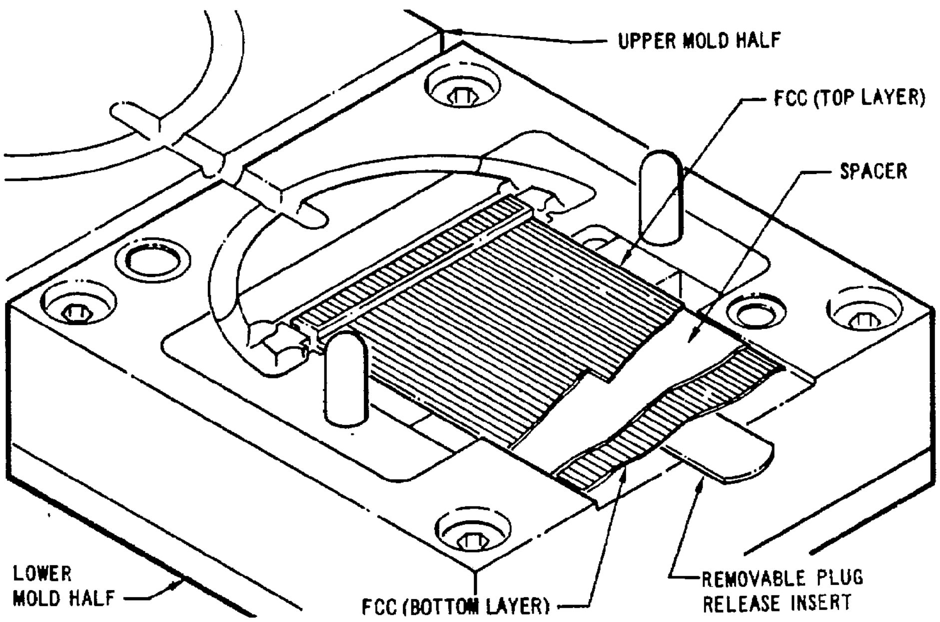


FIGURE 6-30. Plug molding - die.

c. Insert spacer between cable layers. If harness cable segments do not fill both layers, install short lengths of filler cables.

d. Place assembled plug into lower mold-half so that the guide pins of the mold-half fit into the small holes in the conductor separator.

e. Close mold halves and inject molding material.

f. At completion of molding cycle, open mold and remove plug and spacer.

6.3.5.1.1.3 Finishing. The third phase of the procedure for molded-on plugs follows:

a. Remove mold sprue from plug (Fig. 6-31).

b. Using an Xacto knife, trim the flash and excess material.

c. Remove any material that has flowed over the contact area.

d. Visually examine the plug to be potted.

1. Carefully remove pieces of foreign matter from the area to be potted.

2. Use isopropyl alcohol and clean the area to be potted, as well as the flat cable, for at least 2 inches (5.00 cm) above the area to be potted.

e. Place the plug assembly in the potting tool as shown in Figure 6-32.

f. Pot the rear end of the plug with a potting compound, meeting the requirements of MSFC-Spec-202A, Type III, per MSFC-Proc-186C.

6.3.5.1.2 Cylindrical (MIL-C-55544). Cylindrical plugs are composed of PPO (refer to Paragraph 6.3.5.1.1.2).

The assembly procedure listed below for cylindrical plugs (Fig. 6-33) is similar to the procedure used for molded-on plugs.

a. Select cables that have been stripped per Paragraph 6.3.3, plated per Paragraph 6.3.4, and are to be terminated in the same plug. The conductors shall have been exposed a distance of 0.425 ±0.05 inch (1.08 ±0.1 cm).

b. Insert the conductors through their respective openings (beveled side) of the window piece.

c. Separate conductors of one cable from those of the other cable, and insert the conductor spacer into the window piece.

d. Clamp the conductor spacer with the vise jaws, using the conductor folding tool.

e. Rotate the horizontal jaws one complete cycle to bend the conductors over the end of the conductor spacer.

f. Lower the vertical-fold plate actuator until the conductors are seated in the spacer grooves.

g. Press insulator into the conductor spacer groove and trim the insulator flush with the sides of the conductor spacer.

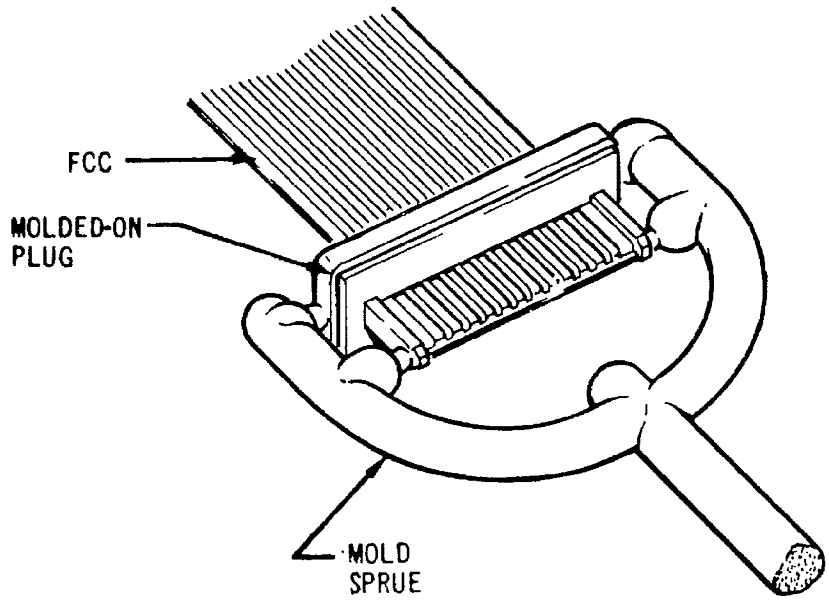


FIGURE 6-31. Molded plug with sprue intact.

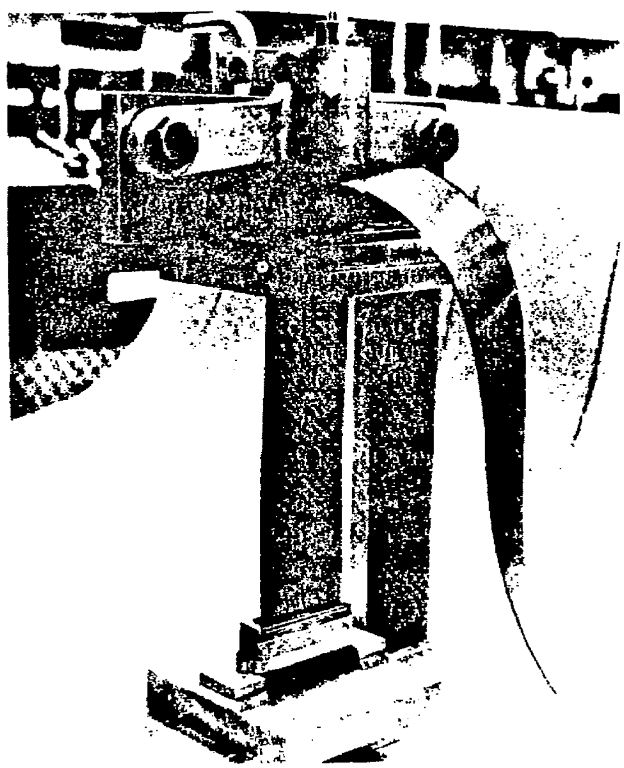


FIGURE 6-32. Plug assembly in potting tool.

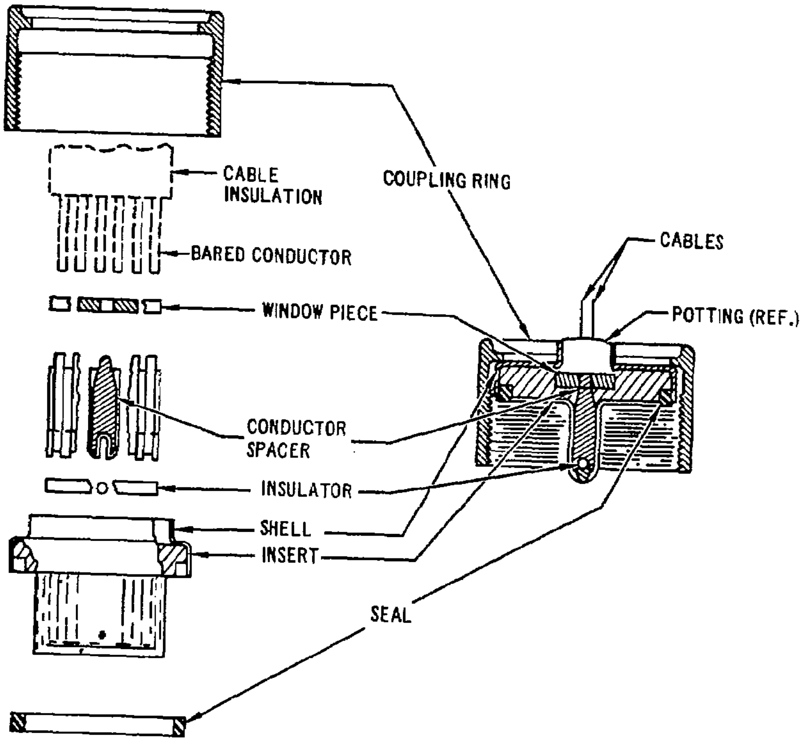


FIGURE 6-33. Cylindrical plug parts.

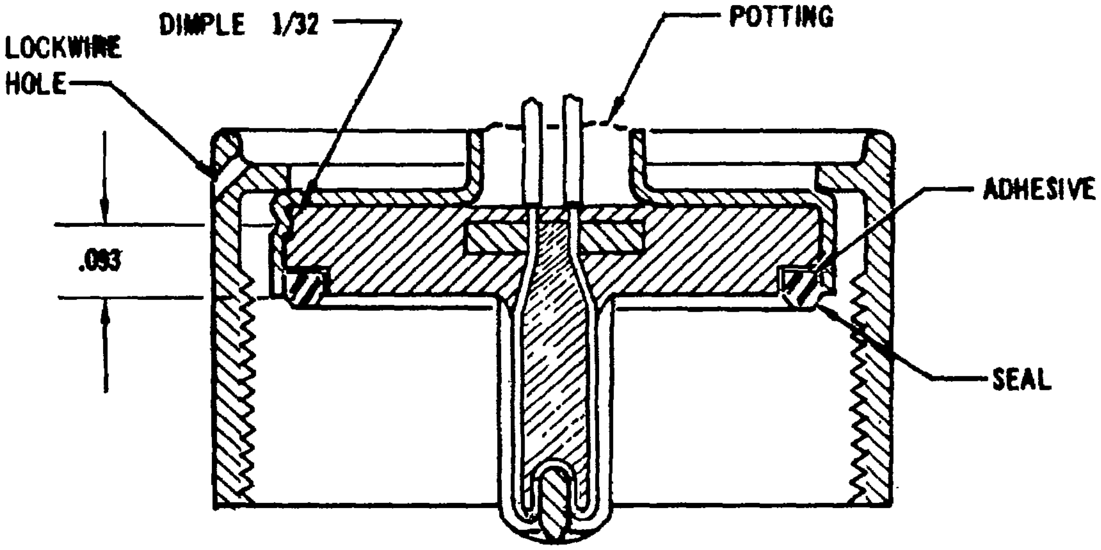


FIGURE 6-34. Cylindrical plug (dimpled).

h. Mold the insert around the assembled parts. The suggested molding procedure is given below:

1. Install proper mold halves into the molding machines, and heat the mold to 285°F (141°C).

2. Load hopper with dry molding material, and heat the material between 590° and 610°F (310° and 320°C).

3. Purge machine, and charge cylinder with approximately 20 percent more material than is required for the part.

4. Insert cable spacer, and place the assembled parts properly in the lower mold half.

5. Close the mold-halves and apply 10,000 to 14,000 psi (700 to 900 kg/cm^2). Hold the pressure for 15 to 20 seconds.

6. Release pressure and recharge cylinder.

7. Allow 40 seconds cooling time between pressure release and opening of the mold halves. (Cycle requires approximately 1 minute.)

8. Open mold halves about 0.5 inch (1.27 cm) and pull bottom insert out. Open mold halves more to eject the molded part.

i. Remove molded part from machine.

j. Remove cable spacer from between cables.

k. Trim sprues from molded plug body with an Xacto knife.

NOTE

The above is a suggested procedure for injection molding. This material may also be compression molded for additional physical advantages at a higher price.

l. Allow 4 hours to cool.

m. Move shell onto body.

n. Dimple shell with a spring-loaded punch to keep shell on molded body.

o. Dimples must be 120 degrees apart and 0.09 inch (0.24 cm) from front rim of shell (Fig. 6-34).

p. Per Paragraph 6.3.5.1.1.3, apply potting compound around and between the cables at the rear of the plug (Fig. 6-34).

q. Apply adhesive to groove around plug body and carefully seat the seal into the groove (Fig. 6-34).

6.3.5.2 Premolded. Premolded plugs are composed of parts that require no additional molding. The premolded parts are assembled and potted to further secure and seal the assembly. A seal is cemented into a groove on the plug housing to seal the junction between plug and receptacle.

The potting compound for bonding the assembly is Lefkoweld Type 185 epoxy structural adhesive manufactured by Leffingwell Chemical Company, Whittier, California (or equal). This is a high-purity epoxy polymer that, when thoroughly blended with Lefko activators LP and LSA, cures at 199°F (93°C) to a pale-yellow casting, with a minimum of shrinkage.

6.3.5.2.1 Unshielded (MIL-C-55544). Unshielded, premolded plugs (Fig. 6-35) are composed of Fiberlite E-2748 manufactured by Fibente Corporation, Winona, Minnesota. This is a glass-reinforced, medium-impact, epoxy molding compound that offers good impact strength combined with very low flow. It also offers good electrical properties and excellent heat and chemical resistance.

The following is a procedure for fabricating these plug assemblies:

a. Strip conductors to a 0.525 ±0.05-inch (1.33 ±0.1 cm) length using the appropriate procedure given in Paragraph 6.3.3.

b. Plate conductors as instructed in Paragraph 6.3.4.

c. Select plug parts that will accommodate the cabling-strip widths.

d. Thread-stripped conductors (both cables) through central opening of base plate. Move base plate back on cabling far enough to give liberty in working with each strip.

e. Position conductors of the cables into the slots of the conductor spacer, moving the stripped margin of insulation against the base of the conductor spacer ribs. Bend conductors into the wedge groove and install the wedge.

f. Thread conductor spacer through housing, making sure that it is seated well into the housing.

g. Move base plate into position in the housing.

h. Insert locking keys and twist ears of each key (Fig. 6-36).

i. Pot base of plug with potting compound Lefkoweld Type 185 (or equal) per Paragraph 6.3.5.1.1.3.

j. Apply a thin film of Dow Corning, No. 140 cement (or equal) into seal groove of plug housing.

k. Install silicone rubber seal into groove. Make sure that the seal is seated well.

l. Stamp conductor numbers on plugs.

6.3.6 Folding Flat Cable. Angular fold or folds shall be made in the following manner:

a. Unshielded cable - Fold the cable over on itself as depicted in Figures 6-37 and 6-38. Each cable may be folded individually and secured with H-Film tape.

b. Shielded cable - Fold the cable over a 0.25-inch minimum diameter rod. The rod shall be 0.25-inch longer than the fold line of the cable. After folding, secure with H-Film tape as shown in Figure 6-39.

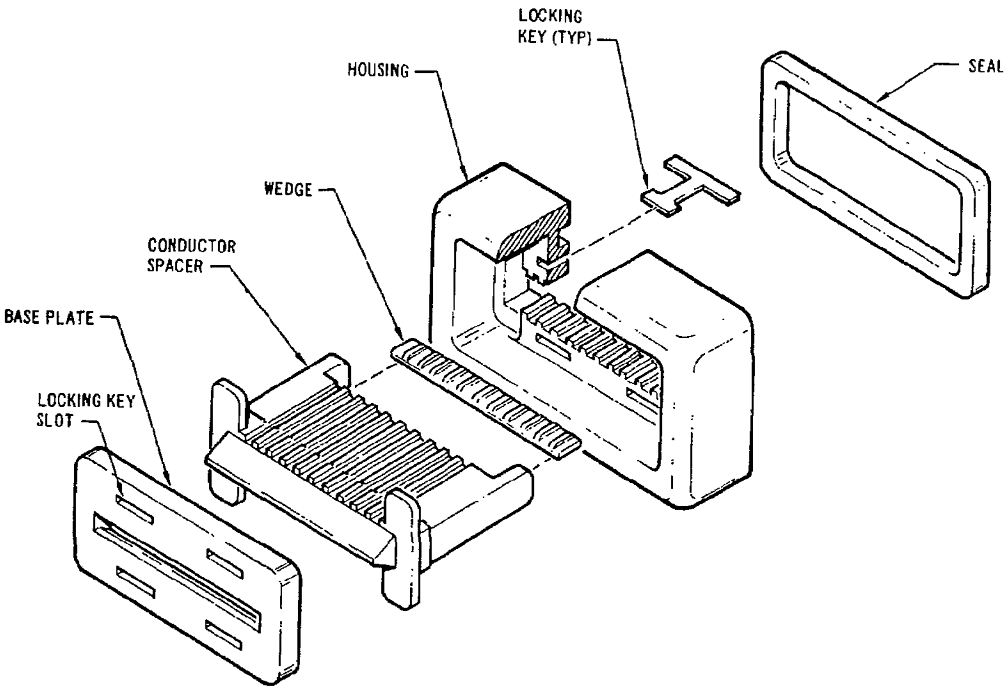


FIGURE 6-35. Typical premolded plug parts.

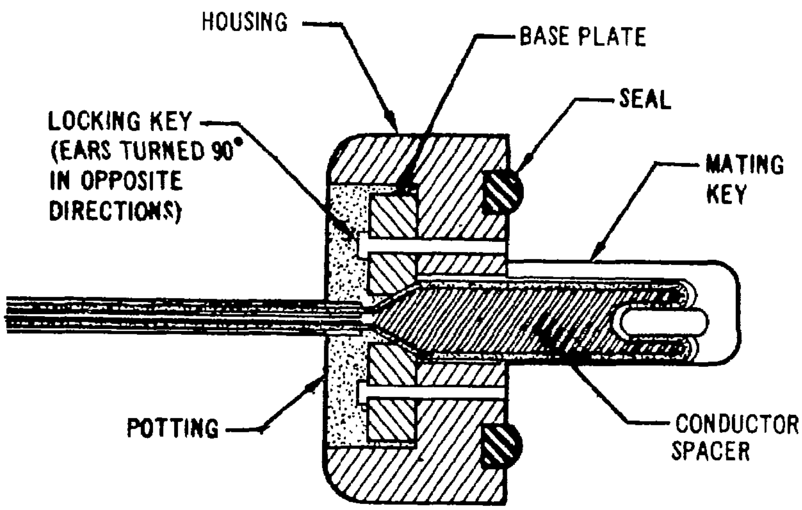


FIGURE 6-36. Premolded plug (section).

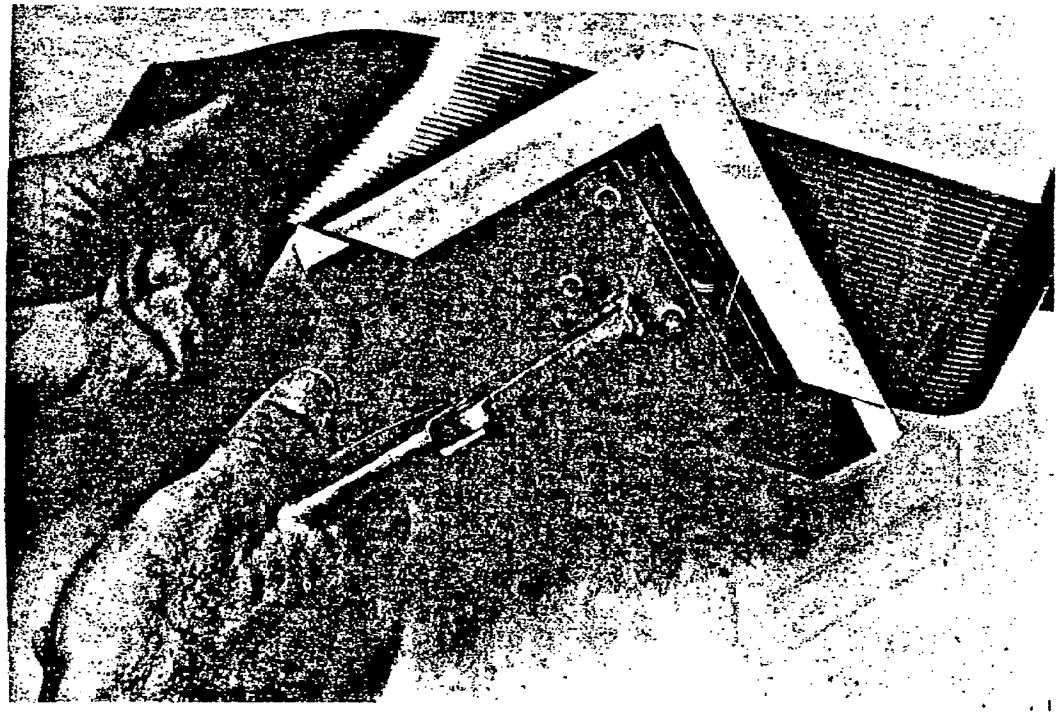


FIGURE 6-37. FCC folding tool.

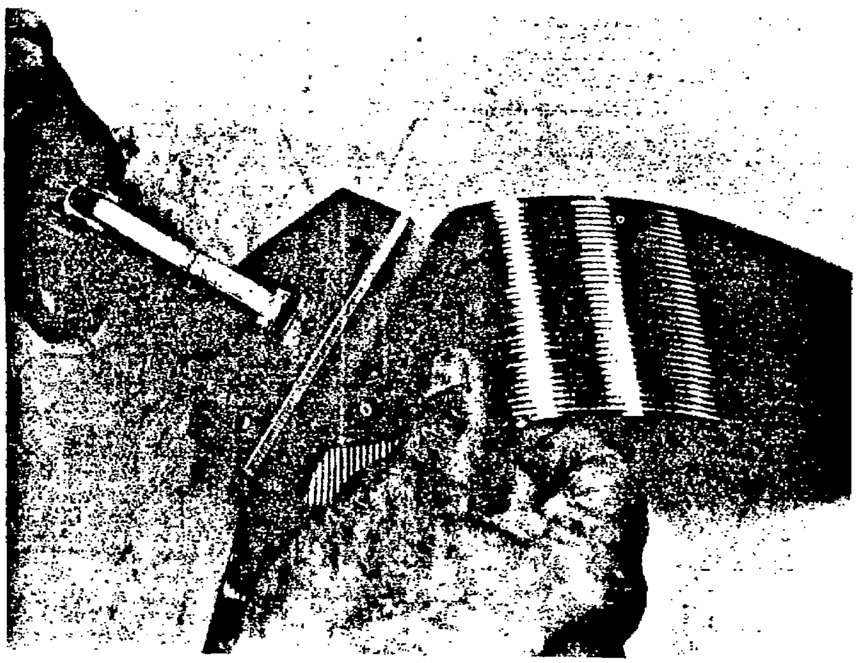


FIGURE 6-38. FCC folding tool.

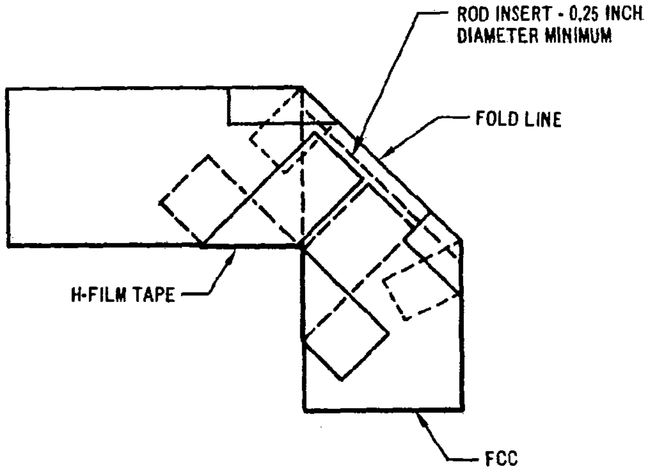


FIGURE 6-39. Shielded cable fold.

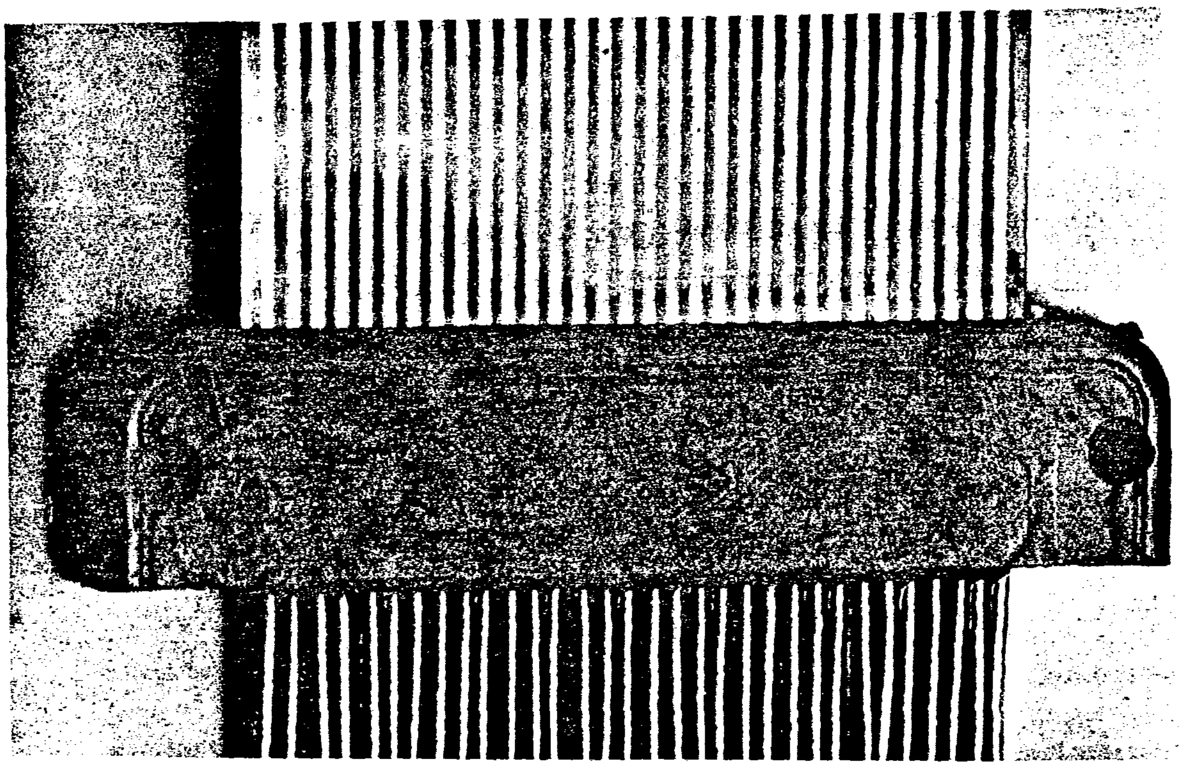


FIGURE 6-40. Transition from FCC to RWC.

c. Angles other than 45 or 90 degrees may be accomplished in a similar manner.

Up to 10 cables may be folded in a bundle. If there are more than 10 cables in one run, a new run should be started along side the first. Refer to Section III, Paragraph 3.2.6.3.2, for other considerations.

6.3.7 FCC to RWC Transition. The transition from flat wires to round wires (Fig. 6-40) is accomplished by preparing the conductors (Fig. 6-41), clamping the conductors in a handling fixture (Fig. 6-42), and soldering. With the soldered conductors still in the handling fixture, molds are installed, and the junctions are molded with a suitable compound. Transitions can be made for all sizes of FCC.

6.3.7.1 Conductor Preparation. All conductors must be stripped, cleaned, and tinned before being fixed into position for soldering. In addition to the stripping, cleaning, and tinning processes, FCC's must be prepared with a window piece, conductor spacer, and insulator (Fig. 6-41).

6.3.7.1.1 Cable Shearing. Shear the cable square as specified in Paragraph 6.3.2.

6.3.7.1.2 Stripping Procedure (Flat Cable). Strip the cable as outlined in Paragraph 6.3.3 in accordance with the type of cable being used.

6.3.7.1.3 Stripping Round Wire. All round wires must be stripped 0.375 ±0.030 inch (Fig. 6-41). Any conventional method may be used, provided the conductor is not damaged and the stripped insulation margin is smooth.

6.3.7.1.4 Cleaning and Tinning. The following steps are recommended for the cleaning and tinning procedures:

a. Clean both flat and round conductors ultrasonically for 5 minutes in Freon-113.

b. Allow the clean conductors to dry, and tin by dipping them into an ultrasonic-excited bath of SN 60 solder at 250° to 260°C for 1 to 2 seconds.

c. Allow the tinned conductors to cool, and remove all flux residues by brushing with ethyl alcohol. Brush away from insulation, giving particular care to the area between the round-wire conductor and insulation, which is most likely to collect residue.

d. Protect conductors from bending (Fig. 6-7) and becoming contaminated.

6.3.7.1.5 Final Preparation of FCC. Thread the conductors into the conductor spacer, fold the conductors into the insulator groove, and insert the insulator.

CAUTION

Repeated flexing of the cables behind the window piece will break the cable conductors. Care must be exercised to prevent cable bending until the potting material is applied.

6.3.7.2 Soldering and Potting. The procedure for soldering and potting is as follows:

a. Insert separator plug (Fig. 6-43) between cables with the unflanged end against the window piece.

b. Place the cables and separator plug in the left slot of the fixture body with the separator plug flanges against the left, outside edge of the fixture (Fig. 6-42).

c. Position the flat-cable retainer plate over the cables, and secure the plate loosely with two short thumbscrews.

d. Insert gage block over cables between window piece and fixture body. With the gage block fitting snugly and the separator plug against the fixture body, tighten the thumbscrews just enough to hold the cables in position.

e. Remove the gage block.

f. Select the proper retainer, or retainers (depending upon the round wires to be installed), and position it on the fixture body, making sure the tapped holes of the central retainer correspond to the untapped holes of the fixture body.

The basic wire installation possibilities are:

1. All unshielded-round wires to both flat cables.

2. All shielded-round wire to both flat cables. Skip every other cable conductor.

3. All unshielded-round wires to one flat cable and all shielded-round wires to the other flat cable.

4. Combination of unshielded-and shielded-round wires to either or both flat cables.

g. Holding the retainer (or retainers) in position, turn the fixture over (Fig. 6-44) and install two short thumbscrews. Use the untapped holes of the fixture body and the tapped holes of the central retainer. Leave retainers just loose enough to receive the anticipated wires.

h. Insert the prepared conductors of the round wires through the appropriate grooves (Fig. 6-44), aline the conductor ends approximately 0.05 inch from the flat-cable conductor spacer, and tighten the thumbscrews just enough to hold the wires snug, but not so tight that the wires cannot be adjusted into the cable conductors. Be sure to arrange the spacing of conductors for convenient soldering and effective potting.

i. Starting with the most remote wire to be soldered, position the round conductor on the corresponding flat-cable conductor as shown in Figures 6-41 and 6-42. (The tolerances are essential to facilitate cleaning between conductor ends and window piece and to prevent particles of insulation from being embedded in the solder fillets.)

j. Add a slight amount of solder to the contact area.

CAUTION

Never use a soldering iron that is hotter than 290°C, nor leave the iron in one place longer than 5 seconds; otherwise, the conductor spacer or round-wire insulation may be damaged.

k. Repeat steps i and j for joining other wires to this particular flat cable, and tighten the thumbscrews slightly to protect the solder joints from any possible strain that might be incurred during further handling.

l. Turn the handling fixture back over and install the peripheral retainer (with grooves up) and round-wire retainer plate with the two long thumbscrews.

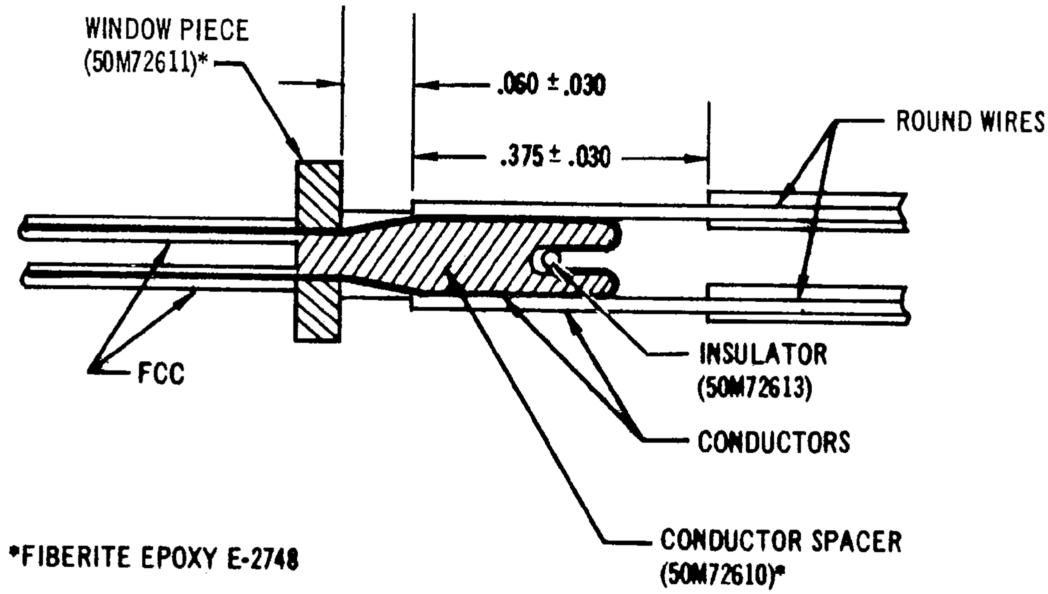


FIGURE 6-41. Conductors prepared for soldering.

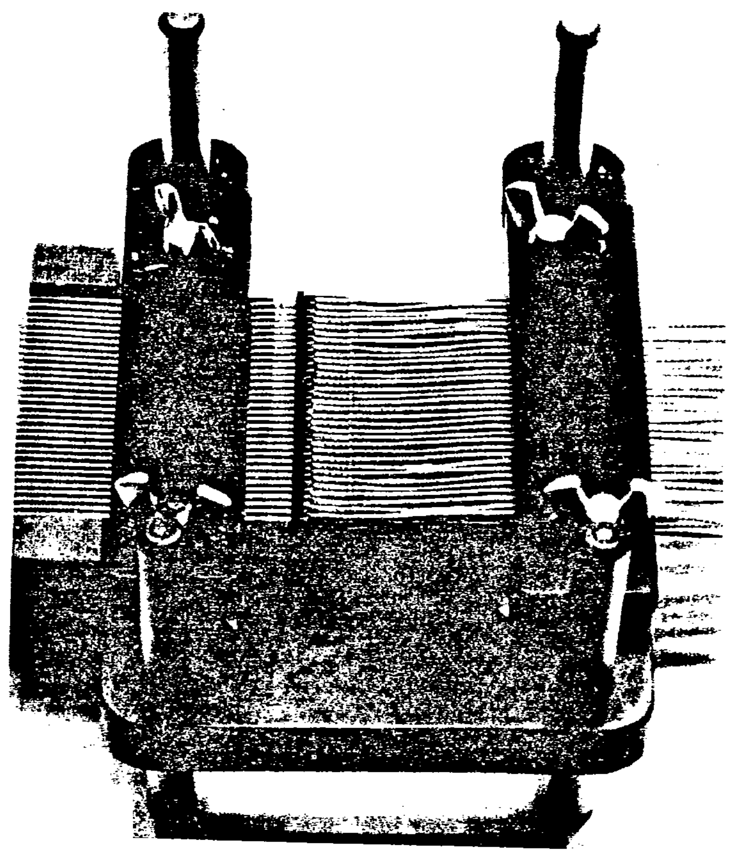


FIGURE 6-42. Handling, soldering, and potting fixture.

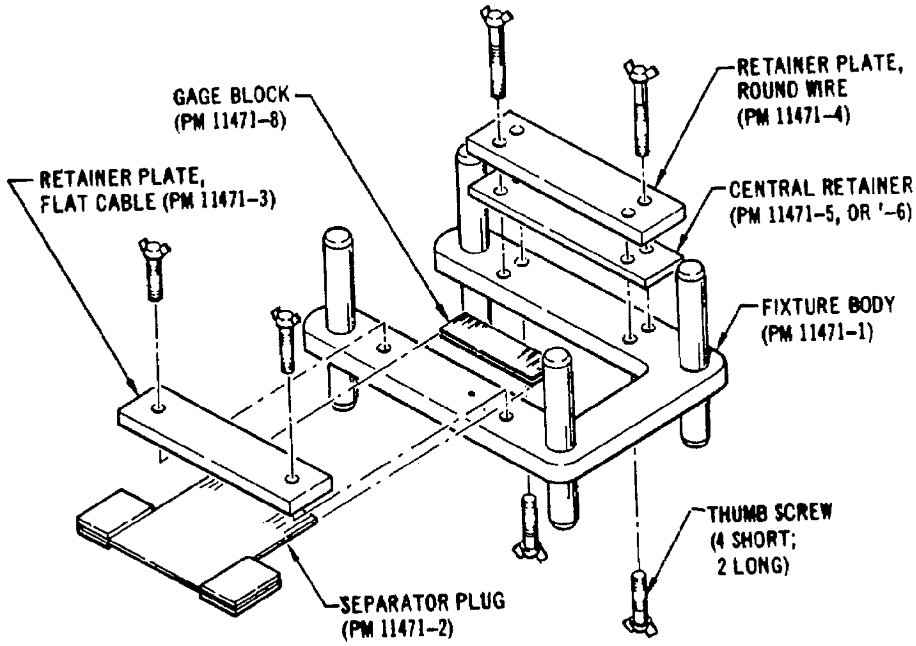


FIGURE 6-43. Handling fixture components.

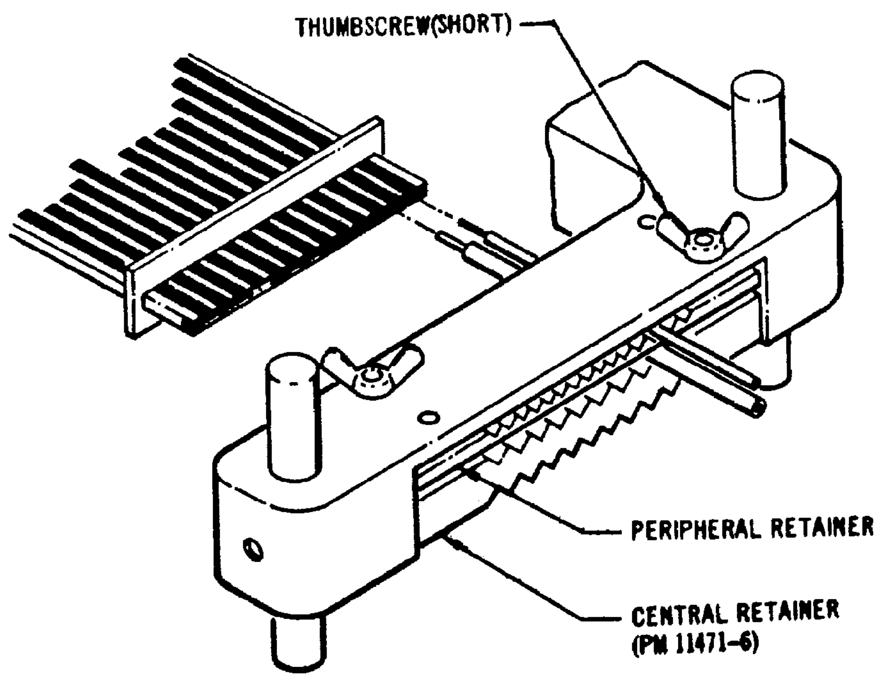


FIGURE 6-44. Shielded-unshielded wire installation (first cable).

m. Repeat steps h through k for joining wires to the second FCC.

n. After all wires are soldered, remove flux residues with a soft brush and ethyl alcohol.

o. Inspect all joints to make sure that joints are secure, that no parts have been damaged, and that excessive solder does not create a possibility of short circuiting.

p. Apply mold-release material to the mold cavity according to the recommendations and processes given in MSFC-Proc-196. If mold leaks, apply a small amount of silicone RTV-501 around the mating surfaces of the mold halves. The silicone RTV-501 must meet requirements on MSFC-Spec-379 and be applied in accordance with MSFC-Proc-380.

q. Install mold halves (Fig. 6-45) and pot with Stycast 2651. The potting material must meet the requirements of MSFC-Spec-222, Type II, and be applied in accordance with MSFC-Proc-196. Care should be given to the flex relief area where cable exits from the potting material.

r. Allow potting material to cure for 8 hours at room temperature (or for 1 hour at a temperature between 71° and 76°C) and remove the mold halves.

s. Remove handling fixture and inspect the molded form.

6.3.8 Procedure for Termination FCC to Ground Lugs. The following describes the joining of FCC conductors to copper ground lugs and the conformal coating of the joint area (Fig. 6-46).

a. Clean the conductors and the area of the ground lug which is to be soldered with an abrasive rubber eraser, being careful at all times not to deform the conductors.

b. Follow the abrasive cleaning by wiping with a clean cloth dampened with Toluene (JT-458).

c. Tin the conductor ends and the ground lug using SN63 resin core solder.

d. Apply flux to the tinned area on the ground lug.

e. Arrange the cable and ground lug so that both parts are firmly held and the conductors are bearing flat against the ground lug.

f. Apply heat to the ground lug with a 100-watt soldering iron, and add solder if necessary.

g. For larger ground lugs, an auxiliary heat source may be necessary.

h. Completely remove the flux residues using a nonmetallic-bristle brush wet with Toluene.

i. Brush-coat epoxy potting compound EPD TC459 over the soldered conductors and over 0.25-inch of the adjacent cable insulation. Cover the corresponding areas on the opposite side of the cable, and fill the space between the cable and the unsoldered area of the ground lug.

j. Cure the epoxy coating for 24 hours at 60°C.

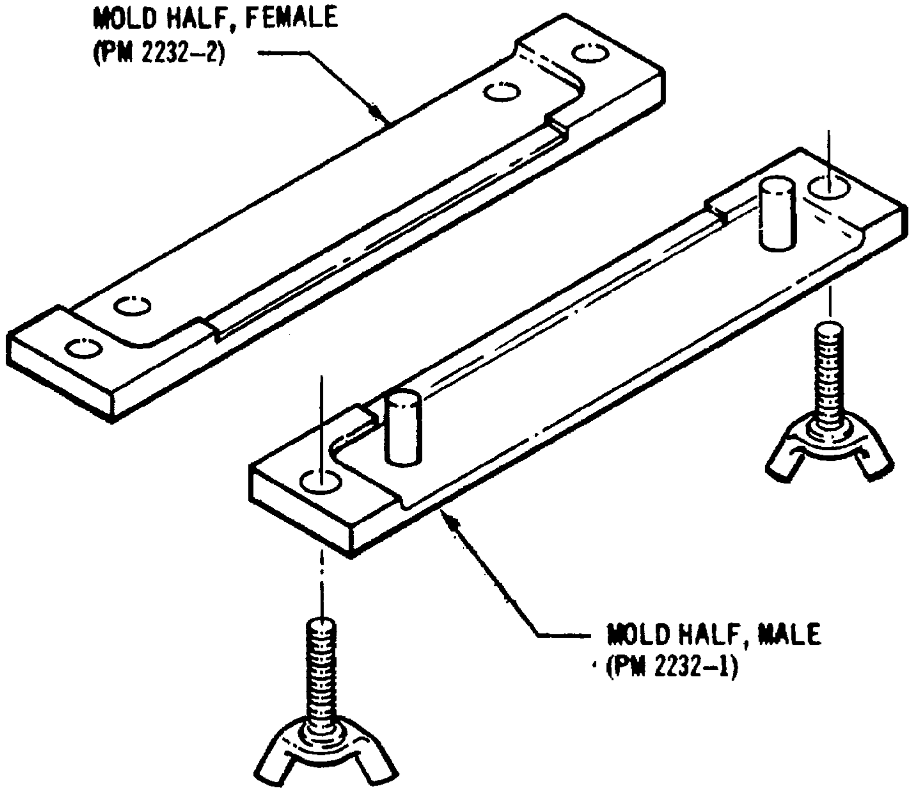


FIGURE 6-45. Mold halves before installation.

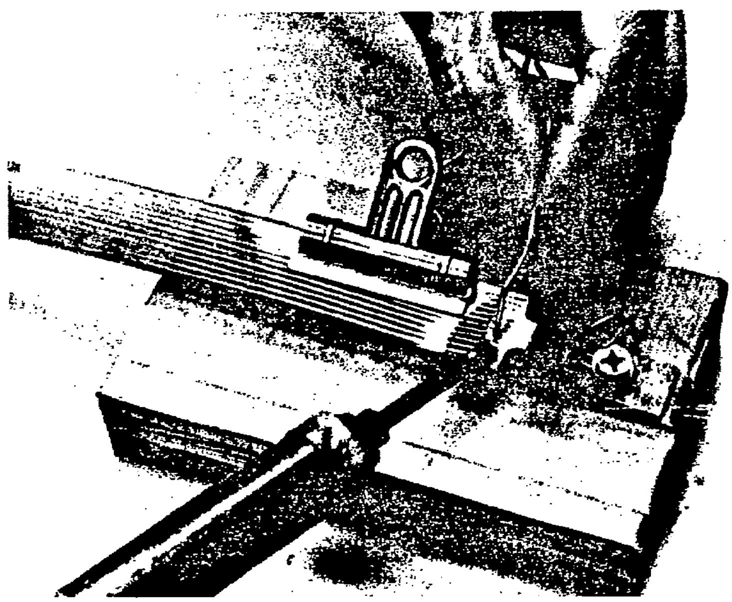


FIGURE 6-46. Soldering FCC to ground lug.

6.4 Assembly and Installation of FCC Harnesses

The mockup is used to develop, route, and support the required FCC harnesses as explained in Paragraph 6.2.

6.4.1 FCC Cable Assembly. The developed Mylar mockup cables are removed from the mockup and used as patterns for the manufacturing of the production FCC harnesses (Fig. 6-47). Particular attention must be paid to cable conductor registration in the plugs and cable segment registration in the harness runs. The cable identification provided by the cable manufacturer, along one edge of the FCC, identifies the index edge for each cable segment.

6.4.2 FCC Harness Installation. The production FCC harnesses are installed on the end items to duplicate the installation on the mockup and to conform to the requirements of the engineering drawings.

6.4.3 Installation of Supports and Clamps. The installation of the supports and clamps for FCC is governed by the number of bundles, the distance between bundles, and the branches of each bundle. Cables are to be supported as required by engineering drawings.

Figure 6-48 shows various types of support sections that have been used for FCC. The modular hole patterns on the FCC mounting surfaces permit the acceptance of the modular-width clamps selected. The various support sections may be bonded, riveted, or bolted to existing structure.

The installation of a typical high-temperature FCC clamp (Fig. 6-49) is accomplished as follows:

a. The FCC harness is aligned and positioned on the support.

b. The clamp is positioned on top of the harness.

c. The fasteners in each end of the clamp are aligned with the holes in the support.

d. Pressure is applied on the clamp until the aluminum spacers of the clamp come in contact with the support.

e. The fasteners are turned to secure the clamp to the support.

The installation of a typical Velcro clamp (Paragraph 2.5.3.1) is accomplished as follows:

a. The Velcro clamp is positioned between the FCC and the support bracket.

b. The fasteners are aligned with the holes in the support bracket and the plungers depressed, securing the cable clamp to the support bracket.

c. The cable clamp is opened by separating the hook-and-pile fabrics.

d. The FCC bundles are positioned over the clamps and the Velcro pile material is attached to the bundles. The bundles are then pressed down in the clamp area and the loose ends of the clamps are secured by applying hand pressure.

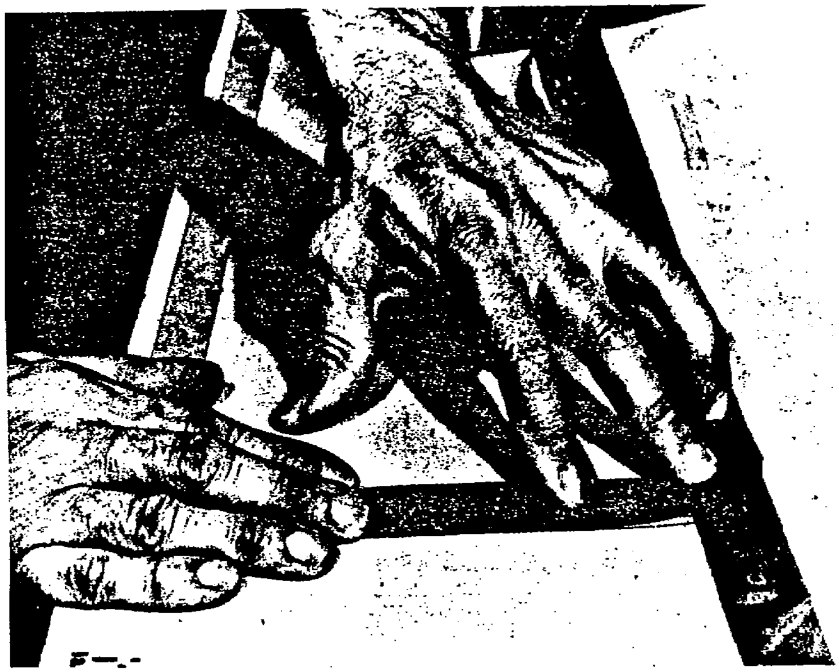


FIGURE 6-47. Duplicating Mylar mockup harness with FCC.

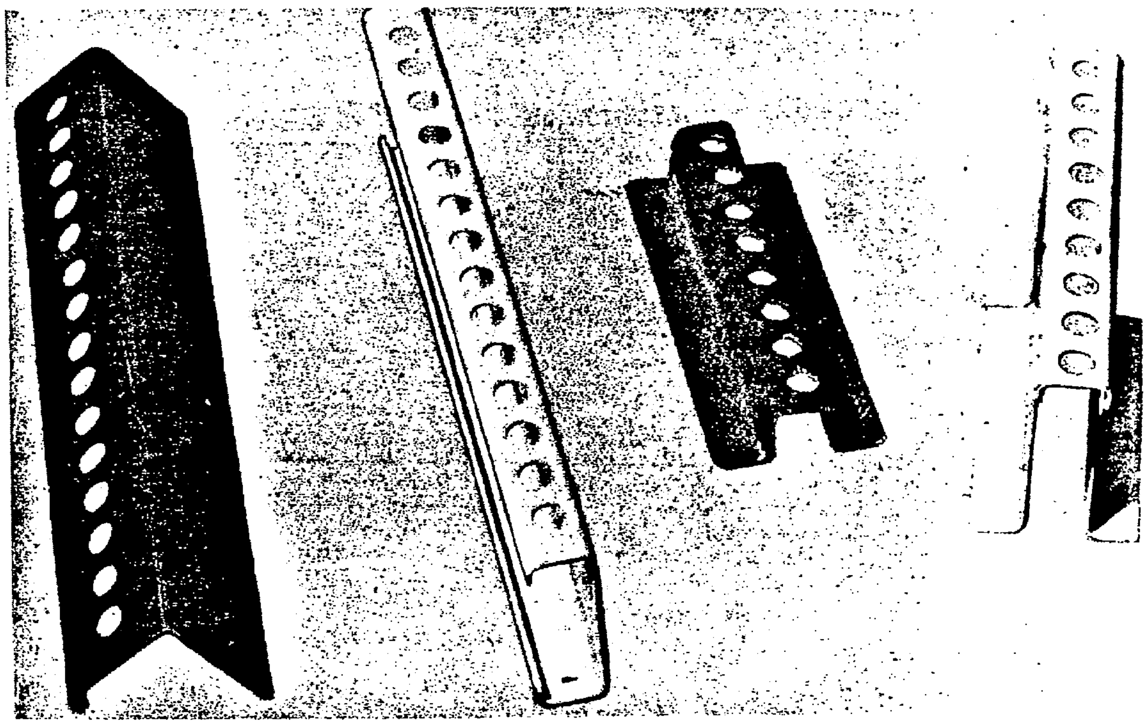


FIGURE 6-48. FCC clamp supports.

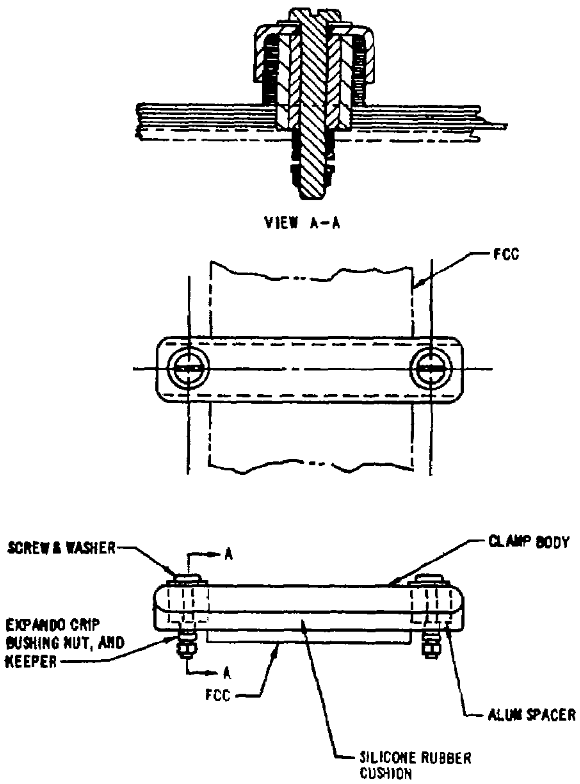


FIGURE 6-49. High temperature, 200° C clamp.

6.5 Summary

This section contains information for the development, fabrication, and installations of interconnecting FCC harnesses, both shielded and nonshielded. Methods for protection of FCC harnesses during manufacturing are also included.

Following is a tooling and materials list which summarizes those discussed in this section for FCC manufacture and installation. This list, plus appropriately selected FCC hardware from Section II, represents the type of physical items required to produce FCC harnesses and systems. Common shop items, such as benches and hand tools, are not included in the tooling and materials list.

MANUFACTURING TOOLING AND MATERIALS LIST

1.0 Mockup Manufacture and Installation.

- 1.1 10-mil Mylar tape (varying widths and appropriate length)
- 1.2 Masking tape
- 1.3 Plastic cables ties
- 1.4 Stapler
- 1.5 Wedge/lock clamp
- 1.6 Clips with plastic fasteners
- 1.7 Other miscellaneous (Fig. 6-2)

2.0 Cable Shearing

- 2.1 Di-Arco precision shear
- 2.2 Heavy duty scissors
- 2.3 Paper cutter
- 2.4 Cutoff line-marking fixture
- 2.5 Handling device (Fig. 6-5); also used in other operations.

3.0 Cable Stripping

- 3.1 Chemical
  - 3.1.1 Heater
  - 3.1.2 Beaker
  - 3.1.3 Thermometer
  - 3.1.4 Maskants
  - 3.1.5 Stripping solutions.

3.2 Mechanical

3.2.1 Abrasion

a. Viking FCC stripping machine

b. Rush FCC stripping machine

c. Carpenter FCC stripping machine

3.2.2 Cold Blade

a. NASA cold stripper

b. Plane stripper

c. Gore stripper

3.3 Conductor protector (Fig. 6-7)

4.0 <u>Conductor and Shield Plating</u>

4.1 Plating rack (Fig. 6-24)

4.2 Nickel-plating equipment

4.3 Gold-plating equipment

5.0 <u>Plug Assembly</u>

5.1 Molded-On

5.1.1 Injection, transfer, or compression molding equipment

5.1.2 Plug mold dies

5.2 Premolded

5.2.1 Seating tool (Fig. 6-28); also used for molded-on plug

5.2.2 Conductor folding tool (Fig. 29); also used for molded-on plug

5.2.3 Potting fixture (Fig. 6-32); also used for molded-on plug

6.0 <u>Cable Folding</u>

6.1 Folding tool (Fig. 6-37)

6.2 Folding tool (Fig. 6-38)

6.3 Permacel H-Film tape (Fig. 6-39)

7.0 <u>FCC Harness Installation</u>

7.1 Temporary supports (Fig. 2-43)

7.2 Silastic impregnated glass cloth tape

8.0 <u>FCC to RWC Transition Manufacture</u>

8.1 Handling fixture (Fig. 6-42)

8.2 Separator plug (Fig. 6-43)

8.3 Mold halves (Fig. 6-45)

SECTION VII. QUALITY ASSURANCE - INSPECTION AND TEST PROCEDURES

7.1 Introduction

The inspection-and-test portion of this handbook contains an accumulation of inspections, tests, and other controls required to assure that the intent of the design is met in the manufacturing cycle, based on the review and analysis of the manufacturing plan, process standards, and engineering requirements. Section VII is intended as a guideline for setting up an adequate inspection system to achieve a high-quality FCC system and should be adapted to the particular quality-control system that may be already in effect.

An inspection plan should be generated, relating inspection points to the manufacturing flow of materials from receiving through in-process assembly, final test, and installation.

The inspection plan is divided into three major areas of concern:

a. Inspection and Test Plan Outline (Paragraph 7.2).

b. In-Process Quality Control Flow Charts (Paragraph 7.3).

c. Narrative descriptions (Paragraphs 7.4 through 7.8) of inspection points and controls.

These major areas present a description of those defects that may be found during receiving, processing, or installation of flat cables. Methods of inspection are also suggested to identify the defect or characteristic to be inspected. Military specifications, federal test standards, photographs, and sketches are referenced throughout this section that provide detailed information on defect identification, test methods, and procedures.

7.2 Inspection and Test Plan Outline

The following inspection and test plan outline (Table 7-1) is divided into four columns.

a. Inspection parameter or point - Identifies a control point or defect to be inspected and references applicable paragraphs of the ensuing text.

b. Method of inspection - Presents a description of the method and tools for identification of a defect or references a federal test standard.

c. Inspection interval - Suggests the interval of inspection, either 100-percent inspection or a sample. The specific size of the sample will not be within the scope of this report. Exact sample plans can be initiated after standards are set, through experience, that will provide a satisfactory quality level. All sample plans that are initiated should adhere to the requirements presented in MIL-STD-105.

d. Acceptance criteria.

7.3 In-Process Quality Control Flow Charts

The in-process quality control flow charts (Figs. 7-7, 7-8, and 7-9) can be used in conjunction with the outline to identify critical inspection points. Each significant manufacturing operation is referenced by paragraph number to the manufacturing procedure in Section VI, and each significant inspection is also referenced: Figure 7-7 is for FCC receiving and cable end preparation for plug termination; Figure 7-8 is for FCC premolded plug assembly; and Figure 7-9 is for FCC molded-on plug assembly.

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4 Receiving Inspection (Visual Mechanical)			
7.4.1 Cable Inspection			
7.4.1.1 Identification	Visual	100%	MIL-C-55543
7.4.1.2 Certification of Conductor Material	Visual	100% Paper Inspection	MIL-C-55543
7.4.1.3 Packaging and Packing Inspection	Visual	100%	MIL-C-12000 & MIL-C-55543
7.4.1.4 Cable Dimensions (Unshielded)			
7.4.1.4.1 Width	See Figures 7-1 & 7-2	100%[a]	MIL-C-55543
7.4.1.4.2 Conductor Spacing	See Figures 7-1 & 7-2	100%[a]	MIL-C-55543

a. 100-percent inspection until a confidence level has been reached.

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.1.5 Cable Inspection (Shielded)	X-Ray	Sample	MIL-C-55543
7.4.1.5.1 Cable Dimension Measurement with Time Domain Reflectometry			
7.4.1.6 Workmanship	Viewing Screen, See Figure 7-1	100%[a]	MIL-C-55543
7.4.1.6.1 Bubbles	See Figure 7-3	100%[a]	MIL-C-55543
7.4.1.6.2 Delamination	See Figure 7-4	100%[a]	MIL-C-55543
7.4.1.6.4 Broken Conductors		100%	MIL-C-55543
7.4.1.6.5 General Damage	See Figure 7-1	100%	MIL-C-55543

a. 100-percent inspection until a confidence level has been reached.

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.1.7 Stripability	Strip Sample & Evaluate	Sample, Each Inspection Lot	See Manufacturing Section on Stripping
7.4.1.8 Receiving Inspection (Electrical Test)			
7.4.1.8.1 Continuity		100%	
7.4.1.8.2 Insulation Resistance	Fed. Test Std. 228	Sample	MIL-C-55543
7.4.1.8.3 Conductor Resistance	Fed. Test Std. 228	Sample	MIL-C-55543
7.4.1.8.4 Dielectric Strength	Fed. Test Std. 228	Sample	MIL-C-55543
7.4.2 Receiving Inspection Premolded Plugs			
7.4.2.1 Identification	Visual	100%	MIL-C-55544
7.4.2.2 Certification of Plug Material	Visual	100%	

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.2.3 Packaging and Packing Inspection	Visual	100%	MIL-C-55544
7.4.2.4 Dimensions	Section Plug, Inspection Tool	Sample	MIL-C-55544
7.4.2.5 Workmanship			
7.4.2.5.1 Flash	Visual	Sample	
7.4.2.5.2 General Damage	Visual	Sample	
7.4.2.5.3 Porosity	Fed. Test Std. 406	Sample	MIL-C-55544
7.4.2.5.4 Plug Material Testing			
7.4.2.5.5 Insulation Resistance	Fed. Test Std. 406, Method 4041	Lot Sample	MIL-C-55544
7.4.2.5.6 Dielectric Withstand Voltage	Fed. Test Std. 406, Method 4031	Lot Sample	MIL-C-55544
7.4.2.5.7 Brittleness	Fed. Test Std. 406, Method 2051	Lot Sample	MIL-C-55544

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.3 Receiving Inspection of Related Plug Materials			
7.4.3.1 Premolded Plug Wedge & Retainer			
7.4.3.1.1 Dimensions	Visual	Sample	MIL-C-55544
7.4.3.1.2 Material Testing	See Paragraph 7.4.2.5.4	Sample	See Paragraph 7.4.2.5.4
7.4.3.2 Gasket	See Paragraph 7.4.2.5.4	Sample	See Paragraph 7.4.2.5.4
7.4.3.2.1 Dimensions	Visual	Sample	MIL-C-55544
7.4.3.2.2 Hardness	Durometer	Sample	Shore A 78 ± 3

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.3.2.3 AGE Control & Storage			MSFC-STD-105
7.4.4 Potting Compound & Adhesives Control			
7.4.4.1 Identification & Storage	Visual	100%	MIL-STD-129D
7.4.4.2 Storage Surveillance			
7.4.5 Receiving Inspection of Receptacles			
7.4.5.1 FCC-FCC Rectangular Receptacle			
7.4.5.1.1 Identification	Visual	100%	MIL-C-55544 & MIL-STD-1290
7.4.5.1.2 Packaging and Packing	Visual	100%	MIL-D-116 & MIL-C-55544
7.4.5.1.3 Dimensions	Visual	Sample	MIL-C-55544

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.5.1.4 General Damage	Visual	Sample	MIL-C-55544
7.4.5.1.5 Material Identification	MIL-C-55544	Sample	MIL-C-55544
7.4.5.1.6 Material Finish	MIL-C-55544	Sample	MIL-C-55544
7.4.5.1.7 Mating and Unmating Forces	MIL-C-55544	Sample	MIL-C-55544
7.4.5.1.8 Electrical			
7.4.5.1.8.1 Contact Resistance	Method 307 of MIL-STD-202	Sample	MIL-C-55544
7.4.5.1.8.2 Low Level Contact	MIL-C-55544	Sample	MIL-C-55544
7.4.5.2 FCC to RWC Rectangular Receptacle	See Paragraph 7.4.5.1 - 7.4.5.1.8.2	Sample	MIL-C-55544
7.4.5.3 FCC to FCC Cylindrical Receptacle	See Paragraph 7.4.5.1 - 7.4.5.1.8.2	Sample	MIL-C-55544

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.4.5.4 FCC to RWC Cylindrical Receptacle	See Paragraph 7.4.5.1 - 7.4.5.1.8.2	Sample	MIL-C-55544
7.4.6 Receiving Inspection of Clamps and Supports			
7.4.6.1 Identification	Visual	100%	MIL-STD-129
7.4.6.2 Packaging and Packing	Visual	100%	MIL-D-116
7.4.6.3 Dimensions	Visual	Sample	
7.4.6.4 Workmanship	Visual	Sample	
a. General damage	Visual	Sample	
b. Plating consistency	Visual	Sample	
c. Spring tension	Calibrated scale	Sample	
d. Cushion hardness	Durometer	Sample	
7.5 In-Process Inspection & Test of Cable Preparation for Terminating			

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.5.1 Cable Shearing Inspection			
7.5.2 Cable Stripping Inspection			
7.5.2.1 Chemical Stripping			
7.5.2.1.1 Conductor Damage	Visual, 5X Magnification	100% In Process	
7.5.2.1.2 Wicking	Visual, 5X Magnification	100% In Process	Nonallowable
7.5.2.1.3 Insulation Damage	Visual, 5X Magnification	100% In Process	Nonallowable
7.5.2.1.4 Insulation Removal	Visual, 10X Magnification	100% In Process	
7.5.2.1.5 Dimensions	Visual	100% In Process	
7.5.2.2.1 Conductor Damage	Visual, 5X Magnification	100% In Process	

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.5.2.2.2 Complete Insulation Removal	Visual, 5X Magnification	100% In Process	
7.5.2.2.3 Conductor & Insulation Cleanliness	Visual, 5X Magnification	100% In Process	
7.5.2.3 Acceptable Stripped Cable	Visual 5X Magnification	100% In Process	
7.5.3 Conductor and Shield Plating			
7.5.3.1 Nickel Plating			QQ-M-290
7.5.3.1.1 Conductor Inspection	5X, Magnification	100% In Process	No Oxidation Allowable
7.5.3.1.2 Appearance	5X, Magnification	Sample	
7.5.3.1.3 Thickness	Microphoto-Cross-Section	Sample	0.000 050 in. Max.
7.5.3.1.4 Adhesion	Test Sample	Sample	No Separation After Test

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.5.3.1.5 Corrosion Resistance	See Fed. Test Std. 151, Method 811.1	Sample	See Fed. Test Std. 151
7.5.3.1.6 Sampling and Testing (Plating)		Sample	
7.5.3.1.7 Sampling and Testing Solutions		Lot Sample	
7.5.3.2 Gold Plating			MIL-G-45204
7.5.3.2.1 Conductor and Shield Inspection	5X Magnification	100% In Process	
7.5.3.2.2 Appearance	5X Magnification	100% In Process	
7.5.3.2.3 Thickness	Microphoto	Sample	
7.5.3.2.4 Adhesion	Test Sample	Sample	No Separation After Test
7.5.3.2.5 Sample & Test Plating		Sample	

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6 Inspection & Test of Cable Terminations			
7.6.1 Inspection of Molded-On Plug Assemblies			
7.6.1.1 Receiving Inspection	See Paragraph 7.4.4		
7.6.1.1.1 Molding Compound			
7.6.1.2 Parts Assembly			
7.6.1.2.1 Cable Preparation for Termination			
7.6.1.2.2 Orientation During Threading	Visual	100% In Process	See Paragraph 6.3.5.1.1.1
7.6.1.2.3 Conductor Threading	Visual	100% In Process	No Conductor Damage
7.6.1.2.4 Conductor Folding	Visual 5X Magnification	100% In Process	No Separation Of Plating

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6.1.3 Molding			
7.6.1.3.1 Environmental Requirements		Bimonthly	
7.6.1.3.2 Verify Manufacturing Steps		100% In Process	
7.6.1.3.3 Molding Sample			
a. Dimensions	Visual	Sample	MIL-C-55544
b. Porosity	Visual	Sample	Fed. Test Std. 406, Method 5021
7.6.1.4 Finishing			
7.6.1.4.1 Verify			
a. Clean Molded Body	Visual	100% In Process	
b. Flash	Visual	100% In Process	None Allowable

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
c. Excess Material	Visual	100% In Process	None Allowable
d. Contamination	Visual 5X Magnification	100% In Process	None Allowable
7.6.1.4.2 Potting			
a. Potting Compound Preparation		100% In Process	See Manufacturers Instructions
b. Air Bubbles During Mixing	Visual	100% In Process	Degas Until no Bubbles Are Visible
c. Air Bubbles	Visual 5X Magnification	100% In Process 10 Min After Potting	No Surface Bubbles Visible
d. Fabricate Test Specimen		Fabricate for Each Lot	
e. Surface Quality	Visual	100% In Process	See Test Paragraph 7.8

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
f. Potting Separation	Visual	100% In Process	
g. Hardness	Durometer	100% for Each Lot or Control Specimen	Shore D25 ± 2
7.6.2 Inspection of Cylindrical Plugs			
7.6.2.1 Receiving Inspection of Plug Material			
7.6.2.1.1 Potting Compound (See Paragraph 7.4.4)			
7.6.2.2 Parts Assembly			
7.6.2.2.1 Cable Stripping	Visual	100% In Process	Conductor Exposure 0.425 in.
7.6.2.3 Molding (See Paragraph 7.6.1.3)			

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6.2.3.1 Environmental Requirements			
7.6.2.3.2 Molding Sample			
a. Dimensions	Visual	Sample	MIL-C-55544 & NASA Drawing 50M72607
b. Porosity	See Paragraph 7.6.1.3.3(b)		
7.6.2.4.4 Finishing	See Paragraph 7.6.1.4		
7.6.3 Inspection & Test of Premolded Plug Flat Cable Assembly (Unshielded)			
7.6.3.1 Conductor Insertion Damage	Visual	100% In Process	No Bends, Kinks, etc.
7.6.3.2 Conductor Folding Damage	Visual 5X Magnification	100% In Process	No Plating Separation

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6.3.3 Wedge Insertion	Visual	100% In Process	See Figure 7-5, View A
7.6.3.4 Potting Base of Plug	Visual	100% In Process	See Figure 7-5, View B
7.6.3.5 Installation of Silicone Rubber Seal	Visual	100% In Process	See Figure 7-5, View C
7.6.4 Special Terminations			
7.6.4.1 Inspection of Flat Cable Conductors to Grounding Terminations			
7.6.4.1.1 Strip Cable Ends	See Paragraph 7.5.2		
7.6.4.1.2 Clean Conductors and Ground Lug	Visual 10X Inspection	100% In Process	No Signs of Oxidation, etc.
7.6.4.1.3 Tinning and Soldering Conductor and Ground Lug	Visual	100% In Process	MIL-S-45743

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6.4.1.4 Epoxy Application			
7.6.4.1.4 Epoxy Application	Visual	100% In Process	See Paragraph 7.6.4.1.4
7.6.5 Inspection of Flat Conductor Cable to Round Wire Transitions			
7.6.5.1 Conductor Preparation			
7.6.5.1.1 Flat Conductor Cable Stripping (See Paragraph 7.5.2)			
7.6.5.1.2 Round-Wire Stripping			
a. Quality Requirements			MIL-S-45743
b. Dimensions	Visual	100% In Process	0.375 ±0.030-Inch Strip
7.6.5.1.3 Cleaning	10X Magnification	100% In Process	No Oxidation Visible

TABLE 7-1. INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Continued)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.6.5.1.4 Conductor Soldering	Visual	100% In Process	MIL-S-45743
7.6.5.1.5 Potting	Visual	100% In Process	MSFC-PROC-196
7.7 Final Inspection and Test of Assembled Cable and Plug			
7.7.1 Visual/Mechanical			
a. Verify All Previous Inspection Points		100%	See Applicable Sections
b. Inspect for Cleanliness	Visual	100%	Extraeous material Unacceptable
c. Conductor Cleanliness	10X Magnification	100%	No Visible Oxidation
d. Mechanical Mating	Mate With Appropriate Receptacle	100%	(1) Smooth Positive Operation (2) No Conductor Damage (3) No Gasket Damage
7.7.2 Electrical			

TABLE 7-1 INSPECTION AND TEST OUTLINE FOR FLAT CABLE ASSEMBLY MANUFACTURING (Concluded)

Reference Paragraph and Inspection Parameter	Method of Inspection	Inspection Interval	Acceptance Criteria
7.7.2.1 Unshielded Systems			
a. Conductor Continuity	See Figure 7-6	100%	All Conductors Continuous
b. Conductor to Conductor Leakage	See Figure 7-6	100%	
c. Dielectric Voltage Test	Mil-Std-202	100%	MIL-C-55544
7.8 Installation of Flat Cables, Inspection and Test Requirements			
7.8.1 Installation of Supports and Clamps			
a. Attach Area Clean	Visual	100%	Free of Oxidation, etc.
b. Alignment	Visual	100%	
c. Clamp Placement	Visual	100% In Process	
7.8.2 Flat Cable Harness Preparation			
7.8.2.1 Folding	Visual	100% In Process	
7.8.3 Routing Cable Bundles	Visual	100%	

7.4 Receiving Inspection

7.4.1 Cable Inspection and Test

7.4.1.1 Identification. The cable, as received, shall be identified in accordance with MIL-C-55543. Each cable roll shall be inspected for proper identification, and information shall be recorded in a receiving log for a permanent record as follows:

DATE RECEIVED	PART NUMBER LOT NUMBER	MANUFACTURE CODE	DATE OF MANUFACTURE

A sample of a convenient length, 6 or 8 inches from each lot received, should be extracted and filed with the receiving and inspection record.

7.4.1.2 Certification of Conductor Material (Shielded and Unshielded). With each shipment of cable, certification of conductor material should be provided by the manufacturer. This information should be filed with the receiving and inspection record.

7.4.1.3 Packaging and Packing Inspection (Shielded and Unshielded). Cables should be received in a condition in accordance with MIL-C-12000. Minimum acceptable lengths for various cable widths shall conform with the requirements outlined in MIL-C-55543.

7.4.1.4 Cable Dimensions (Unshielded). Inspection of cable dimensions on the receiving level should be divided into three inspection areas:

a. Cable width

b. Conductor spacing and alignment

c. Conductor cross-section

All dimensions taken should correspond with the specification sheets of MIL-C-55543. Any variance from these dimensions should be considered a major defect and cause for rejection. Part of these measurements, for unshielded cable, can be checked on a conceptual device as shown in Figure 7-1.

The device illustrated is not presently available, but is a recommended approach for inspecting large quantities of bulk cable. Inspection of FCC by other means can be implemented using the principles of this device.

7.4.1.4.1 Cable Width. Cable widths can be measured on the device shown in Figures 7-1 and 7-2. The entire roll can be checked for width dimensions upon each receipt by observing the gage on the device shown. The need for a 100-percent inspection level can be eliminated after a confidence level has been reached assuring the cable adheres to the requirements of MIL-C-55543. An appropriate sampling plan can then be initiated.

7.4.1.4.2 Conductor Spacing and Alignment. Variance in conductor spacing and alignment can be detrimental to the operation of the cable, particularly when used in RF applications. Checking for spacing and alignment for unshielded cable for both polyester and polyimide can be done visually using the device shown in Figure 7-1. By passing the cable by a standard gradient, which is placed at a relatively small angle to the horizontal, a moire pattern is formed. This pattern, if observed carefully, will change if conductor alignment is not correct. See Figure 7-2 for particulars.

When any change in the pattern occurs, an exact measurement of the spacing can be taken and recorded. Depending upon the extent of the defect, that portion of the cable roll can be rejected. All cable spacing should adhere to the requirements of MIL-C-55543.

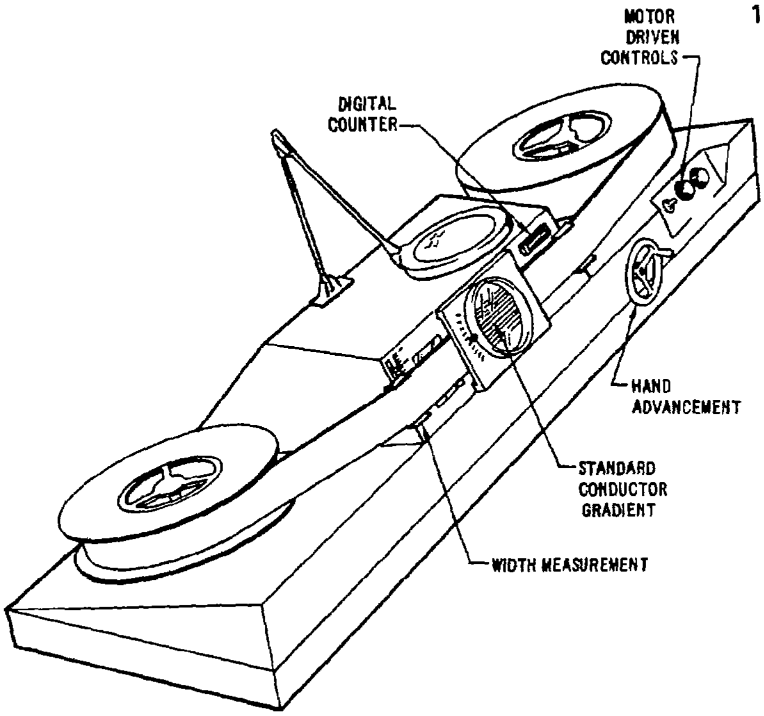


FIGURE 7-1. Flat cable inspection device.

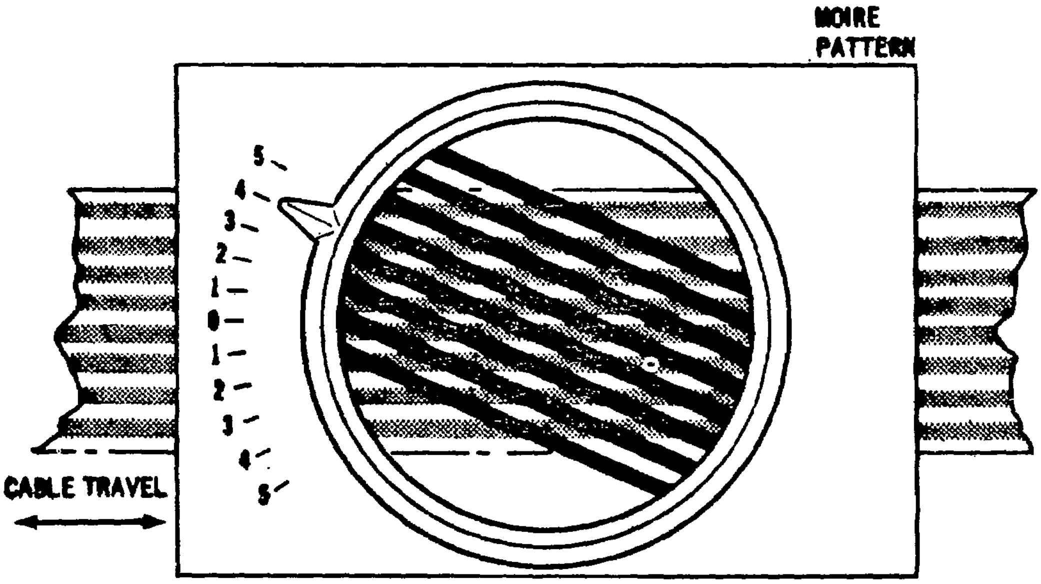


FIGURE 7-2. Unshielded conductor viewing screen.

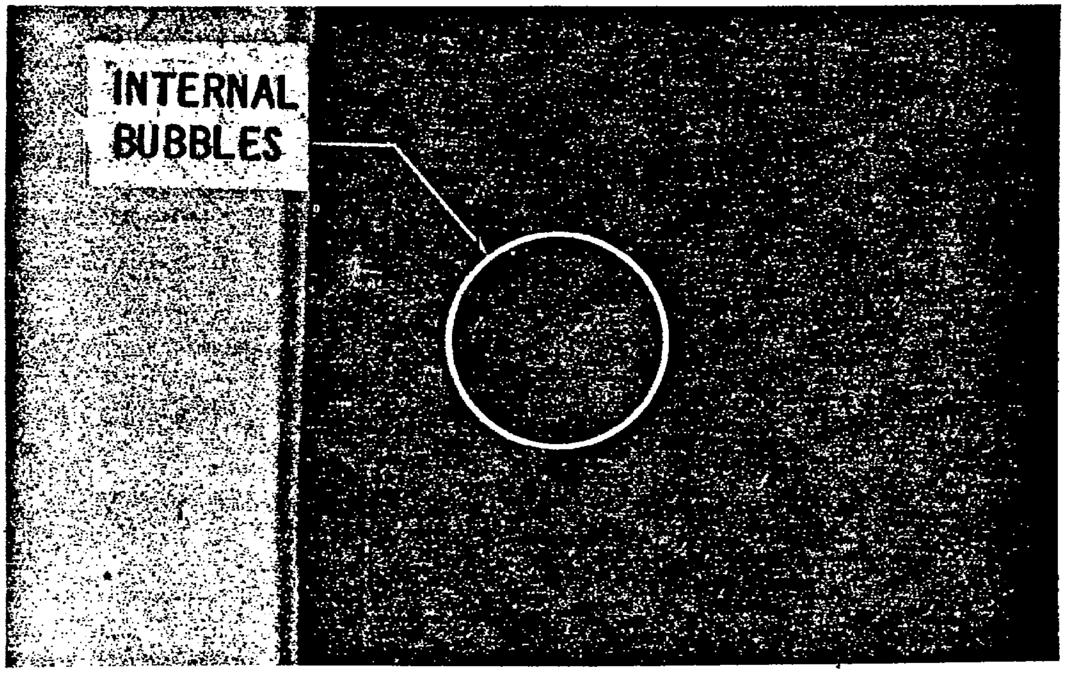


FIGURE 7-3. Internal bubbles polyimide/FEP shielded cable.

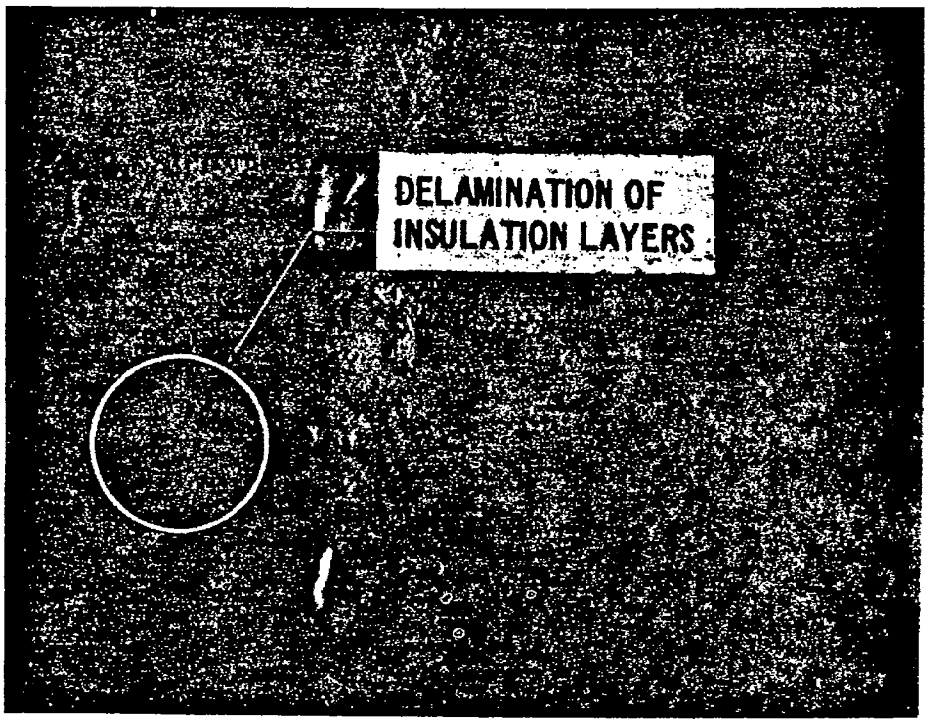


FIGURE 7-4. Delamination of insulation layers.

7.4.1.5 Cable Inspection (Shielded). The checking of the spacing alignment and conductor width of shielded cable (Figure 7-10) cannot be accomplished by the visual method as suggested in Paragraph 7.4.1.4. An X-ray approach to check conductor alignment is therefore suggested for a quick look at conductor profile.

A sampling plan should be initiated to X-ray check specific lengths of cable.

A table-top radiograph device that incorporates a polaroid camera for quick processing of radiographic prints can be utilized. The film can be then analyzed for conductor width and spacing alignment.

7.4.1.5.1 Flat Cable Testing with Time-Domain Reflectometry. Time-domain reflectometry is a system of utilizing pulse reflections to locate discontinuities along cables. A pulse-by-pulse burst is sent continuously down the cable under investigation, and the reflected signals are monitored on a scope. This method enables the user to view the characteristic impedances of the cable. It also will provide both the position and the nature (resistive, inductive, or capacitive) of each discontinuity.

This system may be particularly helpful in the inspection of shielded-cable geometry. Any variance in conductor or shield spacing in modes A, B, and C, as indicated in Figure 7-11 may be detected with the proper equipment.

Further information on time-domain reflectometry and applications can be found in the following publications:

Hewlett Packard Application Note 62, "Time Domain Reflectometry," Hewlett Packard Co., 1964

H & P Application Note 67, "Cable Testing with Time Domain," H & P Co., 1965

Tektronix Service Scope No. 45, "Time Domain Reflectometry Theory and Coaxial Cable Testing," Tektronix, Inc., Aug. 1967.

With time-domain reflectometry each of the modes shown, A, B, and C, (Fig. 7-11), can be inspected without extracting a sample from a cable roll.

7.4.1.6 Workmanship (Polyester and Polyimide Cable). The cable, from an overall quality standpoint, should be inspected over its entire length. Unsatisfactory conditions that may exist are as follows:

7.4.1.6.1 Air bubbles - Below the surface of the insulation (Fig. 7-3).

7.4.1.6.2 Delamination - Separation of insulation material from the conductors (Fig. 7-4).

7.4.1.6.3 Broken conductors.

7.4.1.6.4 General damage - Kinks, abrasions, cracks, dents, etc.

The preceding defects can be cause for rejection if they adversely affect the serviceability of the cable. Identification of visible defects can be accomplished on a device shown in Figure 7-1. The entire length of cable can be checked quickly by passing it over the light source and viewing it under an ample magnification. Gross defects can be identified and marked on the cable with a grease pencil for later analysis. Both sides of the cable should be inspected.

If defects to the insulation are numerous, i.e., pits, bubbles, etc., an additional test may be performed. This test is defined in Federal Test Method Standard No. 228, Method No. 6211. The test consists of passing the cable over an electrode, wet sponge, for detection of insulation flaws.

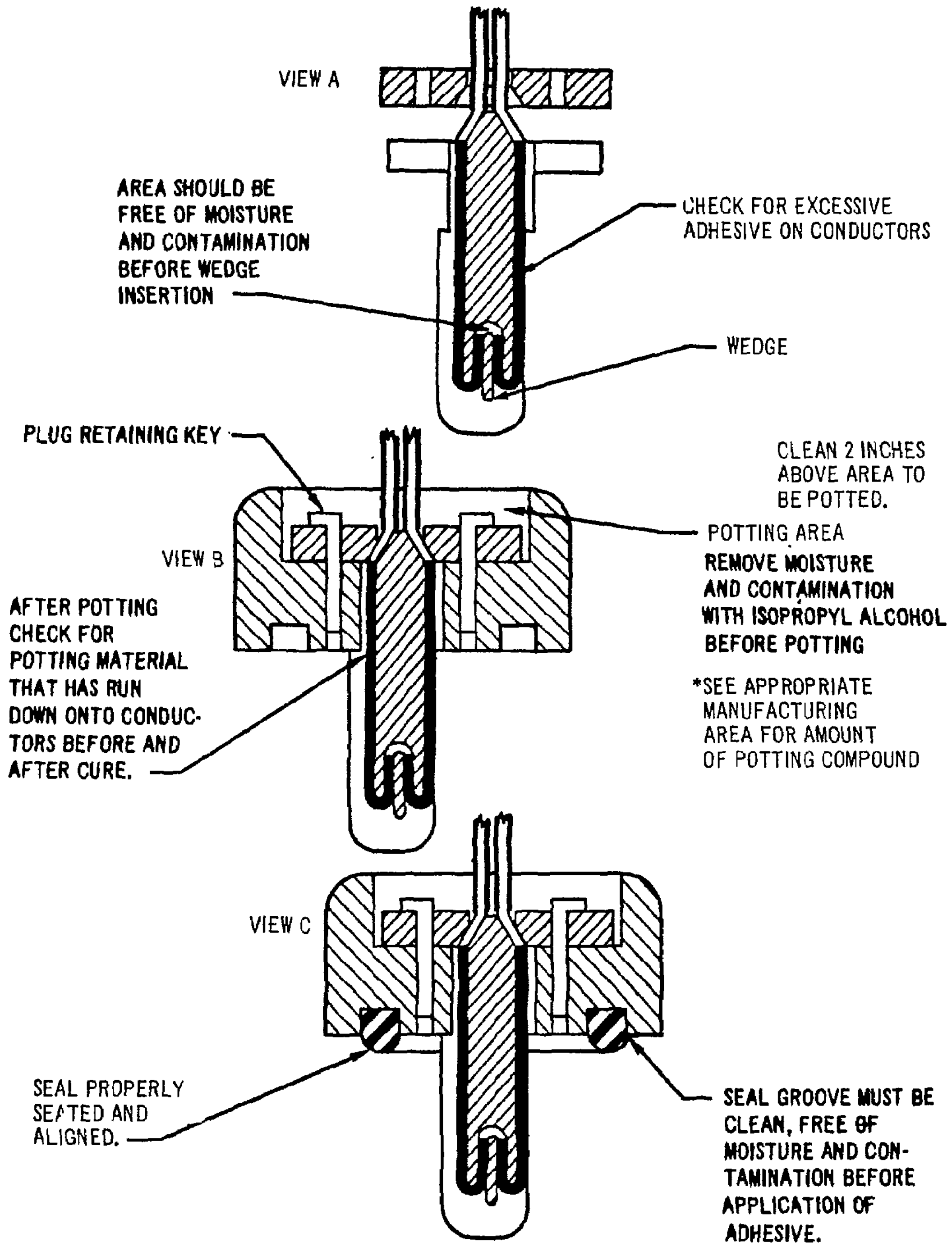


FIGURE 7-5. Unshielded premolded plug inspection.

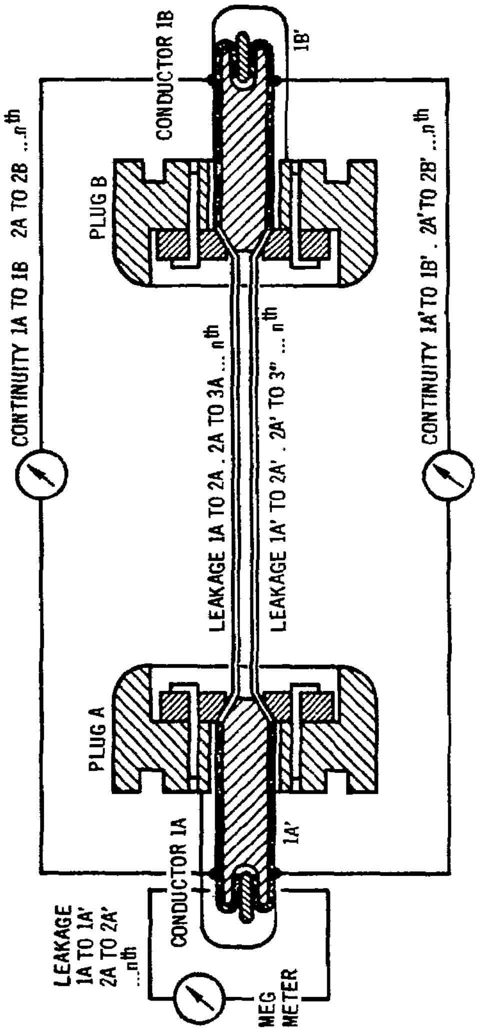


FIGURE 7-6. Unshielded system.

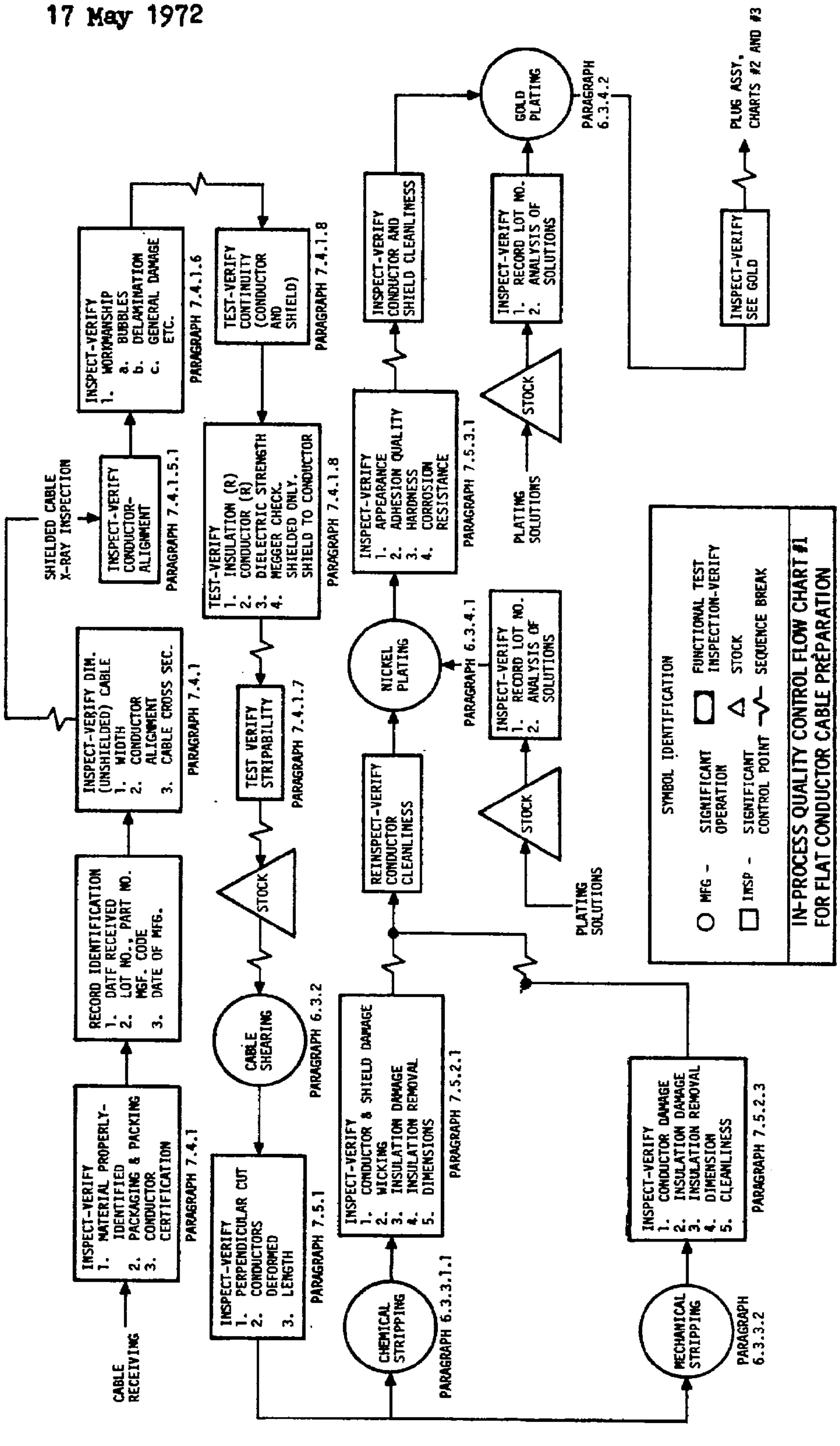


FIGURE 7-7. In-process quality control flow chart for FCC preparation.

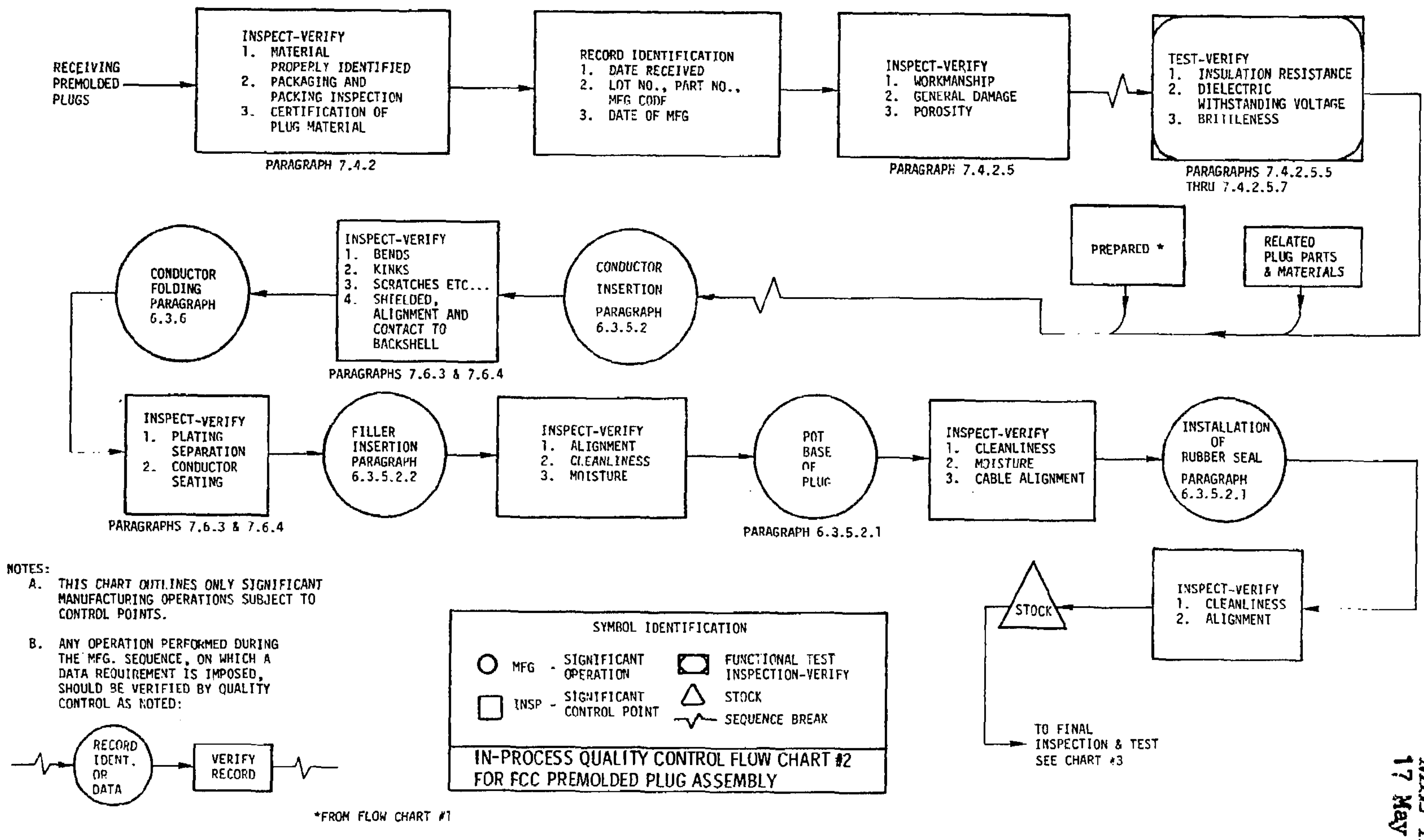


FIGURE 7-8. In-process quality control flow chart for FCC premolded plug assembly.

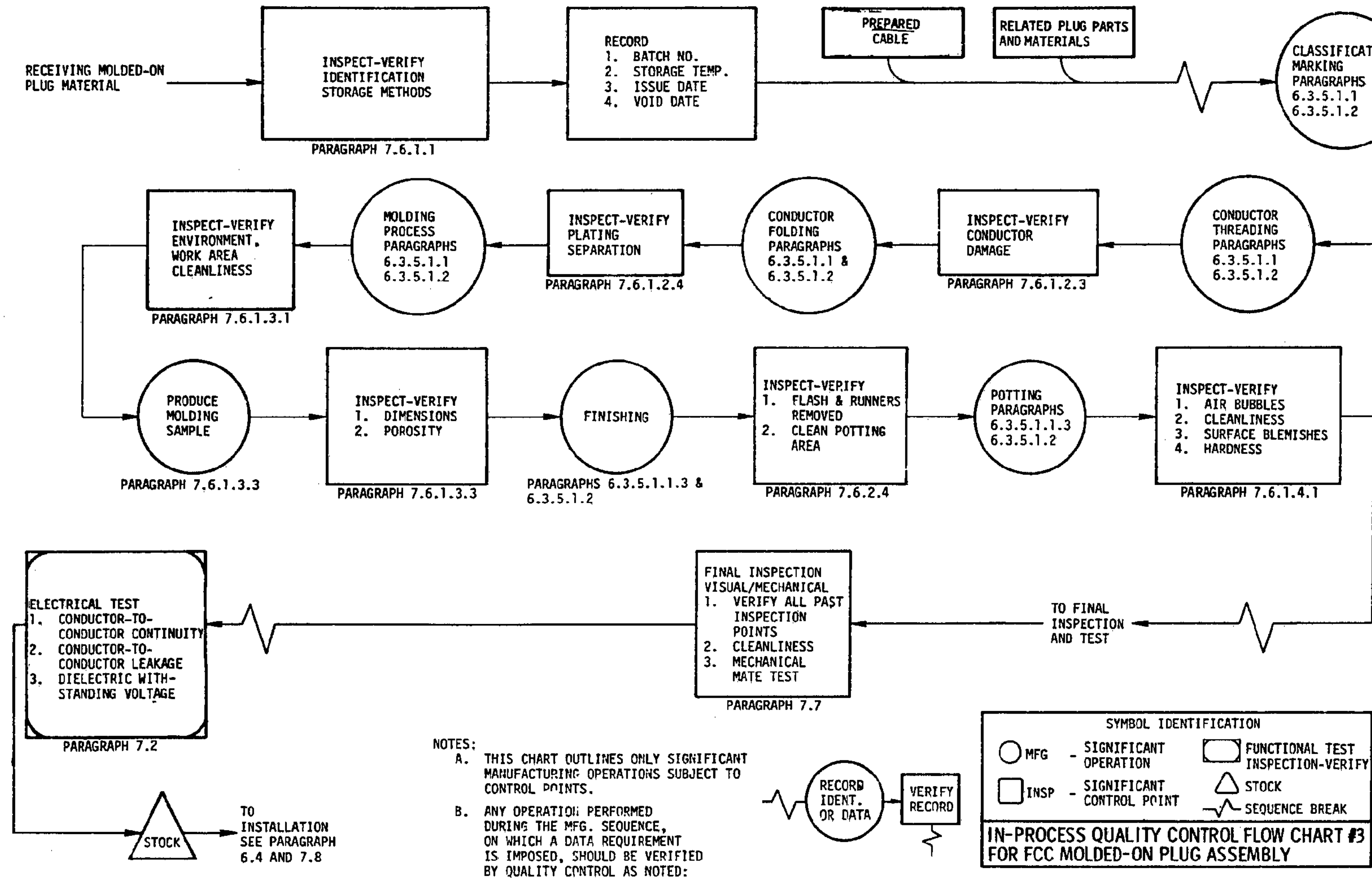


FIGURE 7-9. In-process quality control flow chart for molded-on plug assembly.

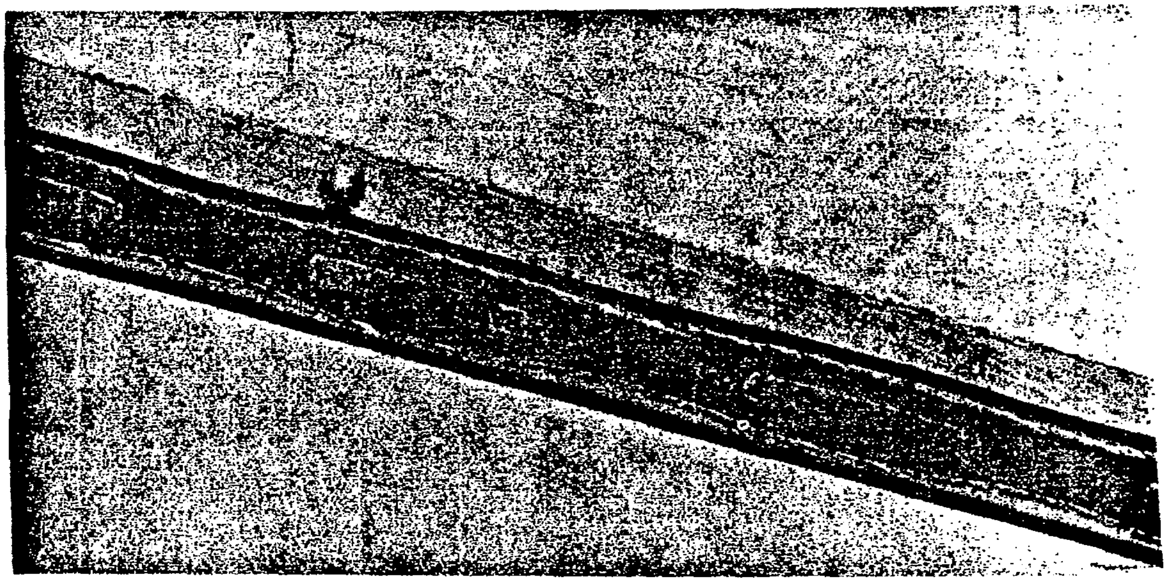


FIGURE 7-10. Cross-section shielded polyimide/FEP cable.

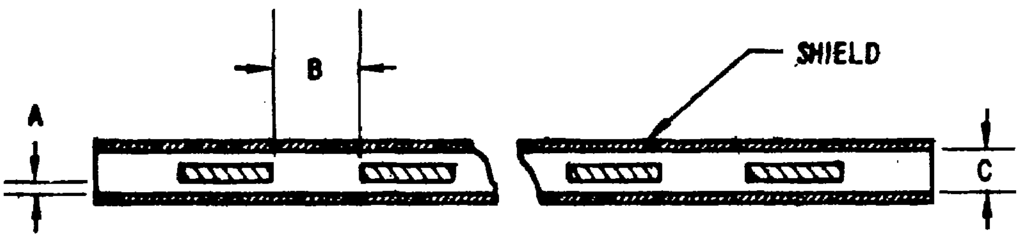


FIGURE 7-11. Cross-section shielded cable.

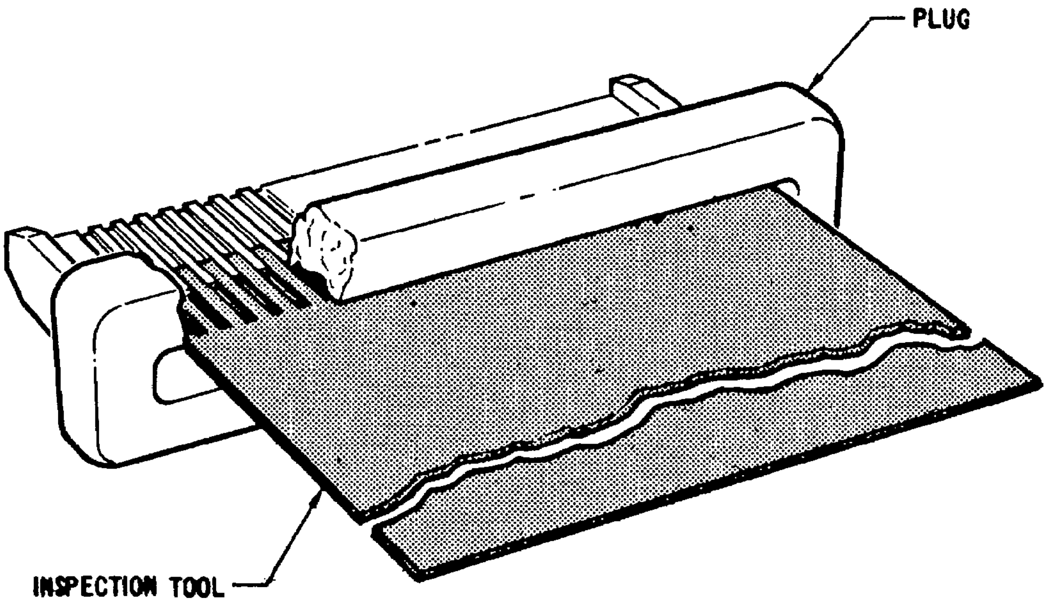


FIGURE 7-12. Plug window dimensional inspection tool and flash remover.

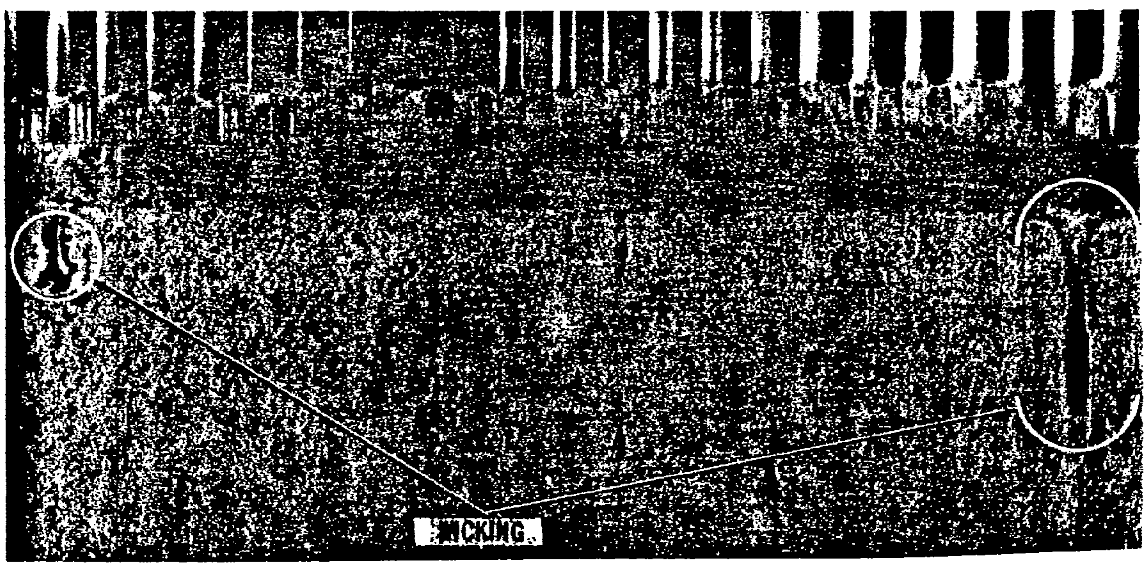


FIGURE 7-13. Chemical wicking.

7.4.1.7 Stripability. To determine before production if the cable received is stripable, a sample should be extracted and stripped according to the standard stripping methods of Section VI.

7.4.1.8 Receiving Inspection (Electrical Test).

7.4.1.8.1 Cable Electrical Continuity. Cable electrical continuity should be inspected on a 100-percent basis. Both ends of the cable roll should be stripped, and a continuity check should be made on each conductor.

7.4.1.8.2 Insulation Resistance. A sample should be cut from the end of the cable roll and tested per MIL-C-55543.

7.4.1.8.3 Conductor Resistance. The dc resistance of the individual conductors should be taken on a sample basis and tested in accordance with Federal Test Method Standard No. 228, Method No. 6021.

7.4.1.8.4 Dielectric Strength. A sample roll from each inspection lot should be subjected to the dielectric test per MIL-C-55543.

7.4.2 Receiving Inspection Premolded Plugs (Shielded and Unshielded).

7.4.2.1 Identification. The plugs as received should be identified properly in accordance with MIL-STD-129D. Each shipment should be inspected for proper identification, and information should be recorded in a receiving log for a permanent record as follows:

DATE RECEIVED	MANUFACTURING CODE	DATE OF MANUFACTURE

7.4.2.2 Material Certification. Certification of plug material should be provided by the manufacturer with each shipment of plugs and filed with each receiving and inspection record.

7.4.2.3 Packaging and Packing Inspection. Connector plugs should be received in a condition in accordance with MIL-D-116. Preservation and packing should be as the contract or purchase order requires. Specifics may be found in MIL-C-55544.

7.4.2.4 Plug Dimensions. An appropriate sampling plan should be initiated to check critical plug dimensions. All dimensions should comply with MIL-C-55544; any variance from these dimensions should be considered a major defect.

The sampling plan initiated should include sectioning of the plug to inspect critical internal dimensions.

An inspection tool, similar to the one illustrated in Figure 7-12, can be used to inspect the plug window area. The tool serves two purposes: (1) a quick dimensional check, and (2) a flash-removal device used by Manufacturing.

7.4.2.5 Workmanship. Overall quality of the plug should be checked in the following areas:

7.4.2.5.1 Flash. Flash, or excessive material on the plug, can be particularly critical if it exists in the plug window area. An appropriate sampling plan to identify this defect cannot be overstressed. The tool illustrated in Figure 7-12 can be utilized. If the insertion of the tool is rough and not smooth, flash may exist. The plug should then be identified and reworked or rejected.

7.4.2.5.2 General Damage. The received plug should be inspected, on a sample basis, for general damage (cracks, nicks, etc.).

7.4.2.5.3 Porosity. A sample should be taken from each inspection lot and sectioned for porosity inspection. The cut section should be viewed for porosity under 5X magnification. The complete procedure for porosity identification is defined in Federal Test Standard No. 406, Method No. 5021.

7.4.2.5.4 Plug Material Testing. Specific parameters to ensure consistent material quality should be checked on an inspection-lot basis until a reasonable confidence level has been reached. The test are as follows:

7.4.2.5.5 Insulation Resistance. For procedure, see Federal Standard No. 406, Method No. 4041.

7.4.2.5.6 Dielectric Withstanding Voltage. See Federal Test Standard No. 406, Method No. 4031.

7.4.2.5.7 Brittleness. See Federal Test Standard No. 406, Method No. 2051.

7.4.3 Receiving Inspection of Related Plug Materials.

7.4.3.1 Premolded Plug Wedge and Retainer.

7.4.3.1.1 Dimensions. Initiate a sampling plan to check critical dimensions. Dimensions are found in MIL-C-55544.

7.4.3.1.2 Material Testing. Same as plug material testing (See Paragraph 7.4.2.5.4).

7.4.3.2 Gasket.

7.4.3.2.1 Dimensions. Initiate sampling plan to check overall dimensions.

7.4.3.2.2 Hardness. Check the gasket for hardness using durometer shore (A). Hardness should be Shore A78 ±3.

7.4.3.2.3 Age Control and Storage. The age and storage control of gasket material should be in accordance with MSFC-STD-105.

7.4.4 Molding Compounds, Potting Compounds, and Adhesives Control. The general requirements for storage and in-plant control of the plating compounds and adhesives, as referenced in Section VI, are specified herein.

7.4.4.1 Identification and Storage. The identification and storage requirements are as follows:

a. Issuance of materials should be on a first-in, first-out basis.

b. Materials should be stored per manufacturer's instructions.

c. All bulk materials should be labelled and identified, and stored and handled per manufacturer's instructions. Label as follows:

Perishable Item

Batch No. (Vendor's batch or lot numbers)
Stored At (Storage temperature)
Issue Date (Date material issued from storage)
Void After (Expiration date after testing and storage)

7.4.4.2 Storage Surveillance. The storage surveillance requirements are as follows:

a. Materials which have aged beyond the void date should be impounded and retested.

b. Materials should be reidentified with a new expiration date, if tested and found acceptable.

c. Records of periodic storage surveillance should be maintained.

7.4.5 Receiving Inspection - Receptacles.

7.4.5.1 FCC to FCC Rectangular Receptacle.

7.4.5.1.1 Identification. The receptacles, as received, will be identified in accordance with MIL-C-55544 and MIL-STD-129. Each shipment should be checked for proper identification, and the information should be recorded in a receiving log as follows:

DATE RECEIVED	MANUFACTURING CODE	DATE OF MANUFACTURING

7.4.5.1.2 Packaging and Packing. Connector receptacles, as received, should be in accordance with MIL-P-116. Preservation and packing should conform to the requirements of the contract or purchase order. Requirements are defined in MIL-C-55544.

7.4.5.1.3 Dimensions. An appropriate sampling plan should be initiated to inspect critical receptacle dimensions. All dimensions should comply with MIL-C-55544; any variances in tolerances should be considered a major defect. Measurement of contact spacing and size should be made using a standard gauge and inserting it into the receptacle.

7.4.5.1.4 General Damage. The receptacle, as received, should be reviewed for any damage, cracks, nicks, etc. Particular attention should be paid to contact pins, checking for bends, etc.

7.4.5.1.5 Material Identification. With each shipment, shell material, contact material, retainer clip, and gasket material should be certified by the manufacturer. This information should be filed with the receiving inspection record. Material requirements are defined in MIL-C-55544.

7.4.5.1.6 Material Finish. Finish requirements for the shell and contact material are defined in MIL-C-55544. A sample plan should be initiated to verify these finishes.

7.4.5.1.7 Mating and Unmating Forces. Receptacles should be capable of being mated and unmated with applicable plugs without the use of any special tool. The force required either to engage or separate the plug and receptacle should not exceed the maximum force specified in the appropriate table of MIL-C-55544. An appropriate sampling plan should be initiated for inspection of this parameter.

7.4.5.1.8 Electrical.

7.4.5.1.8.1 Contact Resistance. Initiate a sampling plan to measure contact resistance in accordance with method 307 of MIL-STD-202. MIL-C-55544 gives the individual millivolt drop values.

7.4.5.1.8.2 Low-Level Contact Resistance. Initiate a sampling plan to measure low-level contact resistance per MIL-C-55544. Reference MIL-C-55544 for specific values.

7.4.5.2 FCC to RWC Rectangular Receptacle. Reference Paragraphs 7.4.5.1.1 through 7.4.5.1.8.2 and MIL-C-55544 for specifics.

7.4.5.3 FCC to FCC Cylindrical Receptacle. Reference Paragraphs 7.4.5.1.1 through 7.4.5.1.8.2 and MIL-C-55544 for specifics.

7.4.5.4 FCC to RWC Cylindrical Receptacle. Reference Paragraphs 7.4.5.1.1 through 7.4.5.1.8.2 and MIL-C-55544 for specifics.

7.4.6 Receiving and Inspection of Clamps and Supports.

7.4.6.1 Identification. The clamps received should be identified per MIL-STD-129. Each shipment should be inspected for proper identification and recorded in a receiving log.

7.4.6.2 Packaging and Packing Inspection. FCC clamps received should be in accordance with MIL-P-116. Preservation and packing received should conform to the contract or purchase order requirements.

7.4.6.3 Dimensions. A sample plan should be initiated for inspecting clamp dimensions per applicable drawing.

7.4.6.4 Workmanship. The clamping device should be inspected for the following:

a. General damage.

b. Plating consistency (if required).

c. Spring tension (if incorporated).

d. Cushion hardness - The rubber used on the clamp should be subjected to a durometer Shore inspection to determine if the cushion hardness is within tolerance.

7.5 In-Process Inspection and Test of Cable Preparation for Termination

The inspection requirements for preparing cable for termination will be discussed in this section. The three basic steps, shearing, stripping, and plating, will be elaborated upon. The particular stripping method used will depend upon what cable type is used. Reference the appropriate manufacturing section for the determining stripping methods.

7.5.1 Cable-Shearing Inspection (Reference Section VI, Paragraph 6.3.2). Three major parameters should be inspected before the cable can be stripped. These parameters are:

a. The shear must be cut perpendicular to the conductor.

b. The conductor ends should not be deformed. Inspection under a magnifying glass of ample power should be performed for identification of deformed conductor ends.

c. The length of the sheared cable should be accurate.

7.5.2 Cable-Stripping Inspection.

7.5.2.1 Chemical Stripping - Polyester and Polyimide Unshielded and Shielded Cables (Reference Section VI, Paragraph 6.3.3.1.1). Chemical stripping of both polyester and polyimide cable consists of the same general inspection procedures. These procedures are as given in the following paragraphs.

7.5.2.1.1 Conductor Damage. Check for oxidation and contamination of conductors. If contamination is found, check the chemical stripping solutions for foreign material and contamination.

7.5.2.1.2 Wicking. Wicking (Fig. 7-13) is the capillary action of the stripping solution to travel past the strip line between the cable conductors and the insulation. Wicking can be prevented if strict adherence to the precautionary measures defined in Section VI are taken.

Any sign of wicking, after inspection under 5X magnification, shall be cause for rejection.

7.5.2.1.3 Insulation Damage. Any chemical degradation of insulation material beyond the designated area of strip should be cause for rejection. The strip line should be clean and straight, and no tape adhesive should remain on and around the strip line.

7.5.2.1.4 Complete Insulation Removal. The stripped cable should be carefully checked for any residual insulation on, or between, the conductors. Inspection of the conductors at this point cannot be overly stressed. Each conductor should be checked individually under a magnification of 10X power. Any residual insulation found should be identified and removed per instructions in Section VI, Paragraph 6.3.3.

7.5.2.1.5 Dimension of Strip. Each stripped cable should be measured for proper strip length. The strip lengths will vary depending upon the type of plug being used, rectangular molded-on, or premolded, or cylindrical. These dimensions may be found in the manufacturing section pertaining to plugs.

7.5.2.2 Mechanical Stripping (Reference Section VI, Paragraph 6.3.3.1.2). The inspection and test requirements for stripping cable by using the following stripping tools are basically the same. Reference the appropriate manufacturing section for specifics.

a. NASA cold stripper - Section VI, Paragraph 6.3.3.2.1.

b. NASA plane stripper - Section VI, Paragraph 6.3.3.2.2.

c. Gore stripper - Section VI, Paragraph 6.3.3.2.3.

d. Viking FCC stripping machine - Section VI, Paragraph 6.3.3.2.4.

e. Rush FCC stripping machine - Section VI, Paragraph 6.3.3.2.5.

f. Carpenter FCC stripping machine - Section VI, Paragraph 6.3.3.2.6.

7.5.2.2.1 Conductor Damage. The above stripping devices employ either a knife blade for stripping or an abrasive wheel for removing of insulation. Particular attention must be given to conductor damage that may be caused by the knife blade, excessive heat, or abrasive. The conductors, under an ample magnification, should be observed for:

a. Nicks, scratches, abrasions, and bends (Fig. 7-14).

b. Plating defects.

c. Conductor heat damage, oxidation, etc.

7.5.2.2.2 Complete Insulation Removal. The stripline should be even, and clean and free of all residual insulation or bonding agents. No insulation should be left between the conductors. Each conductor should be checked under magnification for residual insulation or bonding agents. If the insulation is not properly removed, samples should be run on the particular stripping device being used to determine the appropriate stripping pressure to effectively strip the cable. The bond strength from cable to cable may vary; therefore, it will be necessary at times to perform the task just described. Figure 7-15 shows an example of uneven stripping and excessive insulation between stripping conductors.

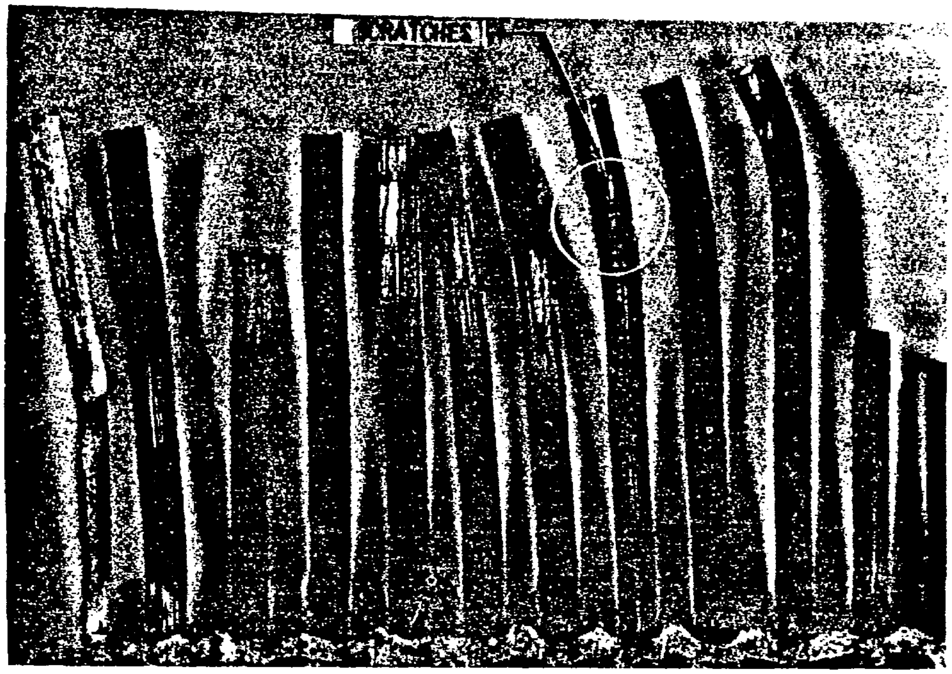


FIGURE 7-14. Scratches, nicks, and bends of conductors.

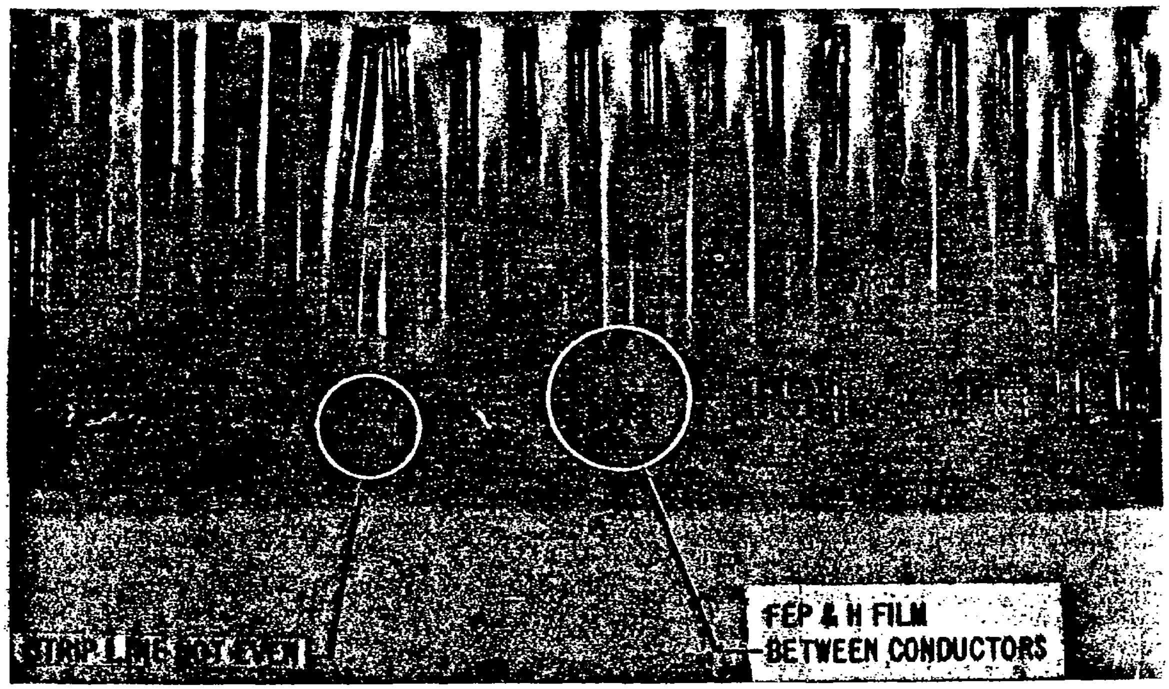


FIGURE 7-15. Polyimide and FEP between conductors.

7.5.2.2.3 Conductor and Insulation Cleanliness. Each conductor should be inspected for cleanliness after stripping, particularly in the case of abrasive stripping. Inspect for metal particles on the conductors or that may have been embedded in the insulation between conductors. The particles can cause short circuits during the electroplating process that follows stripping.

7.5.2.3 Acceptable Stripped Cable. Figure 7-16 is presented to provide visual information in recognizing an acceptable strip. Pay particular attention to the appearance of the conductors and strip line.

7.5.3 Conductor and Shield Plating (Reference Section VI, Paragraph 6.3.4). The inspection procedure for nickel and gold plating of cable conductors and shields is as follows:

7.5.3.1 Nickel Plating (Reference Section VI, Paragraph 6.3.4.1).

7.5.3.1.1 Conductor Inspection. Inspection of the conductors before plating is particularly critical. Each one of the conductors should be reinspected if a period of time has lapsed between the stripping and plating operation. Excessive oxidation and general conductor damage, as discussed in the stripping procedure, is unacceptable. Proper precautionary measures should be taken at all times to protect the conductors from damage and corrosion.

7.5.3.1.2 Appearance.

a. The nickel plating should be smooth, adherent, and free from blisters, laminations, nodules, pits, discontinuities, and porosity. Inspection under a magnification of 5X should be used to identify these defects.

b. The line of demarcation between plated and unplated areas shall be even and smooth.

7.5.3.1.3 Thickness. The thickness should be minimum of 0.000,050 inch unless otherwise specified. A section taken on a sample basis should be microphotographed for measurement purposes.

7.5.3.1.4 Adhesion. A plated sample cable should evidence no separation of plate from conductor after bending 180 degrees around a 1/8-inch rod.

Each time the plating solution is renewed, a sample should be plated before actual production begins, checking for adhesion quality.

7.5.3.1.5 Corrosion Resistance. A plated conductor sample should evidence no corrosion of base metal after 2 hours of salt spray, in accordance with Federal Test Method Standard No. 151, Method No. 811.1.

7.5.3.1.6 Sampling and Testing (Plating). Test specimens of the stripped cable (taken from a production inspection lot) should be plated to a minimum thickness of 0.000,050 inch and evaluated for adhesion and corrosion resistance. Production parts shall not be subject to hardness, adhesion, or corrosion-resistance tests.

7.5.3.1.7 Sampling and Testing Solution. Plating solution sample should be analyzed periodically. Renewals and recharges should be specified when necessary to maintain operating conditions. Records of analyses, additions, dumps, recharges, and lot numbers of solutions should be maintained.

7.5.3.2 Gold Plating - Nickel-Plated Conductors and Shield (Reference Section VI, Paragraph 6.3.4.2). The inspection procedure for gold plating is similar to that of nickel plating. The following procedure will note exceptions:

7.5.3.2.1 Conductor and Shield Inspection. Clean, uncontaminated conductors and shield should be checked before the gold plating is begun. The cleaning procedure for nickel-plated conductors is referenced in Section VI, Paragraph 6.3.4.2.1.

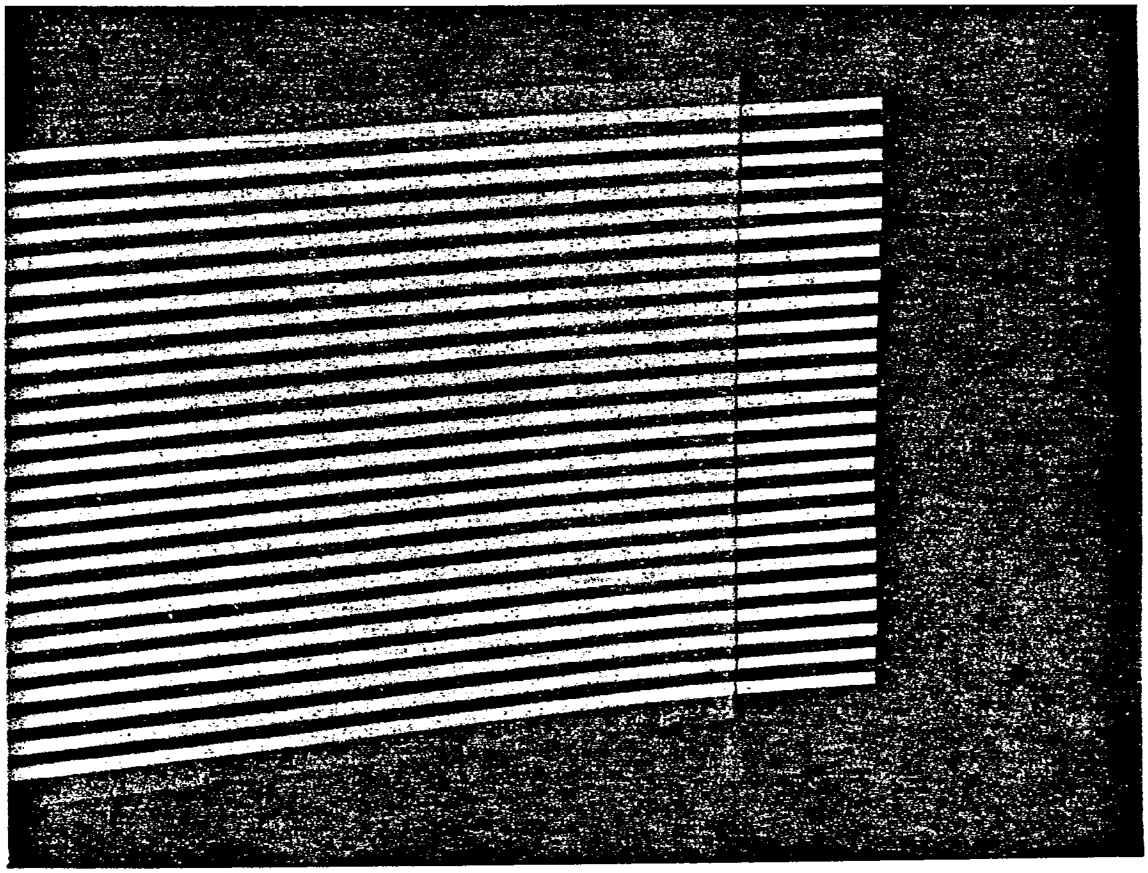


FIGURE 7-16. Properly stripped FCC.

7.5.3.2.2 Appearance. Gold plating should be smooth, adherent, and free from blisters, laminations, nodules, pits, discontinuities, and porosity. Inspection of each conductor and the shield area should be made under a magnification of 5X power.

7.5.3.2.3 Thickness. The thickness should be a minimum of 0.000,050 inch unless otherwise specified.

7.5.3.2.4 Adhesion. A plated sample cable should evidence no separation from the nickel plated conductors, after bending 180 degrees around a 1/8-inch-diameter rod. Each time the plating solution is renewed or recharged, a sample should be plated before production begins, checking for adhesion quality.

7.5.3.2.5 Sampling and Test (Plating). Same as nickel plating (Paragraphs 7.5.3.1.6 and 7.5.3.1.7).

7.6 Inspection and Test of Cable Terminations

7.6.1 Inspection of Molded-On Plug Assembly, Rectangular (Reference Section VI, Paragraph 6.3.5.1.1). The general inspection points for the assembly of molded-on plug assemblies are explained below. Four basic phases of inspection are discussed as follows:

a. Receiving inspection (See Paragraph 7.4.4).

b. Parts assembly.

c. Molding.

d. Finishing.

7.6.1.1 Receiving Inspection of Molded-On Plug Material.

7.6.1.1.1 Molding-Compound Inspection (Reference Paragraph 7.4.4).

7.6.1.2 Parts Assembly.

7.6.1.2.1 Cable Preparation for Termination. Reference Paragraph 7.5.

7.6.1.2.2 Orientation During Threading. Check for proper orientation before threading of the conductors (Reference Section VI, Paragraph 6.3.5.1.1.1 (b)).

7.6.1.2.3 Conductor Threading. The operation of threading the conductors into the plug is particularly critical. Care must be taken not to damage the conductors during the insertion process. Any bends, kinks, or scratches should be cause for rejection if they affect proper seating of the conductors in the windows.

7.6.1.2.4 Conductor Folding (Reference Section VI, Paragraph 6.3.5.1.1). Inspect the conductors, after folding, for separation of plating around the area of the fold after each operation.

7.6.1.3 Molding.

7.6.1.3.1 Environmental Requirements. The environmental requirements are as follows:

a. The work area should have sealed floors to minimize excess dust.

b. The work area should be shielded from excessive dust or fume-producing operations.

7.6.1.3.2 Manufacturing Verification. Verify that steps a through f referenced in Section VI, Paragraph 6.3.5.1.1.2, have been performed per instructions.

7.6.1.3.3 Molding Sample. A sample should be extracted from each manufacturing lot and evaluated for the following:

a. Dimensions per MIL-C-55544.

b. Porosity - A sample taken from each inspection lot should be sectioned and viewed for porosity under 5X magnification. The complete procedure for porosity identification is defined in Federal Test Standard No. 406, Method No. 5021.

7.6.1.4 Finishing (Reference Section VI, Paragraph 6.3.5.1.1.3).

7.6.1.4.1 Verify the following points before potting:

a. Are runners cleanly cut from the molded body?

b. Is all flash, or excess material, removed?

c. Has all the material that has flowed over the contact area been removed?

d. Is the area to be potted free from contamination and foreign matter? The plug and the cable (2 inches above plug) should be cleaned by using isopropyl alcohol.

7.6.1.4.2 Potting. The following areas should be verified during the potting process.

a. Verify that the preparation of the potting compound is per manufacturer's instructions.

b. Air bubbles entrapped during mixing should be removed by degassing before injection.

c. The plug should be inspected approximately 10 minutes after potting for cleanliness, excessive material, and surface bubbles. Surface bubbles can be broken by brushing the surface lightly with a small piece of mylar.

d. From each batch of mixed compound, fabricate a control specimen 0.25-inch thick by pouring compound into a new metal-foil cup. Each control specimen shall accompany the potted connectors throughout the potting and curing operations. Identify each specimen with manufacturer's batch number, date, and time of mixing. The control specimens should be retained until all required potting operations are completed and accepted by Quality Control.

e. The exposed surfaces of the cured potting compound should be free from cracks. No blemishes in cable area are allowable.

f. Separation of the potting compound is not acceptable.

g. The control specimen shall have a durometer hardness of Shore D25 ±2.

7.6.2 Inspection of Molded-On Plug Assembly (Cylindrical) (Reference Section VI, Paragraph 6.3.5.1.2). The general inspection points for the assembly of cylindrical plugs is referenced herein. Since the assembly of cylindrical plugs is similar to that of molded-on plugs, only pertinent exceptions will be noted.

7.6.2.1 Receiving Inspection of Plug Material.

7.6.2.1.1 Potting Compound (Reference Paragraph 7.4.4).

7.6.2.2 Parts Assembly.

7.6.2.2.1 Cable Stripping. Cables used should be stripped to expose the conductors to a distance of 0.425 inch.

7.6.2.3 Molding.

7.6.2.3.1 Environmental Requirements (Reference Paragraph 7.6.1.3.1).

7.6.2.3.2 Molding Sample. A sample should be extracted from each manufacturing lot and evaluated for the following:

a. Dimensions per MIL-C-55544.

b. Porosity (Reference Paragraph 7.6.1.3.3. (b)).

7.6.2.4 Finishing (Reference Paragraph 7.6.1.4).

7.6.3 Inspection and Test of Premolded Plug Assembly (Unshielded). (Reference Section VI, Paragraph 6.3.5.2.1). The following section includes an item-by-item procedure specifying those inspection points necessary in the assembly of a premolded plug-flat cable assembly.

7.6.3.1 Cable-Conductor Insertion. The operation of threading the conductors into the plug is particularly critical. Care must be taken not to damage the conductors during the insertion process. Any bends, kinks, or scratches should be cause for rejection if they affect proper seating of the conductors in the grooves of the plug.

The conductors should be checked carefully for the above defects before the folding operation occurs. Check to assure that the cable stripline aligns with the inside edge of the plug.

7.6.3.2 Conductor Folding. Inspection of the conductors, after folding, for separation of plating around the area of the fold should be accomplished after each operation.

Proper seating of the conductor into the conductor spacer grooves should also be verified.

7.6.3.3 Wedge Insertion. The areas as shown in Figure 7-5, View A, should be checked carefully before and after insertion of wedge.

Remove, immediately, any adhesive left on the conductors after wedge insertion, per instructions in Section VI, Paragraph 6.3.5.2.1.

7.6.3.4 Potting Base of Plug. Before potting verify plug keys are secured properly. The areas shown in Figure 7-5, View B, should be inspected while in process, and before and after potting of the plug base.

After curing, an inspection should be made of excessive potting in the areas shown. The potting compound in the base of the plug should be checked for voids, bubbles, and completeness of curve.

7.6.3.5 Installation of Silicone Rubber Seal. Inspect for the following items before and after installation of the seal (see Figure 7-5, View C).

Excessive adhesive around or on the seal should be removed after each operation. The adhesive should be cured properly.

7.6.4 Special Terminations.

7.6.4.1 Inspection of FCC Conductors to Ground-Lug Terminations (Reference Section VI, Paragraph 6.3.8).

7.6.4.1.1 Strip Cable Ends. See Paragraph 7.5.2 for cable-stripping inspection requirements.

7.6.4.1.2 Clean Conductors and Ground Lug. The FCC conductors and the area of the ground lug to be soldered should be cleaned by an appropriate method, then inspected under a magnification of 10X before tinning.

7.6.4.1.3 Tinning and Soldering Conductors and Ground Lug. The conductor ends and ground lug should be tinned immediately after cleaning. All tinning and soldering should meet the requirements of MIL-S-45743. There should be a fillet of solder visible around the end and two sides of each conductor for at least three-fourths of the stripped length. The contour of the conductors should be visible. All flux residue should be removed before epoxy application; inspect under magnification.

7.6.4.1.4 Epoxy Application. The epoxy brush coat should have a thickness of at least 0.010 inch in flat, open areas. This thickness requirements does not apply to corners or projections. The epoxy coat should be extended over 0.25 inch of the adjacent cable insulation. Inspect for complete covering of the space between the cable and the unsoldered area of the ground lug. The epoxy coat shall be even and free of bubbles and defects.

7.6.5 Inspection of FCC to Round-Wire Transitions (Reference Section VI, Paragraph 6.3.7).

7.6.5.1 Conductor Preparation.

7.6.5.1.1 FCC Stripping. The inspection parameters for flat conductor cable stripping are given in Paragraph 7.5.2.

7.6.5.1.2 Round-Wire Stripping.

a. Quality requirements for stripping round wire are defined in MIL-S-45743.

b. Stripped length of conductors should be 0.375 ±0.030 inch.

7.6.5.1.3 Cleaning. Before soldering of conductors, each conductor should be cleaned ultrasonically for 5 minutes in Freon-113, then inspected under 10X magnification for cleanliness.

7.6.5.1.4 Conductor Soldering. Conductors must be soldered in accordance with MIL-S-45743; quality requirements are defined therein. Inspect all joints to make sure that joints are secure, that no parts have been damaged (thermally or mechanically), and that excessive solder does not create a possibility of short circuiting. After all wires have been soldered, inspect under magnification for flux residues. Perform a simple continuity check of each termination.

7.6.5.1.5 Potting.

a. Reverify cleanliness of the terminations before potting.

b. All potting compound should be applied in accordance with MSFC-PROC-196.

c. Inspect for complete covering of the terminated area, checking for bubbles and other defects after cure.

7.7 Final Inspection and Test of Cable Assembly

Final inspection test of the assembled plug and cable should be accomplished as soon after final curing of the plug assembly as possible.

Each cable should be checked on a 100-percent level in the following major areas:

7.7.1 Visual/Mechanical.

a. Verify that all previous inspection points have satisfactorily passed the inspection points discussed in the foregoing paragraphs.

b. Check the cable assembly for cleanliness; it should be free of all extraneous potting material. Any material found should be removed by an appropriate method.

c. Verify contact-area cleanliness - each contact area should be checked for oxidation and contamination under a magnification of 10X; any contamination found should be immediately removed if possible. Excessive contact-area contamination or damage should be cause for rejection.

d. Mechanical mating operation inspection - Each cable assembly should be subjected to a mating and unmating operation. Choose the appropriate receptacle for plug mating and insert the plug several times, closing spring clamps each cycle. Inspect for the following after each cycle: (1) smooth, positive operation; (2) conductor damage, plating removal; and (3) silicone rubber gasket damage.

7.7.2 Electrical Testing.[1] The following paragraph discusses the major electrical parameters of a cable assembly that should be inspected. The following figures are for illustration purposes only. The conductor placement and pin assignments may not represent an actual production situation but indicate the basic measurements to be made. Electrical testing should be conducted as soon as possible after mechanical testing.

7.7.2.1 Unshielded Systems. The premolded plug is shown for illustration purposes only. An appropriate inspection plan can be initiated for cylindrical and molded-on plugs by utilizing the information shown.

a. Conductor Continuity - Each conductor must be inspected for continuity on each side of the mated connector pair. A dc potential of 6-volt maximum should be applied through an appropriate indicator. The voltage should be applied to the conductors as shown. Each conductor must be continuous with a maximum of 1-ohm continuity.

b. Conductor-to-Conductor Leakage - Each conductor pair (edge to edge and over/under) should be tested for leakage by performing a megger check as shown in Figure 7-6.

c. Dielectric Withstanding Voltage Test - Connector assemblies should be tested in accordance with Method No. 301 of MIL-STD-202, noting those exceptions specified in MIL-C-55544.

7.8 Installation of FCC, Inspection and Test Requirements

Since the type of clamps and the exact method of installation will vary depending upon the particular application of the FCC system, a general inspection plan is presented (Reference Section VI, Paragraph 6.4).

1. All measurements should be made with an appropriate receptacle connected to the plug.

7.8.1 Installation of Supports and Clamps. The installation of clamps and supports should consist of the following general inspection points and areas of concern:

a. Area of clamp or support attachment should be clean and free of all contamination and oxidation.

b. The clamps must be aligned properly to accommodate the number of cable bundles required.

c. The clamps and supports should be placed at appropriate intervals to prevent excessive cable slack. Supports should be placed at least every 18 inches. Slack should be provided to accommodate only the following areas:

(1) To permit ease of maintenance and one or two reterminations, except where space limitations exist. In such cases, slack may be eliminated, providing no strain is placed on cable termination.

(2) To permit free movement of shock-and-vibration mounted equipment.

(3) To prevent mechanical strain on the cable, cable supports, and cable junctions.

(4) Clamps should provide a snug grip on the cable bundles to prevent chafing and travel of the cable bundle.

7.8.2 FCC Harness - Preparation for Installation. The inspection points for preparing cable for installation are as follows.

7.8.2.1 Folding Requirements (Reference Section VI, Paragraph 6.3.6). Inspection procedure for the folding of shielded and nonshielded cable consists of the following:

a. The point at which the fold is made should be accurately defined.

b. Check for the proper bend-angle after folding.

c. Check for damage around the fold area; delamination, conductor breakage, shield damage, etc.

d. Shielded cable must be folded over a 0.25-inch-diameter spacer or rod to prevent damage.

7.8.3 Routing Cable Bundles. Grouping and routing of cables should follow the general requirements specified herein.

a. Cables must be separated from heated equipment and routed away from liquid drainage areas, or position where corrosive liquids may collect.

b. Cables and cable bundles should be separated and supported away from lines containing flammable liquids, gases and oxygen, and associated equipment. Cable and cable bundles shall not normally be attached to lines and equipment containing flammable liquid gases, unless flammable lines and equipment require electrical connections. When clearance is less than 2 inches, separation shall be maintained by attaching a cable clamp to a fitting on the equipment or a clamp on the line, and no less than 0.5-inch separation shall be maintained.

c. All cables and cable bundles should be routed to avoid abrasion, cutting, or piercing of the insulation by contact with rough surfaces or sharp edges. Cables and cable bundles may contact nonabrasive surfaces of other cables or cable bundles.

The cables should be installed and attached in such a way as to prevent damage to insulation from vibration or other movement of the cable with respect to adjacent structure and parts.

d. Strains on cable should not be absorbed by terminations but should be absorbed by clamps, supports or other approved means.

Custodians:
Army - EL
Navy - AS
Air Force - 11

Review activities:
Army - AT, AV, MI, MU, SL
Navy - EC, OS, SH
Air Force - 17, 70, 80
DSA - IS, ES
NSA
NAS

User activities:
Army - WC
Navy - MC
Air Force - 71, 84

Preparing activity:
Army - EL

Agent:
DSA - ES

(Project 6145-0574)

APPENDIX I

Existing FCC Applications

10.1 Saturn 201 Instrumentation Unit.

An FCC system was used to interconnect one measuring rack with its associated equipment in the successful Saturn 201 instrumentation unit. The Mylar-insulated FCC contained 4 x 40-mil conductors on 75-mil center-to-center spacing. It was terminated in NASA/MSFC direct-contact connectors and in existing round wire connectors.

10.2 Standard Missile.

General Dynamics used FCC harnesses in the ordnance section of the standard missile. Kapton H/FEP Teflon-insulated, shielded and nonshielded cables were terminated through transition devices to Hughes Aircraft miniature center-lock screw connectors. Flat cable was used to reduce to a minimum the diametrical space required for the interconnecting harnesses (Figure I-A).

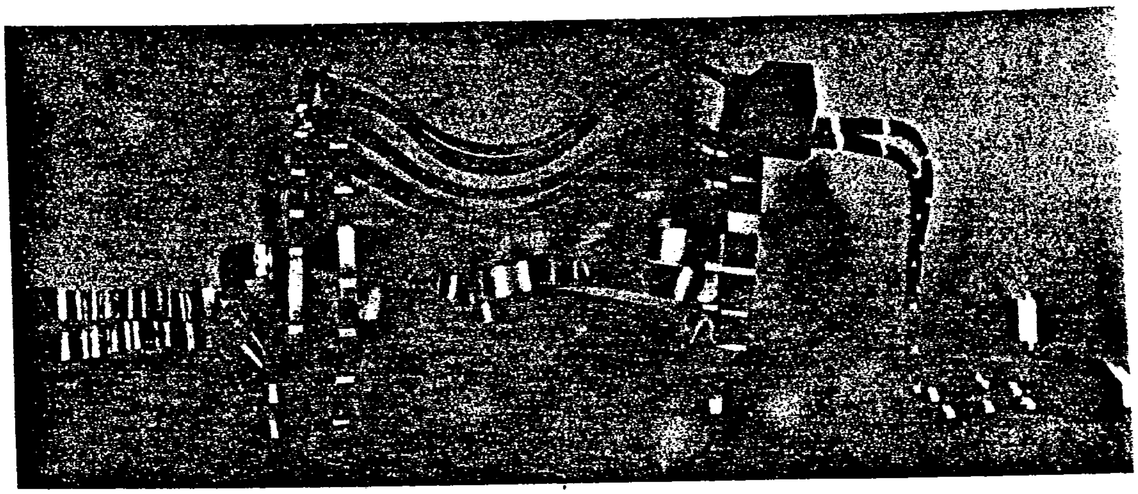


Figure I-A. FCC harness for the standard missile (General Dynamics).

10.3 Apollo Lunar Surface Experiments Package (ALSEP).

In the ALSEP design, Bendix used 50-mil FCC to interconnect lunar experimental packages to a central data package. FCC was selected as the interconnecting cable because of the resulting (1) weight reduction from 10 pounds for conventional wiring to 2.4 pounds for FCC and (2) ease in storing and in extending the lunar packages up to 60 feet from the central data package.

10.4 Hughes Lunar Surveyor Landing Craft.

FCC constructed for specific electrical characteristic requirements was used to interconnect the electronics and the sensor of the alpha-scattering unit used to analyze the lunar soil. This cable contained 4 x 40-mil flat conductors for temperature sensor and heaters, special configuration 3 x 10-mil conductors for alpha and proton gates and 3 x 25-mil conductors for proton sensors. Sprayed-on silver paint was used for the shield, and contact was made directly to grounded connectors through prepunched holes in the insulation (Figure I-B).

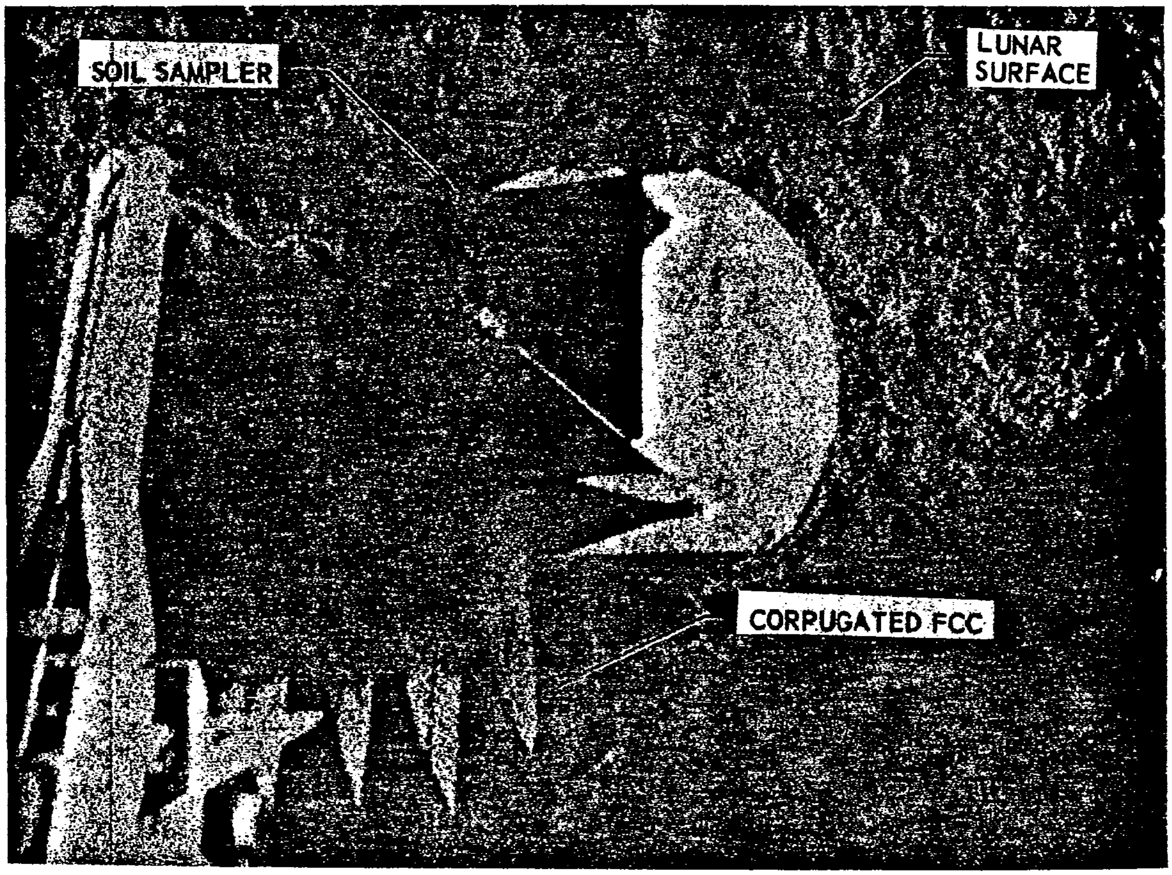


FIGURE I-B. FCC harness on Hughes Lunar Surveyor Spacecraft.

10.5 Lunar Portable Magnetometer (LPM).

In the LPM, FCC is used to connect the sensor head with the electronics and data display assembly. This cable is wound on a spool and can be reeled up when the instrument is not in use. Because the magnetometer assembly was intended to be a portable unit, weight and space considerations were of major importance in the selection of FCC over round wire. FCC used is Kapton insulated, 2-1/2 inches wide and contains 32 conductors (3 x 50 mils). Approximately 50 feet of cable interconnects the assembly parts.

10.6 Electronic Drawer Reels for Saturn-V GSE.

FCC interconnect reels were used to facilitate drawer action on the rack-mounted ground support equipment for the Saturn-V optical tracking system. The reels allowed drawers to be pulled out and tilted 90° up to down while equipment remained in full operation. Two FCC reels were used for each drawer, with 16 cables per reel. Mylar was used for insulating the 1-inch wide cables, and copper shielding was placed between strips where necessary.

10.7 Ships Inertial Navigation Systems (SINS).

Corrugated FCC was used by Autonetics to connect drawers to the console interconnection matrix of an atomic submarine navigation and missile launching complex. Limited space and the need for high reliability under severe operating conditions lead to the decision to use FCC. A corrugated, highly flexible FCC was developed which provided a smooth, rolling action as the drawer was opened or closed. Additional features included copper shielding on both sides, TFE Teflon insulation, and conductor termination by welding through the insulation.

10.8 Naval Shipboard Equipment.

Librascope used 2-inch Mylar-insulated FCC as the total interconnecting medium in a naval shipboard electronics equipment design. Use of FCC enabled drawers to be extended to a service position while equipment continued to operate. The AMP UNTY (trademark of AMP, Inc.) insulation piercing system was used to terminate conductors and shields.

10.9 MK 48 Torpedo Fire Control System.

Librascope used highly flexible corrugated FCC harnesses to connect major unit subassemblies. The shielded Teflon-insulated FCC assemblies, fabricated by Digital Sensors (now part of Ansley West Corp.), provided almost unlimited flex life and a 20 percent saving in space. Use of FCC allowed equipment sections to move both in and out and pivot 90° for service accessibility, while maintaining electrical contact.

10.10 Research Space Vehicle Program.

Digital Sensors (now part of Ansley West Corp.) used FCC in a programmable distributor unit for a research space vehicle program. Round wire cable input-output connectors were interconnected with a wire-wrap plane by continuous FCC. This design permitted programmed, automatic production interwiring and simple hand rework for circuit change to the instrumentation circuits after initial fabrication. Shielding was used between FCC layers. The unit size was 7 x 8 x 5 inches.

10.11 Minuteman II Gyro.

Autonetics used a special FCC gyro cable with very low torque requirements in the Air Force Minuteman II. This cable assembly, manufactured by Digital Sensors (now a part of Ansley West Corp.), provided a rotary electrical connection between gyro and housing. The Teflon insulated multilayered FCC contained 48 conductors with a .050-inch center-to-center spacing. Shielding was used between cable layers. Cable termination was accomplished by welding through the insulation to ITT Cannon MICRO-D connectors.

10.12 Upstage Guidance Command Unit.

Flat conductor jumper cables are used by McDonnell Douglas to interconnect PC cards, multilayer boards and thick film substrates. Two basic types of jumper cables are used. One type uses 3 mils of Mylar plus 3 mils of adhesive on each side of the conductors. These jumpers, procured from Methode, are stripped at the ends and between the ends. Stripped areas are lap soldered to foil type conductors. The other jumpers are Ansley West Flexstrip with one piece conductors which are round in the uninsulated ends and flat between the ends. Teflon insulation is laminated over the flat conductor area. The round pins install through the units to be joined and are soldered in place.

10.13 Spartan Warhead.

McDonnell Douglas uses FCC assemblies on the Spartan vehicle to transmit control and instrumentation signals through the warhead section. The H/FEP flat cable has transitions to round wire cable at both ends to permit the use of existing qualified blind mating connectors. The transitions are made with Thomas and Betts powdered metallurgy molded copper splices.

APPENDIX II

Proposed FCC Applications

20.1 Pershing Missile.

To gain experience and discover problem areas, an instrumentation unit from an Army Pershing Missile, 40 inches in diameter and 60 inches long, was converted to FCC for all except heavy power wiring (Figure II-A).

20.2 Mark 17 Minuteman.

Extensive studies conducted by AVCO indicated the feasibility of converting to FCC aluminum conductors and shields for weight reduction. Termination to existing Bendix LJT round connectors would be made by a transition to aluminum round wire, utilizing weld-through techniques. Shield continuation and termination was to be made at the connector by external conductive coatings over the potted areas.

20.3 Poseidon.

A proposal was made to use FCC in the tunnel area of the Poseidon missile to reduce weight and space requirements. System design, connector design, and prototype procurement was accomplished.

20.4 Apollo Telescope Mount (ATM).

FCC (with a total of 2500 conductors) will be used for transferring electrical signals across two interfaces in the torque-sensitive gimbal system of the ATM. The ATM is being designed and built by NASA/MSFC. FCC was selected over round wire cable primarily because of its low torque requirements (approximately 0.1 of that required for round wire cable). Two types of FCC will be used. The 2-1/2-inch signal cable is Kapton insulated and contains 32 conductors (3 x 50 mils). The 2-1/2-inch power cable is also Kapton insulated and contains 8 conductors (3 x 250 mils) (Figure 3-83).

20.5 Boeing 747 Aircraft.

Boeing designed an FCC configuration to meet requirements of a 200-foot-long, 90kVA, three phase, Auxiliary Power Unit (APU) feeder system used in the 747 commercial transport airplane. FCC was evaluated as part of a continuing effort to achieve greater weight reduction in airplane design. Results of laboratory temperature rise and impedance tests indicated that FCC, with 77 percent of the conductor cross-sectional area of installed round wire, could fulfill electrical requirements of the 747 APU.

20.6 Solar Array.

NASA/MSFC has accomplished the initial design of the solar array for the Saturn I Orbital Workshop using the low profile and small bend radius characteristics of FCC for power and instrumentation interconnections between the solar cells and power junction boxes.

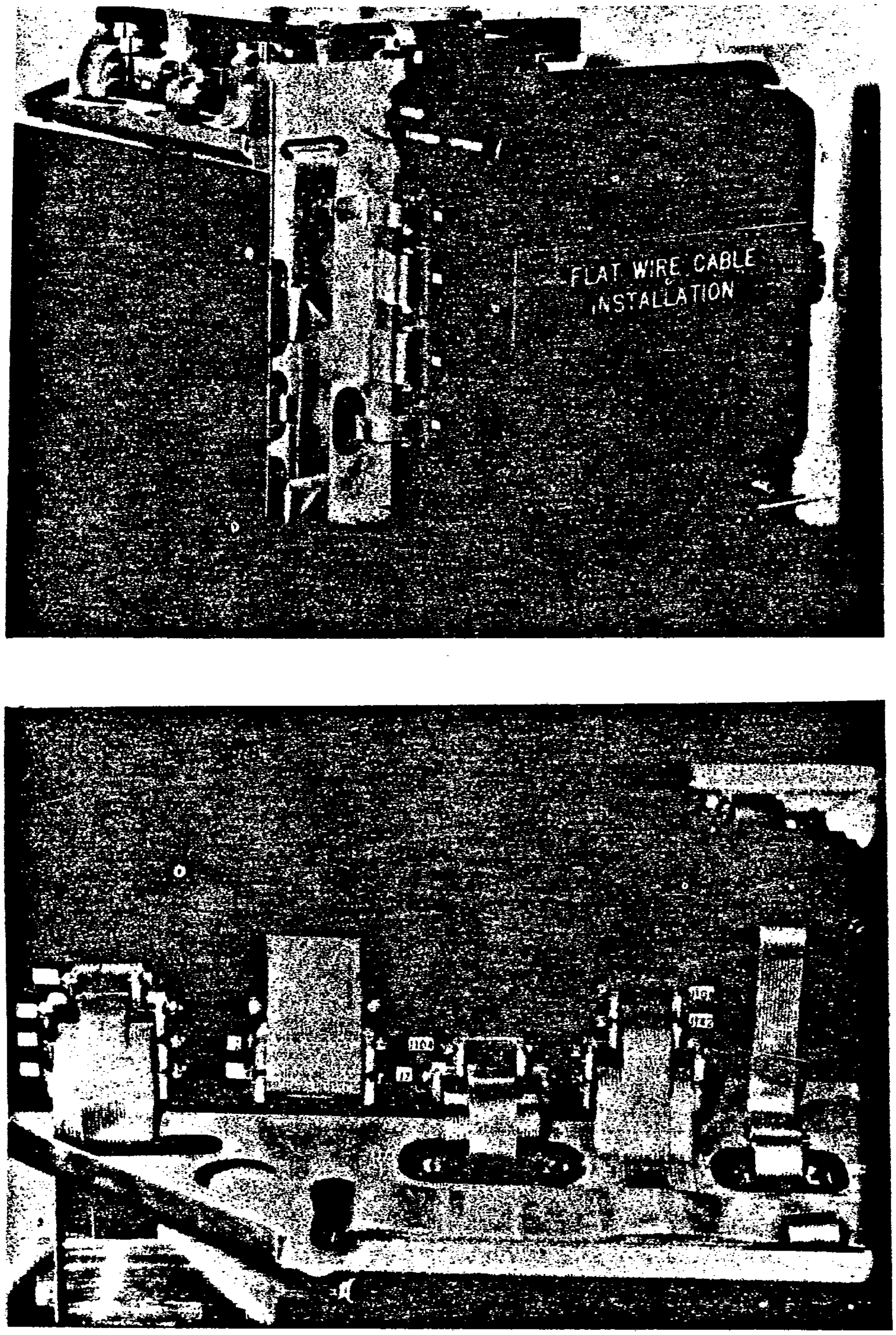


Figure II-A. FCC mockup for the Army Pershing Missile.

APPENDIX III

LIST OF VENDORS FOR VARIOUS TYPES OF FCC

Type Number (From Figure 2-1)	Type Description	Vendor
1	Laminated	Ansley East Corp. (ACI) Flexo-Tek International Inc. Haveg Industries, Inc. Hughes Aircraft Co. Marshall Space Flight Center [b] Methode Electronics, Inc. W. L. Gore and Associates, Inc. 3-M Company Tape Cable Corporation Computer Circuits Micro Cable Company Sylvania Tensolite Division
2	Extruded	International Business Machines Corp. W. L. Gore and Associates, Inc.
3	Preinsulated and Laminated	Ansley East Corp. (ACI) Electro-Mechanism, Inc. G. T. Schjeloahl Company Marshall Space Flight Center [b]
4	Etched and Laminated	Electronic Connective Systems, Inc. Lockheed Missiles and Space Company Rogers Corporation Sanders Associates, Inc.
5	Etched and Spray Coated	Electronic Connective Systems, Inc. Rogers Corporation
6	Woven	Southern Weaving Company

a. See Appendix IV for vendors and addresses, with product coding, for all FCC system components. Althrough efforts have been made to compile as complete a list as practical, the noted vendors do not necessarily represent all available sources.

b. For government development effort only.

APPENDIX IV

VENDOR LISTING FOR FCC HARDWARE

Name	Product [a]	Address
Adjustable Bushing Co.	(10)	North Hollywood, CA
Ansley East Corp. (ACI)	(1) (3) (10)	Princeton, NJ
Ansley West Corp.	(1) (2) (3)	Los Angeles, CA
Amphenol-Borg Corp.	(2)	Chicago, IL
AMP Inc.	(1) (2) (3)	Harrisburg, PA
Bendix Corp.	(2)	Sidney, NY
Berg Electronics	(2)	New Cumberland, PA
Burndy Corp.	(2)	Norwalk, CT
Carpenter Manufacturing Co.	(7)	Manlius, NY
Cinch Manufacturing Co.	(2)	Chicago, IL
Clarkson Laboratories	(8)	Camden, NJ
Computer Circuits Corporation	(1)	Hauppange, NY
Deutsch Co.	(2)	Los Angeles, CA
Di-Acro Precision Machinery Co.	(11)	Lake City, MN
Dow Corning Corp.	(4)	Midland, MI
Elco Corp.	(2)	El Segundo, CA
Electro-Mechanisms, Inc.	(1)	Nashua. NH
Electronic Connective Systems	(1) (2) (3)	Brockton, MA
Electronic Production and Development, Inc.	(6)	Long Beach, CA
Enthone, Inc.	(8)	West Haven, CT
Ercona Corporation	(2)	Bellmore, NY
Fasson Products Corp.	(4)	Painesville, OH
Flexible Circuits, Inc.	(1)	Warrington, PA
Flexo-Tex International, Inc.	(1)	Fairfield, NJ
G. T. Schjeldahl Co.	(1) (2)	Northfield, MN
Haveg Industries, Inc.	(1)	Winooski, VT
Hughes Aircraft Co.	(1) (2) (7)	Newport Beach, CA

VENDOR LISTING FOR FCC HARDWARE - Continued

Vendor	Product[a]	Address
International Business Machine Corp.	(1) (2) (3)	Owego, NY
ITT Cannon Elect. Co.	(2)	Phoenix, AZ
Kings Electronics Co., Inc.	(2)	Tuckahoe, NY
Lockheed Missile and Space Co.	(1)	Sunnyvale, CA
London Chemical Company, Inc.	(8) (9)	Melrose Park, IL
Methode Electronics, Inc.	(1) (2) (8) (10)	Chicago, IL
Micro Cable Company	(1)	Methuen, MA
Microdot, Inc.	(2)	Pasadena, CA
Minnesota Mining and Manufacturing Co. (3-M)	(1) (4) (5) (9)	St. Paul, MN
NASA/MSFC[b]	(1) (2) (3) (4) (6) (7) (8) (10) (11)	Huntsville, AL
Organoceram, Inc.	(9)	Placentia, CA
Permacel	(5)	New Brunswick, NJ
Products Research and Chemical Corp.	(6)	Burbank, CA
Rockbestos Division, Cerro Corp.	(1)	New Haven, CT
Rogers Corporation	(1) (2) (3)	Chandler, AZ
Rush Wire Stripper Division of the Eraser Company, Inc.	(7)	Syracuse, NY
SAE Advanced Packaging	(2)	Santa Ana, CA
Sanders Associates, Inc.	(1)	Manchester, NH
Shell Chemical Corporation	(4)	Pittsburg, CA
Southern Weaving Company	(1)	Mauldin, SC
Sylvania	(1)	Warren, PA
Tape Cable Corporation	(1)	Rochester, NY
Tensolite Division	(1)	Peekskill, NY
Bexdix Corporation	(2)	Sidney, NY
The Hartwell Corporation	(10)	Los Angeles, CA

VENDOR LISTING FOR FCC HARDWARE - Continued

Name	Product[a]	Address
Transition Electronic Corp.	(2)	East Boston, MA
Viking Industries, Inc.	(2) (7)	Chatsworth, CA
Western Coating Company	(9)	Los Angeles, CA
Western Electric Co.	(3)	Winston-Salem, NC
W. L. Gore and Associates, Inc.	(1) (7)	Newark, DE
Winchester Electronics	(2)	Oakville, CT

a. Product numbers listed are coded as follows:
   (1) Flat-conductor cable (see Table 2-1 for types)
   (2) Flat-conductor cable connectors
   (3) Flat-conductor cable harness assemblies
   (4) Adhesives
   (5) Tapes
   (6) Potting materials
   (7) Mechanical strippers
   (8) Chemical strippers
   (9) Chemical maskants
   (10) Clamps and fasteners
   (11) Cable cutters

b. NASA/MSFC has development capability only for new design and evaluation.

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