NASA TECHNICAL MEMORANDUM

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THE MANUFACTURE OF FLAT CONDUCTOR CABLE

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THE MANUFACTURE OF FLAT CONDUCTOR CABLE

SUMMARY

In less than 20 years, the manufacturer of flat conductor cable (FCC) has grown from an experimental project at Marshall Space Flight Center (MSFC) to a multimillion dollar industry. Numerous cable configurations and production techniques have been developed. During that same time span, military and MSFC specifications have been published to standardize FCC for government applications and the Institute of Printed Circuits has published a specification to cover industrial FCC.

Unshielded and shielded cables are being fabricated for power and signal applications, using a wide variety of materials and techniques. FCC is fabricated by various processes including laminating (the most widely used), etching, extruding and weaving. Copper is generally used for conductors and shields, while polyesters, polyimides, and fluorocarbons are most frequently used for insulation systems. The bulk of cable produced to date has been unshielded, since shielded FCC is not generally required and its production involves additional processing.

SECTION I. INTRODUCTION

A. Purpose and Scope

The objective of this document is to present a survey of the various processes used in manufacturing the principal configurations for flat conductor cable (FCC). Existing designs, as well as potential designs are described. Although not intended as a comprehensive study of the FCC manufacturing industry, this document should provide the reader with a general overview of current designs and fabrication methods/equipment, along with a critical comparison of the relative advantages and disadvantages of each.

Lamination is the most widely used process for manufacturing unshielded FCC and is the one with which Marshall Space Flight Center (MSFC) personnel have worked most extensively. It is described in more detail than other manufacturing techniques, which are used to varying degrees: etching, extrusion, and weaving.

The treatment given shielded cable is less extensive than that given unshielded cable, and deals primarily with developmental and conceptual configurations rather than existing ones. Shielding is not required for most applications and, consequently, a lesser effort has been applied to this area.

B. Background

FCC was developed in response to the huge military and space vehicle programs of the 50's, 60's, and 70's, which required increased equipment reliability along with decreased weight, volume, and costs.

FCC development was begun by the Army Ballistic Missile Agency at Redstone Arsenal, Alabama during 1957. Early attempts at fabricating FCC involved the print-and-etch process. As a consequence, batches were small and relatively costly, being produced for experimental purposes only. At that time, the FCC market was virtually non-existent. This same working group later transferred to NASA's Marshall Space Flight Center where they continued their development efforts.

Through the concerted efforts of the MSFC group and various industrial researchers, FCC production has grown into a multimillion dollar industry in less than 20 years. One source [1] cites over 20 companies which fabricate FCC by at least one of the methods to be described in this document: laminating, etching, extruding, and weaving.

SECTION II. BASIC CABLE DESIGN

Flat Conductor Cable (FCC) consists of rectangular conductors (usually bare or plated copper) which are arranged parallel to each other, and held together in one plane by an insulating material. The conductors may be: flattened round wires (the most widely used conductor type); slit from foil or etched from a metal-plastic laminate; or formed by electrolytic deposition. Insulation can be applied by several techniques, including lamination, extrusion, spray coating, and weaving. FCC can be fabricated for signal as well as power applications and, when necessary, can be shielded for attenuation of both electrostatic and electromagnetic fields.

A. Configurations

1. Unshielded. Typical cross-sections of various unshielded FCC constructions are shown in Figure 1. The most widely used fabrication method is lamination; others are etching, extrusion, and weaving.

In the symmetrically laminated form (Figure 1.a), individual conductors are sandwiched between plastic films which have an adhesive applied to one side. The adhesive embeds the conductors and keeps them properly spaced to assure integrity of the cable configuration when exposed to various operating conditions. Laminated cable with preinsulated conductors (Figure 1.b) is manufactured by the standard laminating process, except that the conductors are first coated or tape-wrapped with insulation. Preinsulation allows conductors to be laid in close proximity to each other.

Cables having etched conductors are shown in Figures 1.c and 1.d. Although etched cable fabrication costs are higher than for laminated cable, conductor center spacing can be better controlled, thereby permitting smaller gaps between conductors.

Insulating material is applied by the extrusion process for the configuration shown in Figure 1.e. This method is often used when a thicker cable is desired in order to achieve a certain characteristic impedance between conductors, especially when the cable installation requires several layers of cable in a harness assembly that does not permit the use of a foil shield.

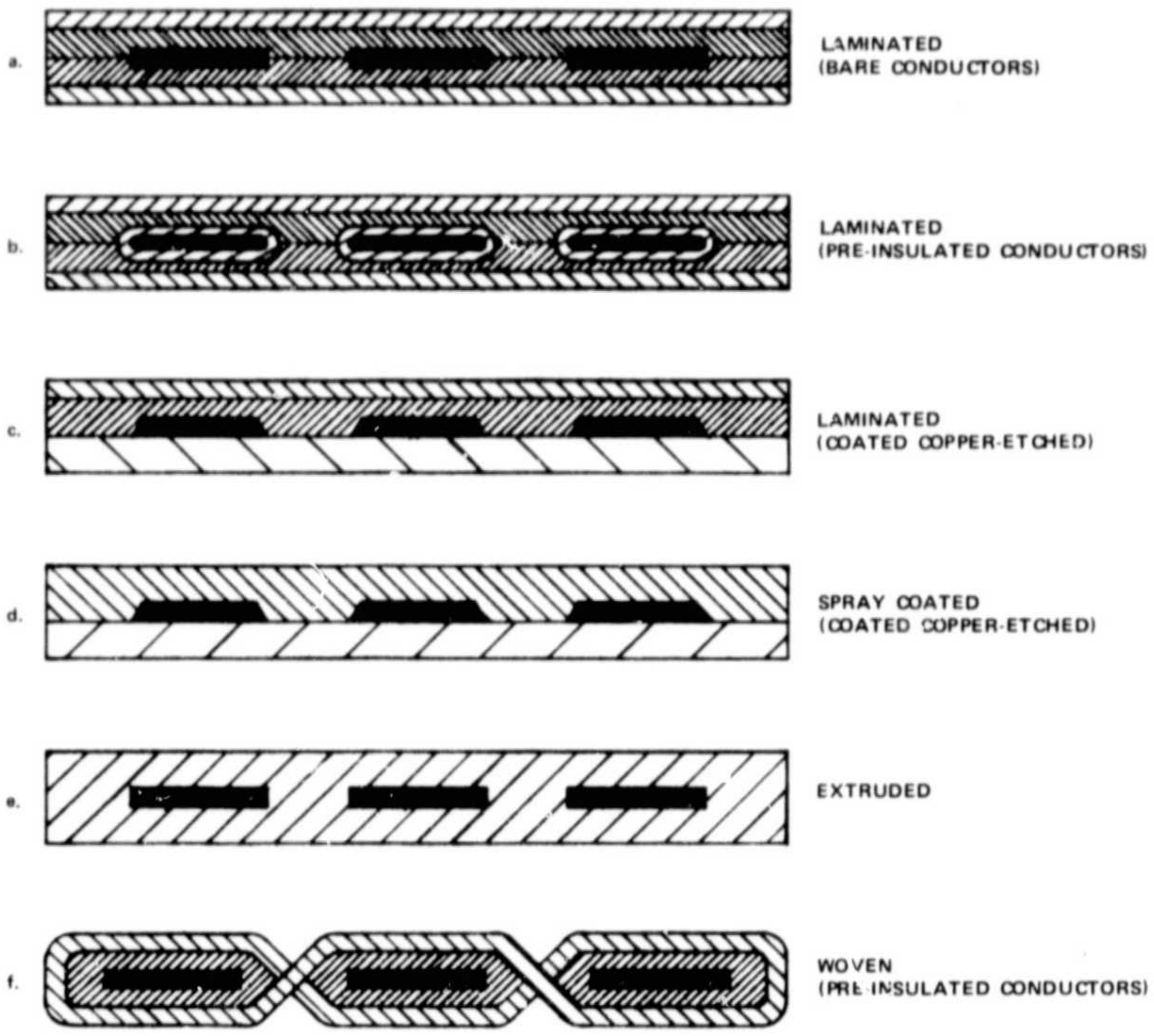


Figure 1. Typical cross sections of unshielded FCC manufactured by various methods.

Woven cable (Figure 1.f) is made using commercial weaving techniques to apply insulating threads which space the conductors and hold them securely in place. Conductors may be preinsulated prior to being woven together, or the completed cable can be impregnated against moisture using silicone or any other soft suitable material to keep the cable flexible and protected.

In addition to those previously described, there are several other methods for making flat cables. These include bonding, molding, spray coating, milling, etc.

Bonded type cable is produced using either flat or round conductors. The conductors are preinsulated (mostly by extrusion) and then fused together in a side-by-side orientation. Most any electrically-qualified, heat-fusible material can be used in this process. Industry is producing a substantial volume of cable in this way.

Molded flat cable is produced by holding the conductors in proper orientation in a mold, into which the insulating material is pressure injected and cured.

Spray coated cable is produced by positioning the conductors and spraying them with repeated coats of insulation until a cable of the desired thickness is obtained.

Milled cable is produced by using a cutter to machine the desired conductor configuration in a foil-clad substrate; the outer layer of insulation is subsequently added by spray-coating or by lamination.

2. Shielded. Only a few critical situations require the use of shielded FCC. In some cases, sensitive conductors can be physically separated from disturbing circuits. In other cases, adequate shielding can be provided simply by mounting the FCC to a grounded metal substrate or by grounding alternate conductors so as to electrically separate the sensitive conductors. A number of effective shield designs are available, and these are generally designated as loose or fixed. Loose shields are attached only to the end of an unshielded cable, while fixed shields are attached along the full length of the cable.

A typical loose shield method is illustrated in Figure 2. In this configuration, the preinsulated shield foils are attached to an unshielded FCC at the terminal end(s) through the use of solder tabs. The shield is terminated into the cable plug in a manner similar to the FCC, so that no metal surface of the shield is exposed. The loose shield method should provide adequate attenuation for all except low-frequency magnetic fields, and is considerably more flexible than methods which employ a shield fixed to the full length of the cable.

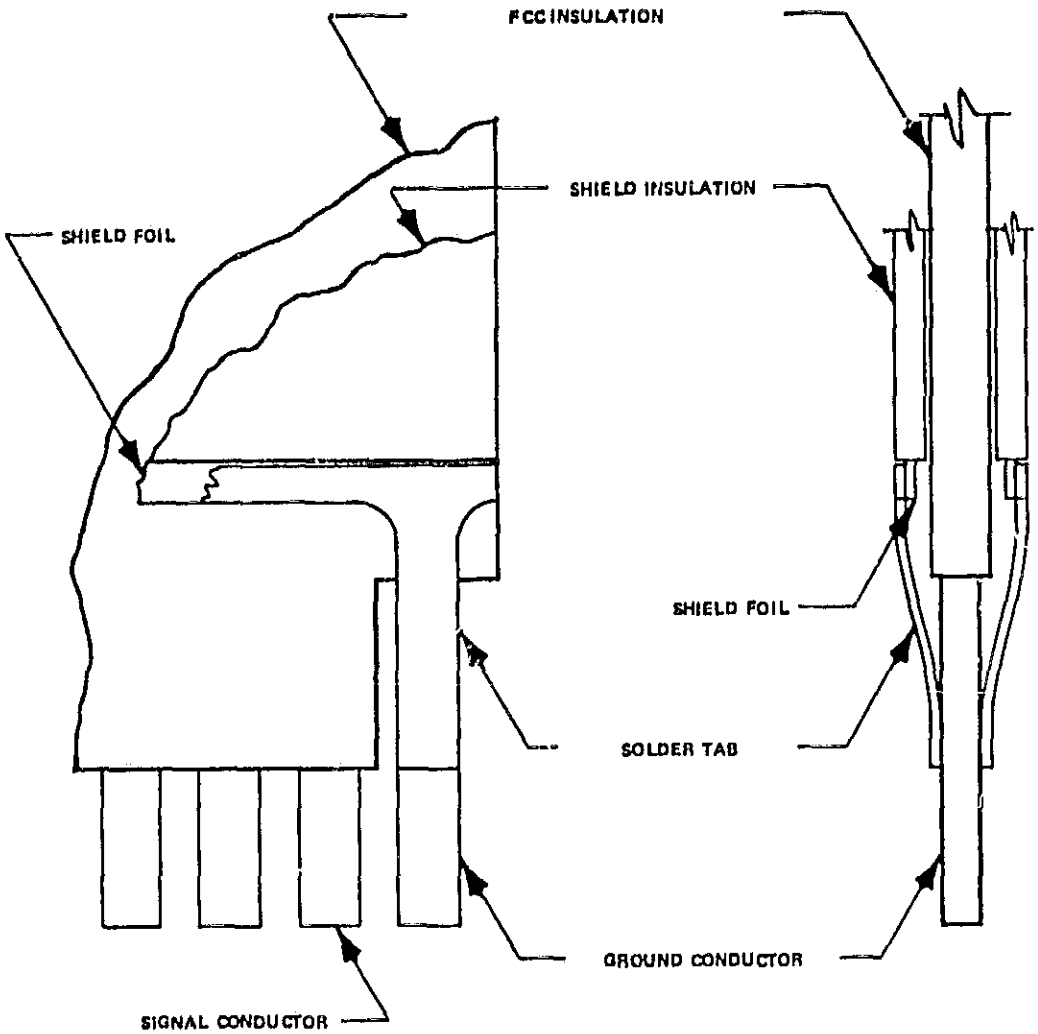


Figure 2. FCC with typical loose shield method.

Typical integral fixed shield methods are illustrated in Figure 3. These methods are generally categorized as open or closed. Simply stated, an open method is electrically discontinuous around the cable edges while the closed method is electrically continuous around the cable edges.

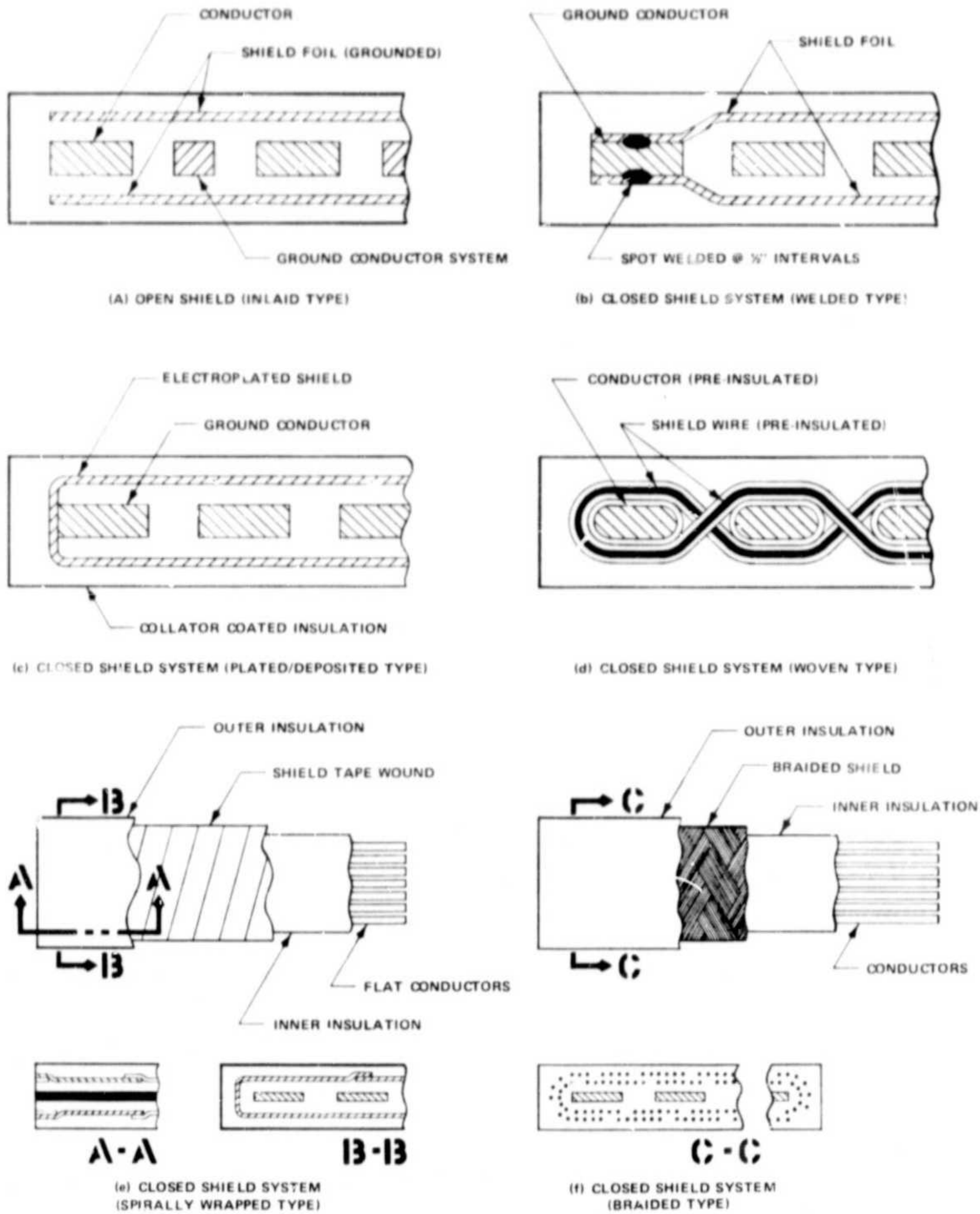


Figure 3. FCC with typical integral fixed shield systems.

Figure 3.a is an example of the open shield method. It provides essentially the same shielding as the loose assembly (Figure 2) with less flexibility. In the open method, the shielding foil is mechanically attached to both sides along the entire length of the FCC, but it is not electrically continuous around the cable edges.

The most effective total shielding is provided by a completely closed electrical envelope around the cable edges. A closed shield method, fabricated of high-permeability material is essential for effective attenuation of low frequency magnetic fields. For protection against high frequency magnetic fields, copper shields serve well. Figures 3.b through 3.f illustrate several typical closed method designs which could be used for this purpose. The necessary ferromagnetic material could be deposited in configurations shown in Figures 3.b and 3.c. The wrapped configuration would need to be welded continuously along the cable edges in order to be effective at all frequencies.

B. Materials

1. Conductors. Conductor materials of various types can be used successfully in FCC. Copper conductors, both bare and plated, have seen the most extensive use. Slit conductors (per QQ-C-576) and flattened round wires (Type S, solid soft or drawn and annealed per QQ-W-343) are used for most constructions, including laminated cable. For etched conductor cable, rolled copper foils or electrolytically deposited copper can be used. Plating on the copper conductors is often desirable to prevent corrosion or discoloration of the conductors during storage, and is sometimes selected for compatibility with terminating processes. Plating material is usually nickel or, in rare cases, silver. Other conductor materials and protective coatings may be used to meet unusual application requirements. For example, when compared to copper, aluminum has a 30 percent lower weight to conductivity ratio, is more economical, and is not usually affected by shortages or procurement priorities. Aluminum conductors also have an improved resistance to nuclear radiation, which makes their use a requirement on some programs. Other metals are used when flat conductors are employed as heater cables or for thermocouples.

2. Insulation. One of the primary considerations in selecting insulation materials for FCC is the type manufacturing method to be employed. For example, the bondability of the insulating film is critical in the laminating process, while in the weaving process, it is not a factor. Tower coating or

spray painting requires the material to be soluble. Another characteristic is dimensional stability during processing and moisture absorption, a factor which could substantially reduce allowable drying speeds, so as to avoid blistering.

A critical analysis of the conditions to which the cable will be exposed is equally important. For example, the length of exposure to maximum and minimum operating and storage temperatures is an important environmental factor. For space applications, exposure factors include ultraviolet and infrared wavelengths, electron and proton particle bombardment, nuclear radiation, and outgassing in vacuum.

Other important considerations are: the termination process which the cable will undergo; the ease with which the cable may be stripped, crimped, soldered, and welded-through; and its bondability to the potting compound.

Addittional factors influencing selection are cost and various electrical, mechanical, and chemical properties such as: tensile strength, wear resistance, tear resistance, cold flow characteristics, flexibility, electrical insulation resistance, dielectric properties, chemical compatibility, flame retardant properties, flammability, and memory characteristics (for self-retracting cables).

Typical properties of insulation materials used in FCC are given in Tables 1 and 2. The most frequently used are polyesters, polyimides and fluorocarbons. Other FCC materials used to a lesser extent are polyvinyl chloride, polyethylene, polypropylene, and silicone rubber. The first three are priced about the same as Mylar (perhaps the least expensive FCC insulation) but have only about 25 percent of its tensile strenght. Their upper temperature limits are low, ranging from about 80°C (176°F) for polyethylene to 125°C (257°F) for polypropylene. Only polyimide is self-extinguishing. Silicone rubber is possibly the best choice for continuous flexing applications; however, as previously mentioned, it has only 1/25th the tensile strength of mylar.

Polyester insulations have good dielectric strength, good heat conductivity characteristics, and exhibit few shrink, stretch or cold-flow problems. They also have high flex life, good tensile strength, and excellent abrasion resistance. Perhaps the most widely used polyester is Mylar. As can be seen from Table 1, it is one of the most outstanding insulations in terms of high dielectric strength and modulus of elasticity. However, it does

TABLE 1. TYPICAL PROPERTIES OF SOME FLAT CABLE DIELECTRICS

	Dielectric Material						
	Polyimide (e.g. Kapton)	Polyester (e.g. Mylar)	Polyvinyl Chloride	Tetrafluro-ethylene (Teflon TFE)	Silicone Rubber	Fluorinated Ethylene Propylene (Teflon FEP)	Polyethylene
IPC-FC-220 Cable Type	C, D	BN, BS	AN, AS	D		BS, C	
Specific Gravity	1.42	1.4	1.25	2.15	1.2	2.15	0.93
Service Temperature, °C							
Maximum Continuous	250^{a}	150^{a}	85	250	200	200	85
Minimum Continuous	-250^{a}	-60^{a}	-40^{b}	-255	-40	-255	-70
Flammability	Self-extinguishing	Slow Burn	Slow to Selfextinguish	Non-flammable	Slow Burning	Nonflammable	Flammable - Unless additives used
Appearance	Amber[a]	Clear[a]	Translucent to Opaque	Opaque	Opaque	Clear	Clear to opaque
Bondability with Adhesives	Good	Good	Yes	Good when Treated	Fair to Good	Good when Treated	Must be treated
Heat Sealable	No	No	Yes	No	Yes	Yes	Yes
Tensile Strength, kg/cm^2 at 25°C	1 [illegible]	1750	210^{b}	210	70	210	210
Modulus of Elasticity, kg/cm^2 at 25°C	30 100	37 500	b	5600	35	3010	3500
Tear Strength-Elmendorf, gm/mil at 25°C	8	12 to 15	b	15	High	125	-
Volume Resistivity, ohms-cm	$>10^{17}$	10^{17}	10^{10b}	10^{16}	10^{13}	$>10^{17}$	10^{16}
Dielectric Constant, 25°C 10^3 to 10^6Hz	3.5^{a}	$3.0 - 3.2^{a}$	$3 - 8^{b}$	2.1	3.0 - 2.7	2.1	2.2 - 2.7
Dissipation Factor, 25°C 10^2 to 10^8 Hz	0.002 to 0.014	0.002 to 0.017	0.05 to 15^{b}	0.0002	0.003	0.0002 to 0.0005	0.0005 to 0.001
Chemical Resistance							
Acids	Good	Fair to Good	Fair	Excellent	Good	Excellent	Excellent
Bases	Degrades	Degrades	Fair	Excellent	Good	Excellent	Excellent
Solvents	Good	Fair to Good	Poor	Excellent	Fair to Good	Excellent	Affected by Aromatics
Water Absorption, %	2.9	<0.8	0.1	<0.01	0.2	<0.01	<0.01
Flex Resistance	Good	Good	Good to High[b]	Fair to Good	Excellent	Good	Good

a. Depends upon adhesives and amounts used.
b. Depends upon amount and type of plasticizers present.

Courtesy of Institute of Printed Circuits (IPC-FC-220-A)

TABLE 2. BASIC PHYSICAL CHARACTERISTICS OF WEAVING MATERIALS

Class	Nylon		Polyester		Glass		Olefin		Fluoro-Carbon	
Type	High Tenacity Filament Nylon 66	Staple Nomex*	Filament	Staple	E-Glass	Multi-Filament	Mono-Filament	Staple	TFE	FEP
Breaking Tenacity gpd. (std.)	5.9 - 9.5	4.0 - 5.3	6.0 - 9.5	2.2 - 6.0	15.3	9.6	3.5 - 7.0	3.0 - 6.5	1.2 - 1.4	0.5
Tensile Strength (psi)	66 - 134,000	90,000	106 - 168,000	39 - 106,000	450 - 550,000	313,000	40 - 90,000	35 - 75,000	32 - 38,000	14,000
Breaking Elongation %	16 - 28	22 - 32	12 - 16	12 - 55	4.8	3.1	14 - 30	20 - 60	15 - 33	32
Plastic Recovery %	100	–	100 @ 1	100 @ 1	100	100	98	97	–	–
Average Stiffness (gpd)	21 - 58	–	46 - 82	12 - 17	320	310	20 - 60	20 - 40	15	2.2
Average Toughness	0.74 - 0.84	0.65	0.50 - 0.70	0.20 - 1.10	0.37	0.15	–	0.6 - 1.1	0.15	0.10 - 0.12
Specific Gravity	1.14	1.38	1.38	1.38	2.55	2.5	0.90 - 0.91	0.90 - 0.91	2.1	2.1
Water Absorbency 70F, 65% rh	4.2 - 4.5	6.5	0.4 - 0.8	0.4 - 0.8	None	None	0.01 - 0.1	0.01 - 0.1	–	–
Effect of Heat	Sticks @ 445F, Melts @ 480-500F, Yellows slightly @ 300F after 5 hrs.	Does not Melt, Decomposes @ 700F.	Sticks @ 445F Melts @ 482F		Will not burn, softens @ 1,350F		Softens @ 285-330F, melts @ 320-350F, 0-5% shrinkage @ 212F & 5-12% @ 265F		Melts @ 550F Operate @ 400F	
Effect of Acids and Alkalis	Dissolves in HCL, H_2SO_4 & H_2NO_3-Formic Acid.	Unaffected by most acid some strength loss after prolonged immersion in HCL, H_2SO_4 & H_2NO_3	Good Resistance to most mineral acids		Resist most acids and alkalis		Excellent resistance except con. H_2NO_3		Inert	
Effect of Solvent	Insoluble	Some loss of strength in Sodium Chlorite	Excellent resistance		Unaffected		None		None	
Resistance Aging & Abrasion	Excellent Resistance	Excellent Resistance	Excellent Resistance		Excellent		Good Resistance		Excellent Resistance	

Courtesy Electroweave, Inc.
*Registered DuPont trademark

not have as wide a service temperature range as several other materials, and it is flammable. Mylar can be laminated to itself and to practically any other material. It can be stripped chemically or with different types of stripping equipment, such as a hot blade, an infrared source, and flame. In terms of cost, Mylar is perhaps the cheapest of the commonly used dielectrics for high quality FCC.

The most widely used polyimide insulation is Kapton, which combines outstanding physical and electrical properties with thermal stability over an extremely wide temperature range. Kapton films also remain tough and flexible at cryogenic temperatures, have good radiation resistance, and are nonflammable. From Table 1, one notes that Kapton also is an outstanding insulation in terms of high dielectric strength and modulus of elasticity. In addition, Kapton is stable over a considerably wider temperature range than Mylar and is more resistant to mechanical abuse. However, Kapton is also the most expensive of the commonly used FCC insulations.

Because of its infusible nature, a binder must be used if Kapton is to be laminated. Most Kapton systems incorporate Teflon FEP as a binder, which adds many desirable features but limits the upper working temperature of the system. In DuPont's Kapton Type F film, the base polyimide film (Type H) has been coated on one or both sides with a thin layer of FEP resin. The FEP provides a heat-sealable surface, enabling Kapton to be heat-bonded to itself or to other thermally stable substrates such as metal, glass cloth, and paper. For a laminated cable using polyimide as the primary insulation system, Kapton/Teflon FEP appears to be a good choice. Stripping techniques for this system include abrasive, infrared laser, and cold blade.

Among the fluorocarbon resins, Teflon TFE and FEP are widely used because of their outstanding chemical, electrical, surface, and thermal characteristics. Teflon TFE (tetrafluoroethylene polymer) and FEP (tetrafluoroethylene-hexafluoropropylene copolymer) are, with few exceptions, inert to all known chemicals. They have high dielectric strength, low dissipation factors, stable dielectric constants, very high electric resistivity, absorb practically no moisture, and exhibit negligible outgassing.

Teflon TFE and FEP resins share all the preceding properties. The principal difference is that TFE has a maximum continuous service temperature of 250° C (482° F), whereas that of FEP is 200° C (392° F). Both can be stripped with abrasive, heat, or cold blade techniques. Comparing

Teflon w' other plastics (Table 1), we find that both TFE and FEP have a tensile strength roughly a tenth that of Mylar or Kapton, and thus are susceptible to cold flowing. Also, Teflon resins are among the more expensive FCC insulations.

Teflon FEP film can be bonded directly to itself, metals, and certain other high temperature plastics. Melt bonding above 275° C (525° F) is the technique normally used in the construction of FEP-insulated flat cable. Standard FEP laminated insulation systems use FEP as the adhesive in conjunction with either FEP or some other material as primary insulation, such as Teflon TFE or Kapton. Etched cables are available with TFE used as the base layer and FEP film or TFE/FEP used as the cover.

Teflon TFE can be made bondable by chemical etching of the surface. Even then TFE will not bond to itself without an adhesive. Teflon FEP is normally used for this purpose, providing a heat-sealable surface. Flat conductor cables with total TFE insulation are fabricated using extrusion processes.

3. <u>Shielding</u>. Shielding for FCC may be a material of high electrical conductivity (for high frequency magnetic fields) or ferromagnetic material of high permeability (for low-frequency magnetic fields), or both. Copper is preferred for shielding from high frequency energy (i.e., from one kHz to one MHz and higher). At lower frequencies, or for shielding from electromagnetic interference, copper is less effective and ferromagnetic materials are preferred.

C. Dimensions

Most of the agencies and industries involved in FCC development and production have generally agreed to establish cable widths in 12.7-mm (1/2-inch) increments and conductor center-to-center spacing in increments of 0.635mm (25 mils). Table 3 contains some typical dimensions for standard and high density unshielded cable, as specified in MIL-C-55543.

Power cables (Figure 4) may have conductors of any desired width, preferably in multiples of the standard center spacing of 1.3 or 1.9mm (50 to 75 mils) and as wide as the present maximum standard of 75mm (3 in.). The thickness of copper is limited only by the cable flexibility requirement -0.25mm (10 mils) seems to be generally acceptable. Figure 5 shows

TABLE 3. TYPICAL FCC DIMENSIONAL DATA (MIL-C-55543)

Cable Widths	No. of Conductors	Centerline Spacing	Centerline Spacing	Conductor Configuration	Conductor Size		Nearest AWG Size
					Width	Thickness	
0.50	7	0.050	0.050	Standard	0.025	0.003	30
	6	0.075				0.004	29
	4	0.100				0.005	26
	3	0.150		High density	0.040	0.003	28
1.00	17	0.050				0.004	27
	12	0.075				0.005	26
	9	0.100	0.075	Standard	0.040	0.003	28
	6	0.150				0.004	27
1.50	27	0.050				0.005	26
	18	0.075		High density	0.065	0.003	26
	14	0.100				0.004	25
	9	0.150				0.005	24
2.00	37	0.050	0.100	Standard	0.065	0.004	25
	25	0.075				0.005	24
	19	0.100				0.006	23
	12	0.150		High density	0.090	0.004	24
2.50	47	0.050				0.005	23
	32	0.075				0.006	22
	24	0.100	0.150	Standard	0.115	0.004	22
	16	0.150				0.005	22
3.00	57	0.050				0.006	21
	38	0.075		High density	0.140	0.004	22
	29	0.100				0.005	21
	19	0.150				0.006	20

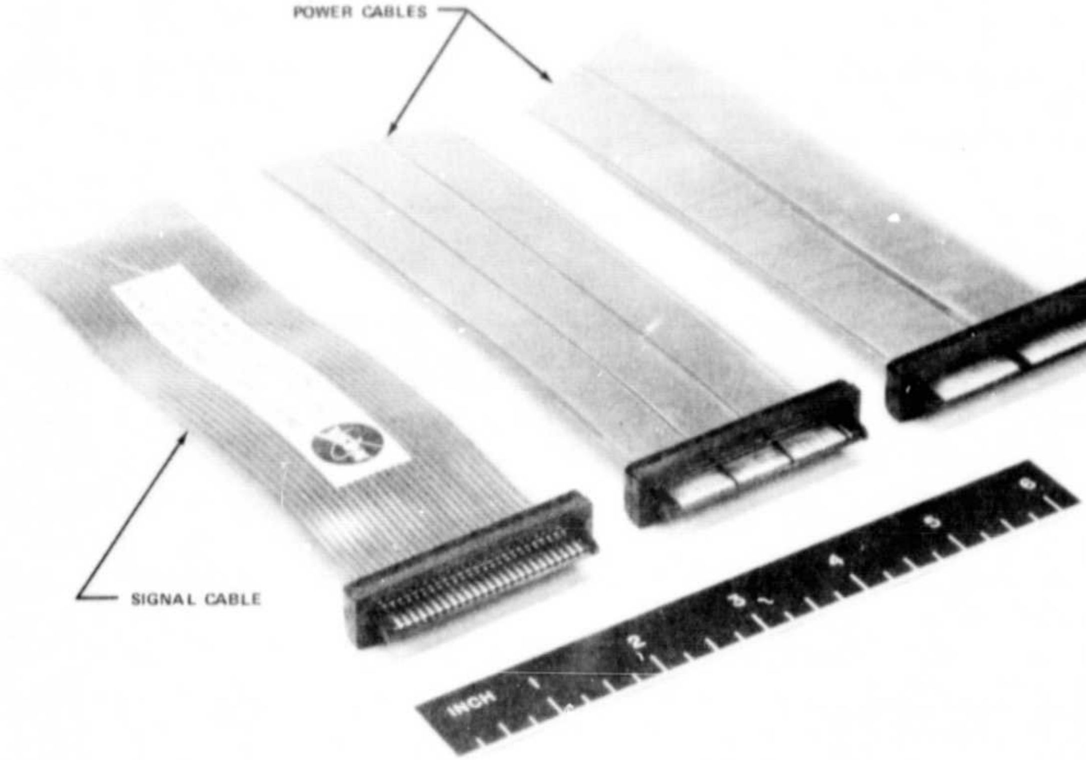
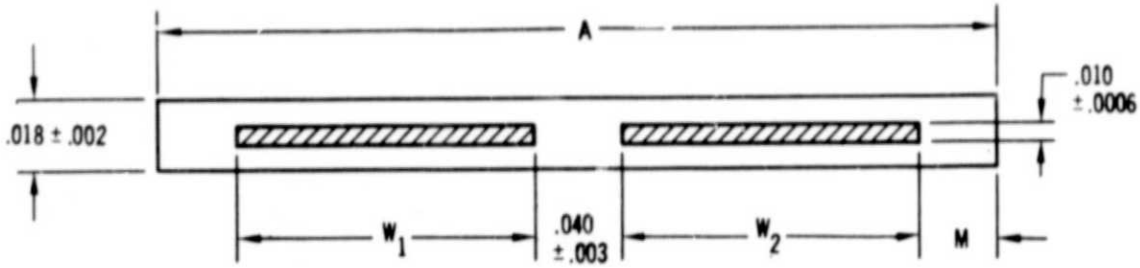


Figure 4. Power cables compared with regular cable.

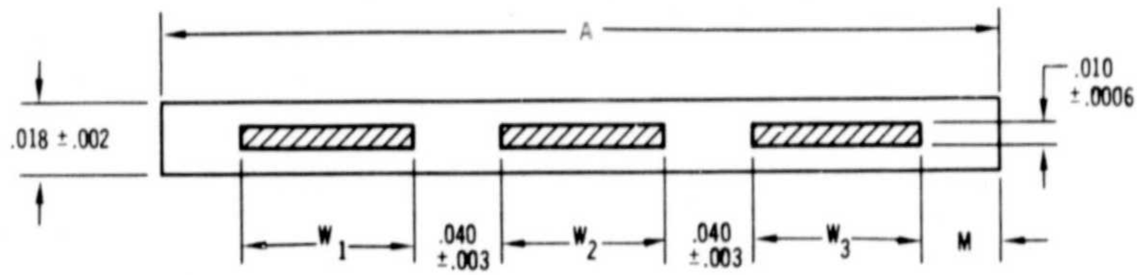
several typical Kapton/Teflon FEP power cables that have been designed and used by MSFC. The widths of these cables are in increments of 25.4mm (1-inch) and the center-to-center spacing of conductors appears in 0.635-mm (0.025-inch) increments so that they can be terminated in MIL-SPEC FCC Connectors using parallel contacts.

D. Specifications

Owing to the practically limitless possibilities for configuring FCC and the general trend to diversification, the need for standardizing FCC became apparent during the very early stages of development. Without reasonable standards, the logistics problem would quickly become insurmountable. The Institute of Printed Circuits and The Aerospace Industries Association combined efforts in 1963 to produce an industrial flat cable specification known as NAS 729 (now obsolete). Marshall Space Flight Center published MSFC-SPEC-220B covering unshielded FCC in 1966. In 1968, a military specification,



A ±.010	$W_1 \pm .002$			$W_2 \pm .002$			M ±.008	WEIGHT g/ft
	WIDTH	EQUIV. AWG	PER Ω1000'	WIDTH	EQUIV. AWG	Ω PER 1000'		
1"	.410	13	2.0	.410	13	2.0	.070	17.4
2"	.860	10 +	.97	.935	9 −	.90	.082	37.0
3"	1.385	8 +	.61	1.385	8 +	.61	.095	56.7



A .010	$W_1 \pm .002$			$W_2 \pm .002$			$W_3 \pm .002$			M ± .008	WEIGHT g/ft.
	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	16.9
2"	.560	12 +	1.5	.635	11 −	1.3	.560	12 +	1.5	.082	36.5
3"	.935	9 −	.90	.860	10 +	.97	.935	9 −	.90	.095	56.2

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

Figure 5. Typical FCC power cable configurations.

MIL-C-55543, was published to standardize military requirements. The unshielded FCC defined by this specification is suitable for aerospace, defense, and other government contracts requiring operation under severe envitornmental conditions, minimum size and weight, and space savings consistent with service requirements. This military specification was followed in 1970 by IPC-FC-220, prepared by the Institute of Printed Circuits, which covers commercially equivalent flat conductor cable.

Table 3 is a tabulation of FCC dimensional data contained in MIL-C-55543. Cable configurations now covered by this specification are shown in Table 4. It is anticipated that other configurations will be added.

TABLE 4. TYPICAL MIL-C-55543 FLAT CONDUCTOR CABLE CONFIGURATIONS

Military Specification Sheet No.	Insulation	Conductor Plating	Conductor Construction	Voltage Rating (Volts)	Max. Oper. Temp. (0°C)	Conductor Configuration (Density)
MIL-C-55543-1	Polyester	Nickel	Strip-Copper	300	100	Standard
MIL-C-55543-2	Polyester	Nickel	Strip-Copper	300	100	High
MIL-C-55543-3	Polyimide/FEP	Nickel	Strip-Copper	300	200	Standard
MIL-C-55543-4	Polyimide/FEP	Nickel	Strip-Copper	300	200	High
MIL-C-55543-5	Polyimide or Polyimide-Type Homopolymer/FEP	Bare	Etched-Copper	300	200	Standard
MIL-C-55543-6	Polyimide or Polyimide-Type Homopolymer/FEP	Bare	Etched-Copper	300	200	High
MIL-C-55543-7	Polyester	Bare	Strip-Copper	300	100	Standard
MIL-C-55543-8	Polyester	Bare	Strip-Copper	300	100	High
MIL-C-5543-9	Polyimide/FEP	Bare	Strip-Copper	300	200	Standard
MIL-C-55543-10	Polyimide/FEP	Bare	Strip-Copper	300	200	High
MIL-C-55543-11	FEP	Nickel	Strip-Copper	300	175	Standard
MIL-C-55543-12	FEP	Nickel	Strip-Copper	300	175	High
MIL-C-55543-13	TFE/FEP	Nickel	Strip-Copper	300	200	Standard
MIL-C-55543-14	TFE/FEP	Nickel	Strip-Copper	300	200	High

SECTION III. FABRICATION OF UNSHIELDED FCC

A. Lamination

Laminating is the most widely used technique for fabricating FCC. Basically, it involves the sandwiching of flat wires in a parallel orientation between thin sheets of adhesive-coated plastic, and the application of heat and pressure to bond the components together. In addition to bonding together the thin sheets of plastic insulation, the adhesive keeps the conductors properly spaced and assures the integrity of the FCC when exposed to various operating conditions. With the exception of materials preparation and testing of the completed laminate, MSFC uses one piece of equipment to perform all laminating operations (Figures 6, 7, and 8).

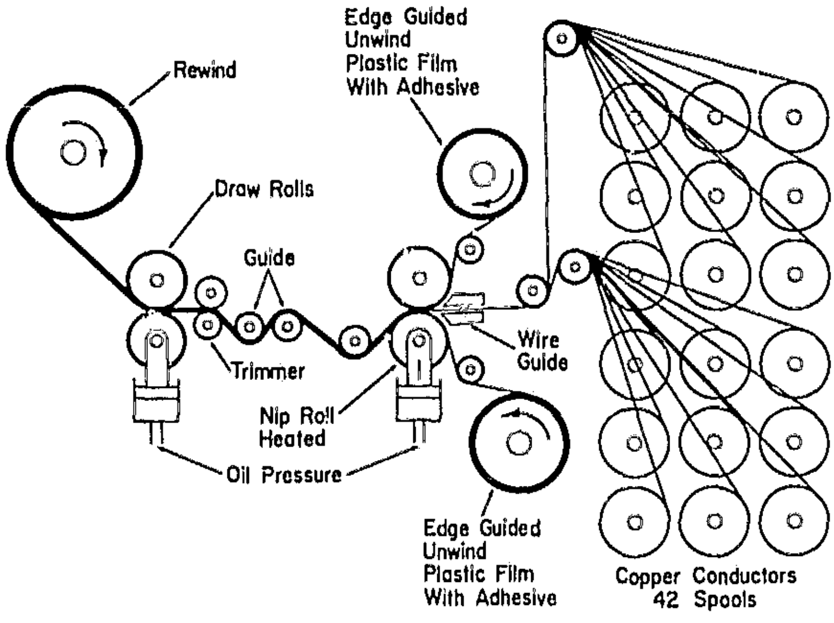


Figure 6. FCC laminating principle.

1. Conductor Preparation. The flat conductors can be produced in a variety of ways. One is by slitting metal foil (of large width) to the desired conductor dimension in a single operation. For example, a sheet of metal foil which is 1 meter wide and 0.1 millimeter thick can be slit into 1000 conductors (1mm in width) by one pass of a production slitter. Flat conductors are slit and then spooled onto pancake reels in much the same fashion as

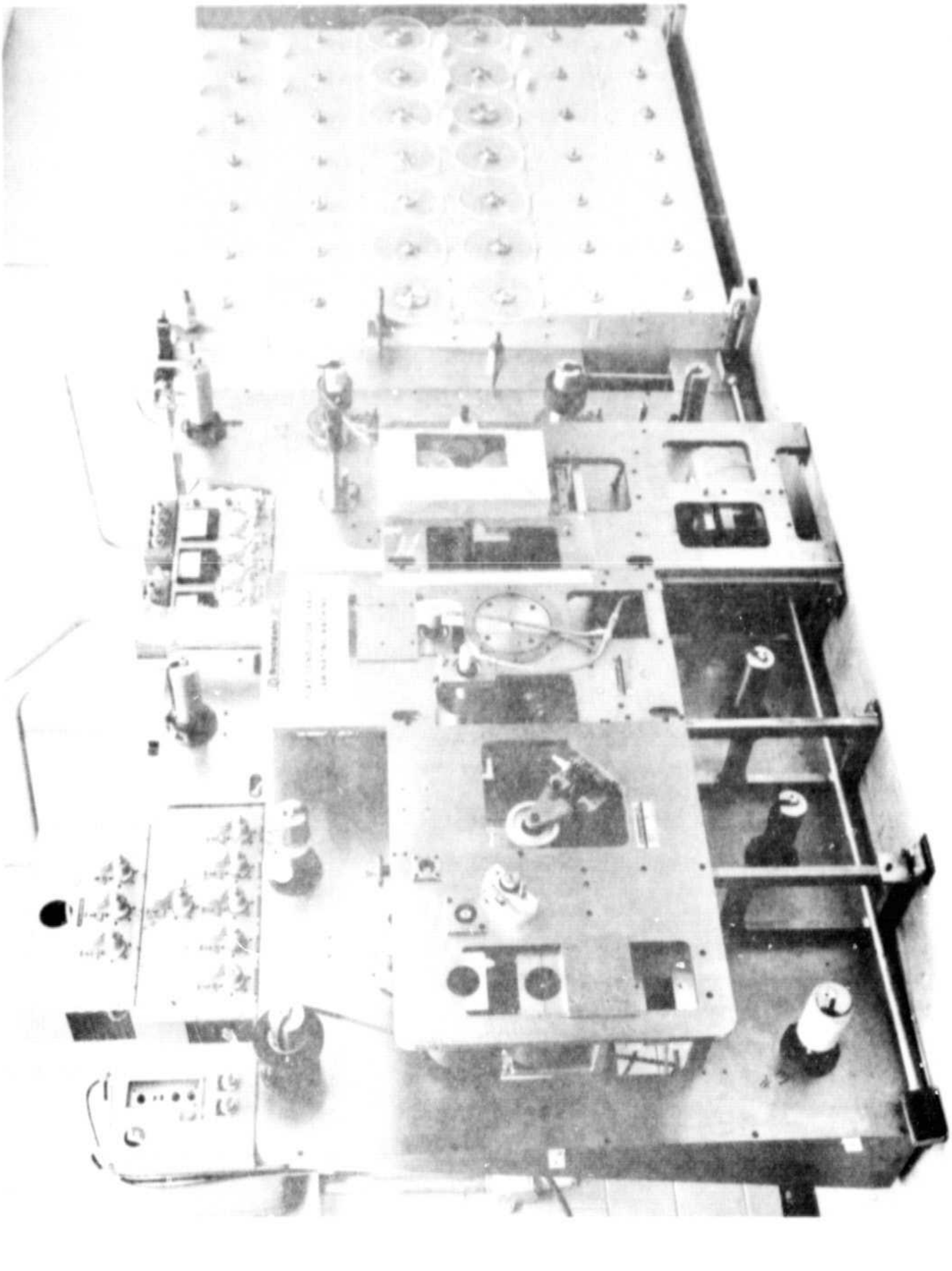


Figure 7. Overall view of MSFC laminator.

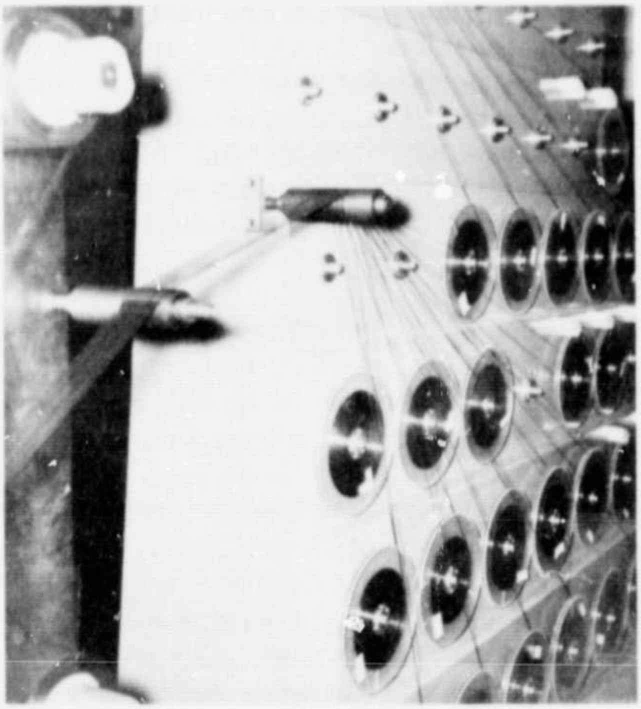


Figure 8. View of loaded conductor spools on MSFC
MSFC laminator.

magnetic tape is slit and spooled. The slit conductors must be deburred by a chemical or mechanical process if the conductors are to be used in making FCC rated higher than 200 volts.

Another process for making flat conductors is by rolling round wire to the desired flat conductor thickness. Rolling results in two desirable features, namely: a) no burrs, and b) round corners. No other treatment is needed except annealing, cleaning, and (in some cases) plating. To roll a flat conductor of 0.1 by 1.0mm (4 by 40 mils) requires a round wire of AWG No. 20, 0.813-mm (0.032-inch) diameter. The rolling operation does not make the round wire much wider, but it does make it about five times longer (due to the tension used to stretch the wire at the rewind side of the unit).

a. Conditioning. A prerequisite for achieving consistently a accurate center spacing is the use of straight and flat conductors, as even slight deformations invariably cause irregularities in center-to-center spacing. Distortions are often produced when flat wires are wound on standard spools, in typical helical fashion. Because the helix must be reversed at the completion of each layer, permanent deformations are formed in the wire. If the wire is not straightened, these irregularities will cause spacing errors in the flat cable. Additional deformities occur when the pitch of winding is not accurately adjusted to the width of the flat wire. As will be pointed out later, these difficulties are eliminated by storing the conditioned wire on specially designed pancake spools.

To anneal, clean, and straighten the flat wires in final preparation for lamination, MSFC uses the unique wire conditioner illustrated in Figure 9. This equipment functions in the following manner. The flat wire is pulled by two metal pulleys from the supply reel and immersed twice in a temperature controlled bath of distilled water. The initial pass, conducted over Pulley No. 1, is for the purpose of preliminary cleaning and to establish a uniform temperature condition in the wire. As the wire emerges from the bath, it passes over Pulley No. 2 and is conducted through the center of a toroidal coil, thus forming what amounts to a shorted-turn secondary winding of an electric transformer. As a consequence, large currents flow in the single wire part of the secondary winding, causing it to become hot as a result of I^2R heating. When the hot wire enters the constant temperature bath on this pass, several important actions take place: (1) steam is generated which performs a mechanical scrubbing of the wire to complete the cleaning operation, (2) the wire is quenched and annealed, and (3) the wire is stretched by one percent. The stretching((which produces a straightening action on the wire) is brought about as a result of the one percent difference in diameters between Pulley No. 2 and Pulley No. 3. After passing over Pulley No. 3, the wire emerges from the bath and is conducted over Pulley No. 4, where it is finally wound on a specially designed pancake spool (having the width of one flat wire) for storage. These flat spools, each holding approximately 244 meters (800 feet of 0.1mm (4 mil) thick conductor, prevent damage during storage and are later used as wire dispensers for the cable laminator.

b. Plating. The conditioned conductors may be plated with about 0.0025mm (0.0001 inch) of nickel, which must be stress free and well adhered to the copper. This is done for several reasons. First, it enhances flex life and permits bending the bare conductors without cracking during termination. Second, plating enhances appearance, because pure copper rapidly becomes discolored on exposure to air. Conductors in the completed laminate may appear to be inadequately cleaned, even though a thorough cleaning has been performed. Nickel plating removes this doubt and also functions as a receiving surface for gold plating, which is often applied to stripped conductor ends during cable termination.

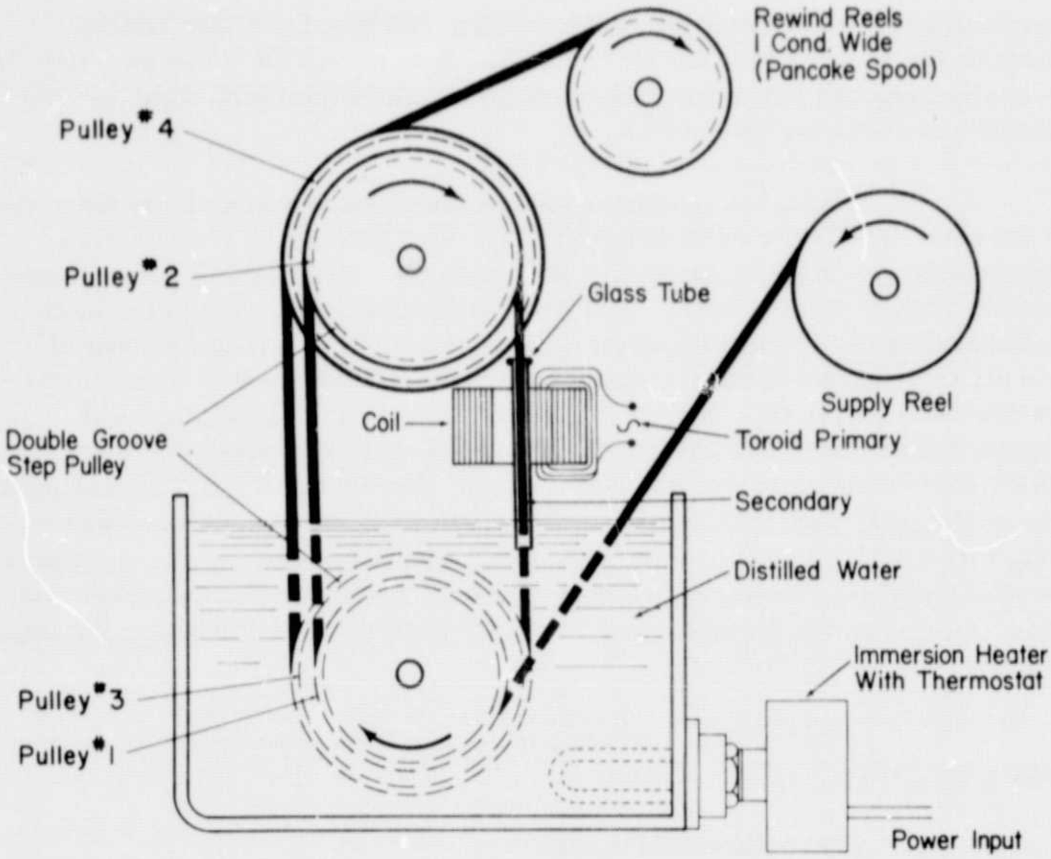


Figure 9. Wire conditioner.

c. Lubrication. Mechanical stripping is greatly enhanced by lubricating the conductors prior to manufacturing the cable. However, if this is done, the type and amount of lubricant must be carefully selected with an eye to compatibility with subsequent operations performed on the cable ends. Only the minimum of lubricant required to permit a standard cold-blade stripper to easily break the bond between conductors and film should be used. This trace amount of lubricant should be applied such that all conductors are uniformly coated over the full length of the cable. The exact amount of lubricant required must be established by experiment and must be a material which can readily be removed from stripped conductor ends, leaving clean conductor surfaces for electroplating or soldering.

One potential probelm should be noted. Since there is no strong bond between film layers and conductors, wicking will occur during electroplating of stripped conductors unless the cable end is sealed. This can be done by immersing the cable end in liquid wax for a few minutes, allowing the wax to soak into all openings. A wax must be selected which can be easily removed from the conductors so as not to interfere with electroplating and soldering operations.

MSFC has performed some preliminary work on the feasibility of the conductor lubrication process. The most promising results were obtained using a high-temperature, water-soluble oil, CIP99U (proprietary product of Lier Siegler Inc.). CIP99U evaporates partly during lamination and can be easily removed from stripped conductors. A trace amount of this oil was applied to bare copper conductors just before they reached the hot laminating rollers. The lubricated wires were then laminated with Kapton/FEP films. The end of the completed cable was stripped, using the MSFC cold-blade stripper, conductors were cleaned of oil, and the cable end was sealed with wax. After removing excess wax, the conductors were plated first with nickel and then with gold. Conductor ends were also tested for solderability. Good results were obtained during all of these laboratory tests, indicating the feasibility of the lubrication process for use in the large-scale production of FCC.

Certain other advantages accrue from lubricating conductors before laminating, as lubrication:

(1) enhances stripping,

(2) provides longer flex life of cable,

(3) requires less critical adjustment of the cold blade stripper (MSFC type),

(4) increases efficiency of commercial mechanical strippers, and

(5) produces a cleaner conductor surface with no plastic particles during stripping.

2. Tape Preparation and Testing. In addition to preparing the conductors, the cable manufacturer must also assure that the insulating tapes (substrate as well as thermoplastic adhesive) to be used are suitable for laminating. Properties of the adhesive layer must be checked for compatibility with the lamination process. Tapes also should be inspected for pinholes, dried, and finally enclosed in airtight containers to prevent reabsorption of moisture.

a. Adhesive Properties. When selecting films for lamination, the cable manufacturer should consider several important aspects of the adhesive layer. The most suitable adhesive thickness will depend on the width, thickness and spacing of the cable conductors. During lamination, the adhesive melts and flows around the conductors. Most of the adhesive fills the gaps between conductors so that only a very thin layer is left between substrate layer and conductors. If the quantity of adhesive exceeds the voids to be filled upon application of heat and pressure, there will occur an outward flow of adhesive from the center of the cable. This flow tends to carry the conductors with it, thus increasing the space between conductors, and the greatest spacing will occur near the edge of the cable. Variations with the adhesive layer can create the same problem. The conductor guides, however closely spaced to the nipline of the laminating cylinders, cannot fully prevent side drifting. Therefore, to achieve the most accurate center spacing of conductors, the amount of excess adhesive must be carefully restricted.

Drifting of the edge conductor can be minimized or compensated for by carrying a filmstrip (of conductor thickness) at both margins. The margin should be generous during lamination and trimmed to the proper width later. When laminating very wide cables, edge conductor drifting becomes a lesser problem since practically all the drift is restricted to the two outside conductors. Compensating for drifting by using narrower spacing of the edge conductors has never been successful, since the amount of drift is highly irregular.

Minimal drift problems were encountered by letting the conductors sink into one of the tapes first before laminating. This is easily accomplished by permitting the conductors to pass over one quarter of one hot cylinder under tension before lamination takes place. Although the adhesive must flow under heat and pressure in order to fill gaps between conductors, the material must be sufficiently viscous during lamination to avoid side-slipping of conductors.

If the top and bottom adhesive layers do not have the same thickness, a shrinkage problem will occur during the lamination process. The outer layers of the FCC (the insulating films) will generally have a smaller thermal expansion than the inner layers (adhesive). After lamination, when the cable returns to room temperature, the inner layers will be under tension while the outer layers will be under compression. If one adhesive layer is substantially thicker than the other, the cable will exhibit a near cylindrical bending along the longitudinal axis of the cable. The crosswise and lengthwise forces are equal, but the bending resistance of the cable is smaller crosswise.

b. High-Voltage FCC Film Tester. The High-Voltage FCC Film Tester employed at MSFC uses the dielectric strength characteristic to provide a simple, convenient method for detecting pinholes or other dielectric defects in FCC insulating films [2]. A front panel layout of the apparatus is shown in Figure 10 and the basic principle of operation is illustrated in Figure 11. The unit consists essentially of a high-voltage source (0-4000 Vac), a motor driven film movement, tension and test rollers, drive and drag rollers, a steel test band, and appropriate controls.

For testing, the FCC insulating film is mounted on the drag roller and is threaded around the tension rollers and between the steel belt and insulated roller. During operation, the steel belt, the idler roller, and both tension rollers are at ground potential while the insulated roller has the required high voltage applied. Tension in the test band is adjustable by the tension rollers. The insulated roller, which has a circumference of 0.3 meter (12 inches), is motor driven at 10 rpm, thus producing a linear film speed of 3 meters (10 feet) per minute. Based on this rate of travel, the film remains exposed to the high voltage for approximately 3.3 seconds. The drive roller is powered by a friction clutch, thus compensating for the constantly decreasing shaft rotation rate necessary to accommodate the constant linear film speed of 3 meters (10 feet) per minute. Figure 12 shows the steel belt to be 1.3 cm (1/2 inch) narrower than the 10.2 cm (4 inch) wide film under test; this is a deliberate design feature which prevents arcing around the edges of the insulating film. As such, it allows 1.3 cm (1/2 inch) of the film to go untested. However, this creates no problem since the untested portion is eventually trimmed off and discarded during the final stages of laminating.

At the start of operation, the test voltage (2000 Vac) is applied between the insulated roller and ground (Figure 11). As the insulation film under test moves between the steel belt and the insulated roller, it is exposed to the test voltage. An examination of the following data will indicate the voltage that the film and adhesive should withstand.

Insulating Film	Dielectric Strength (V/mil)
Mylar	3500
Kapton	3600
Teflon (FEP)	3000
Teflon (TFE)	800

Thus, if the film thickness is assumed to be 0.76mm (3 mils) and the adhesive thickness is assumed to be 0.051mm (2 mils), it is obvious that the combination can easily withstand the test voltage of 2000 Vac.

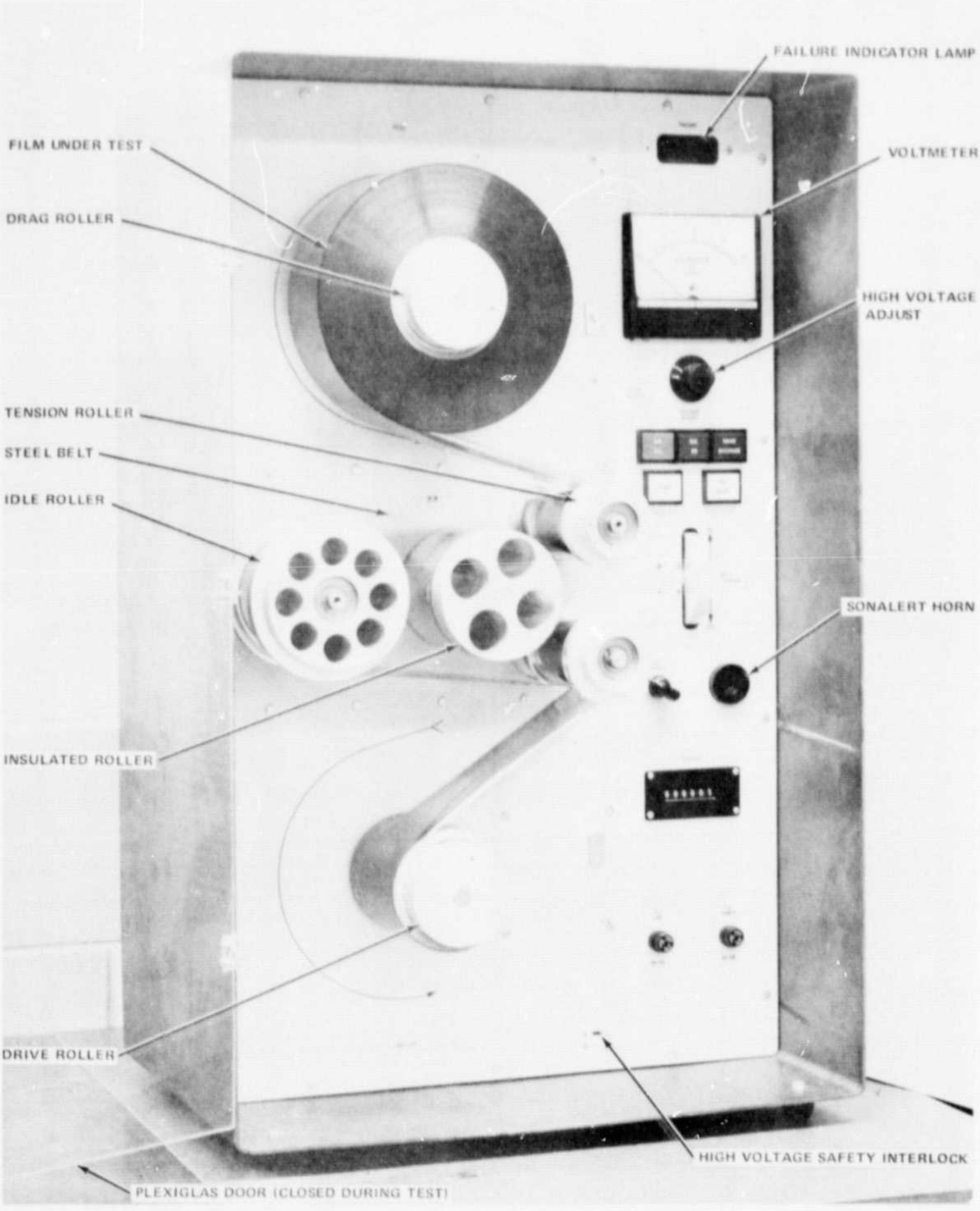


Figure 10. High voltage FCC film tester.

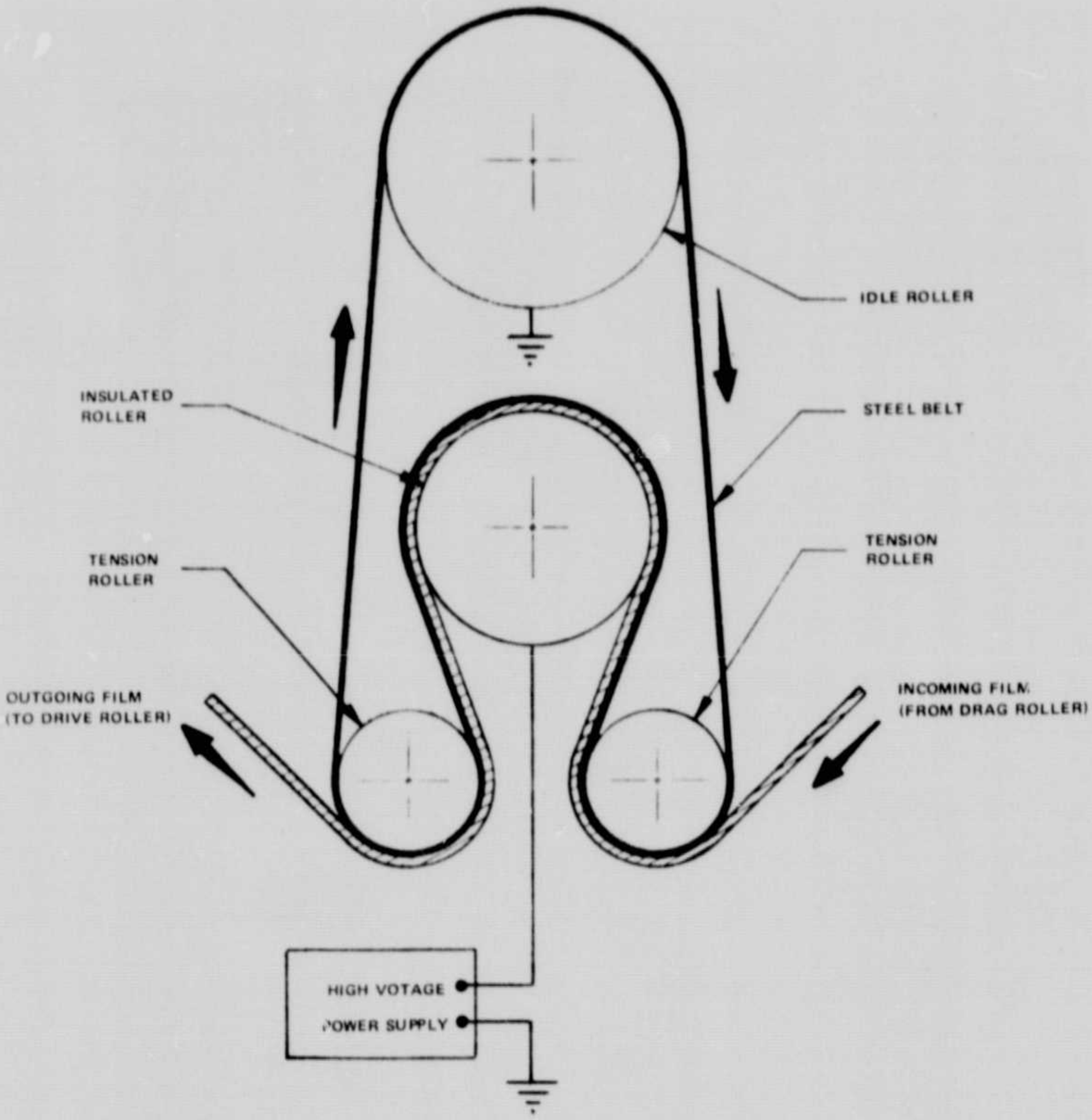


Figure 11. Operating principle for FCC film tester.

However, any dielectric defect in the film (a pinhole, an embedded metal particle, etc.) will act as the focal point for a disruptive arc through the film, thus marking the defective area with a small carbon deposit. When this occurs, the drive motor is automatically cut off and a buzzer and warning light are automatically actuated. Using the drive override push-button, the motor is force driven just enough to move the flaw from between the roller and belt; the flaw is then marked with masking tape for future removal, and the test is continued.

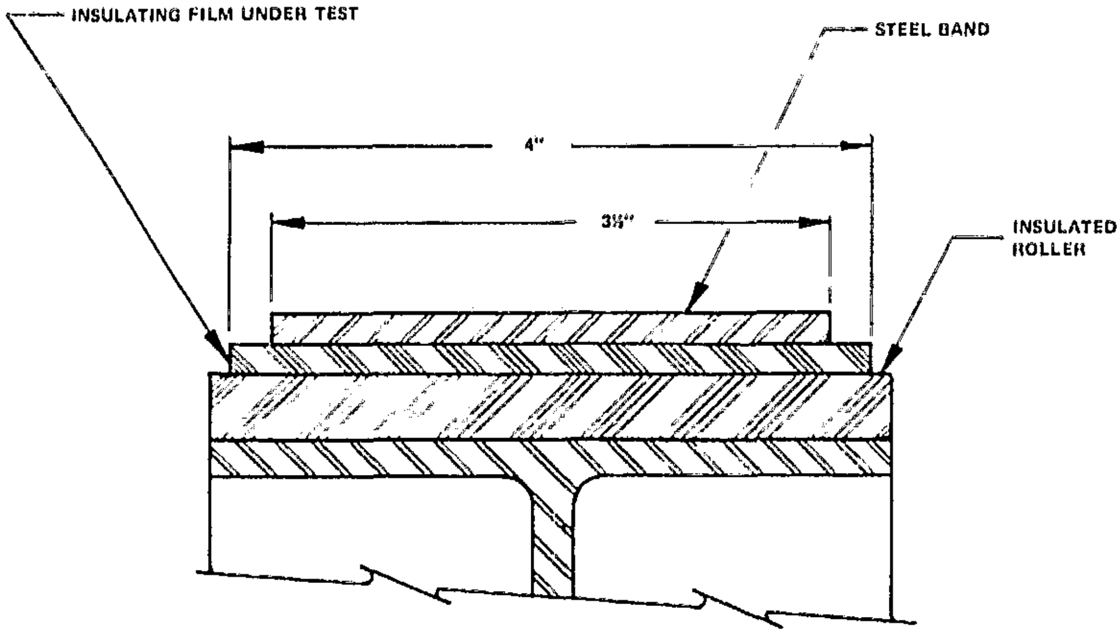


Figure 12. Orientation of film and electrodes in FCC Film Tester.

c. Tape Dryer. Any material in the film (such as water or other solvents) which will volatilize during lamination will result in bubbles in the finished cable. Also, moisture reduces the insulation quality of the cable. To prevent this from occurring, some means must be devised for drying the tapes and for maintaining this dry state while the tape is being stored. Hayes International Corporation (under contract to MSFC) has recently designed drying equipment for thermoplastic tapes (Figure 13). For thermosetting tapes, a device employing vacuum rather than heat would be needed.

Using the FCC insulating film dryer designed by Hayes, the tape is moved along at a slow speed, variable from 0.6 to 3 meters (2 to 10 feet) per minute, so that it passes over six heating elements which are thermostatically controlled to 71°C (160°F). A total of 18.3 meters (60 feet) of film is heated at a time. Air, which has been passed through a desiccator at the air intake, picks up the vaporized materials and is pulled out of the dryer by a reverse blower. The dried tape is rewound on a spool which is then inserted in an airthight cannister for storage. The tape should remain in the air tight cannister except during the actual lamination process. While installed in the laminator, reabsorption of moisture by the tape is not a significant problem since the heat of the rollers and the low relative humidity (40 percent) of the laminator room combine to vastly reduce reabsorption rates.

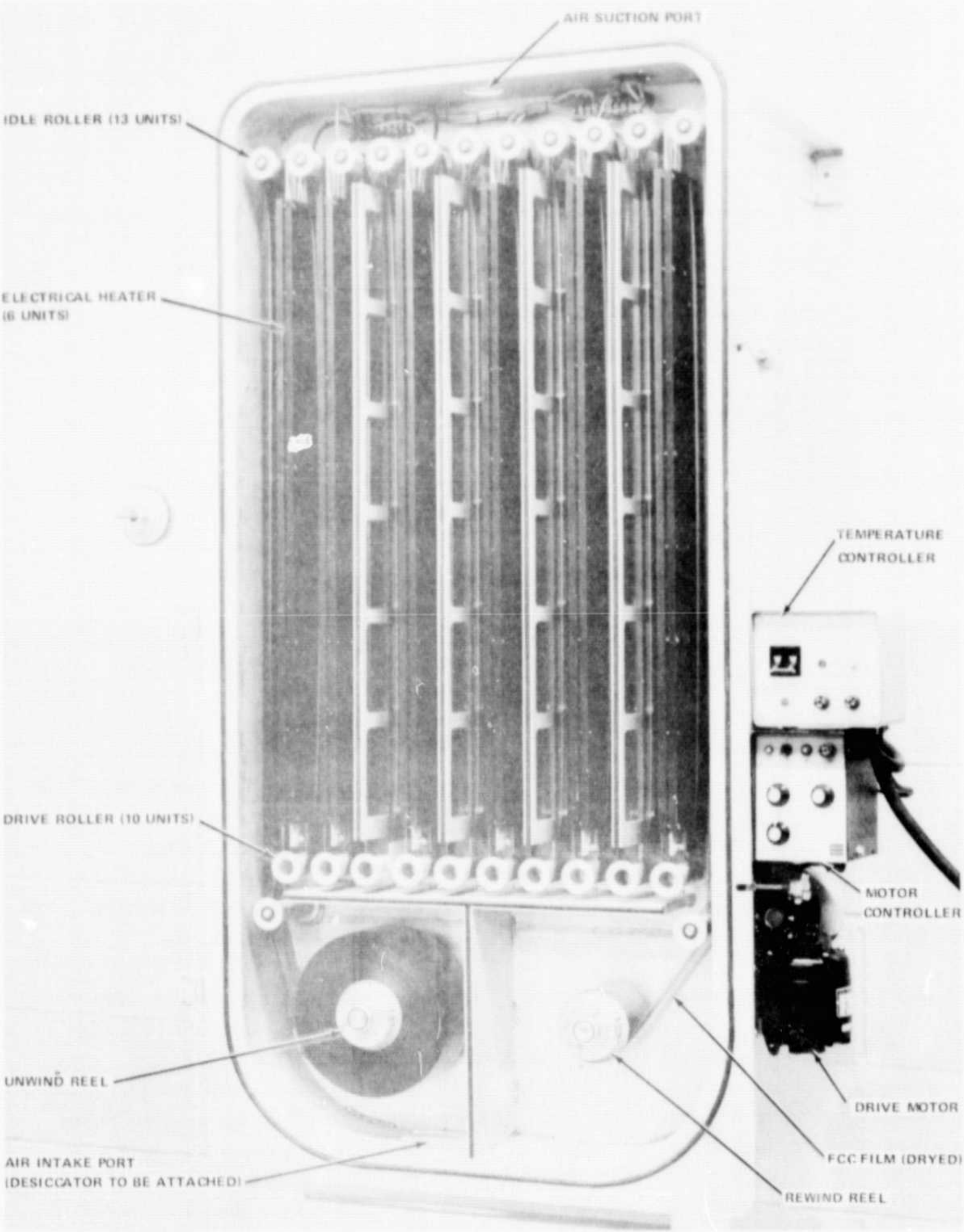


Figure 13. Dryer for FCC insulating film.

3. Tension Control. Throughout the fabrication process, tension must be controlled on conductors, tapes, and the completed laminate. There must be a means of measuring and controlling the tension in order to prevent the development of problems from insufficient, excessive, or nonuniformly applied tension.

If conductor tension is too low, the conductors will waver and become unevenly spaced. If too high, the conductors will be pulled down toward the lower laminating roller, sinking into the adhesive of the lower film; the end result will be a cable with unsymmetrical layers of insulation (Figure 14).

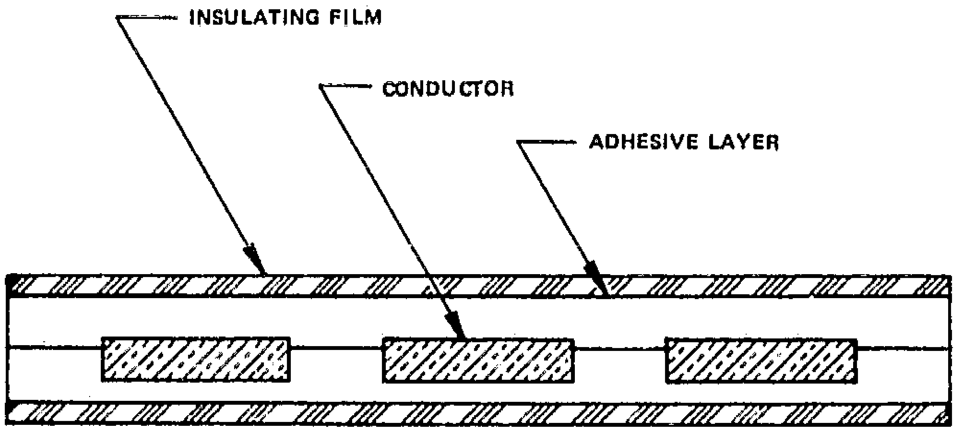


Figure 14. Typical cross section of FCC manufactured with unsymmetrical layers of insulation.

Excessive tension also can produce a stretching or breaking of the conductors. If the amount of tension applied to the conductors is nonuniform, the position of the conductors within the cable will also be nonuniform, whereby the conductors under greater tension will tend to move toward the lower laminating roller. In this case, the end result will be a cable with nonuniformly positioned conductors, as shown in Figure 15.

Uneven tension applied to tapes will result in a warped cable. The tension applied on both sides of an individual tape must be the same, for if more tension is applied to one side than the other, camber will result because of uneven stretching. Tension must also be the same for both films being laminated, or bending (curling)will invariably occur.

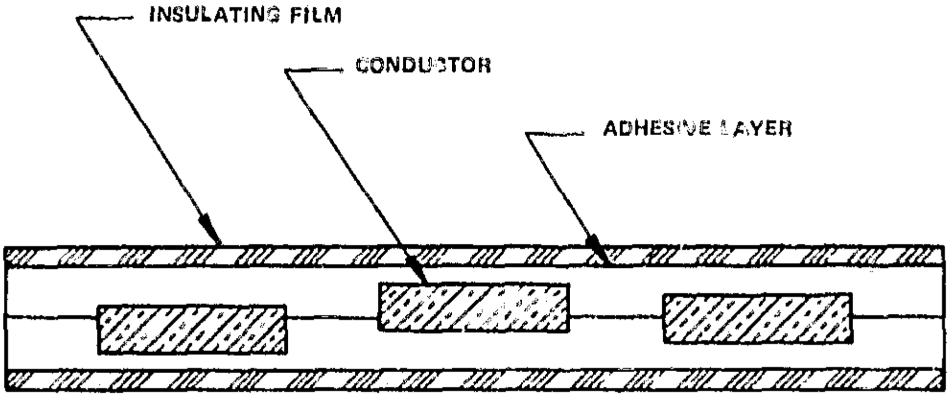


Figure 15. Typical cross section of FCC manufactured with nonuniformly positioned conductors.

In the MSFC laminator, two types of devices are used for tension control of components. The conductor spool shafts have adjustable spring-loaded slip-clutches for tension control. Air-operated brakes perform this same function for the plastic tapes and the completed laminate. The tension in individual conductors must be measured and carefully controlled to assure uniformity. Special tensiometers developed by the fabric industry are available on the commercial market to measure and control yarn tension in weaving looms. These same devices are readily adaptable to the requirements of FCC lamination.

It is also important that tension be constant with time and independent of spool diameter, from the beginning to the end of the run. The tension devices used in fine-wire, coil-winding machines are the best type for this purpose.

As a matter of interest, it may be noted that the requirement for precision tension control is less critical for the wider flat conductors (larger gauges).

4. Edge Control of Tapes. Provisions must be made to assure that tapes are fed in a straight and uniform manner from the supply reels to the laminating station. Edge detection systems include: (1) mechanical feeders, (2) pneumatic mechanisms, in which air passing through a hole detects the tape edge, and (3) photo-optical systems, in which the edge of an opaque film is sensed as it passes between a light beam and a photocell. The latter system could not be used for guiding transparent film.

5. Spacing of Conductors. Stripping and cable termination operations require highly accurate conductor spacing, and cumulative spacing errors cannot be tolerated. For example, ±0.13mm (5 mils) would be typical of the maximum allowable position error in a cable having a center-to-center conductor spacing of 1.9mm (75 mils). If conductors are not uniformly sandwiched within the cable (Figure 15), mechanical or abrasive stripping would probably damage them. Whether the hot roller or the heat-and-quench method of lamination is used, there are several basic causes for improper conductor positioning; however, there are definite preventive measures which can be taken.

To obtain more uniform center spacing, it is necessary to use some method of guiding conductors to the laminating cylinders. The technique must account for tape width-changing influences such as temperature and tension. MSFC equipment uses three guide rollers (shown in Figures 6, 7, and 16) which are grooved to properly space the conductors. The final roller is located as close as possible to the hot roller nipline to assure retention of conductor alignment. Arnold and Gore (Patent No. 3,540,956) describe a technique in which conductors are positioned in a grooved plastic tape, then covered with a top film as they pass between the nip rollers [3]. Marcel (Patent No. 3,481,802) reports first positioning and embedding conductors within the surface of a heat-softenable adhesive bonding film, then passing this composite, along with a cover film, between the laminating rollers [4].

Composite position errors can result from factors other than inadequate guides. Several of these were discussed earlier along with their corrective measures: (1) conductor "swimming" due to excess adhesive, (2) spacing irregularities caused by kinks in the wires, and (3) nonuniform positions resulting from varying tension on conductors.

Conductor position errors also can occur when the conductors are fed to the laminating cylinders from a position below the roller nipline, as is done in the MSFC laminator. This angle of entry results in a slight tension against the lower roller and causes the conductors to sink down into the lower adhesive layer, producing unsymmetrical cable insulation layers. With the MSFC hot roller laminator, this tension effect can be offset by maintaining the upper cylinder at a temperature slightly above that of the lower cylinder. The effect of increased fluidity of the upper adhesive layer should cancel the effect of increased tension on the lower cylinder.

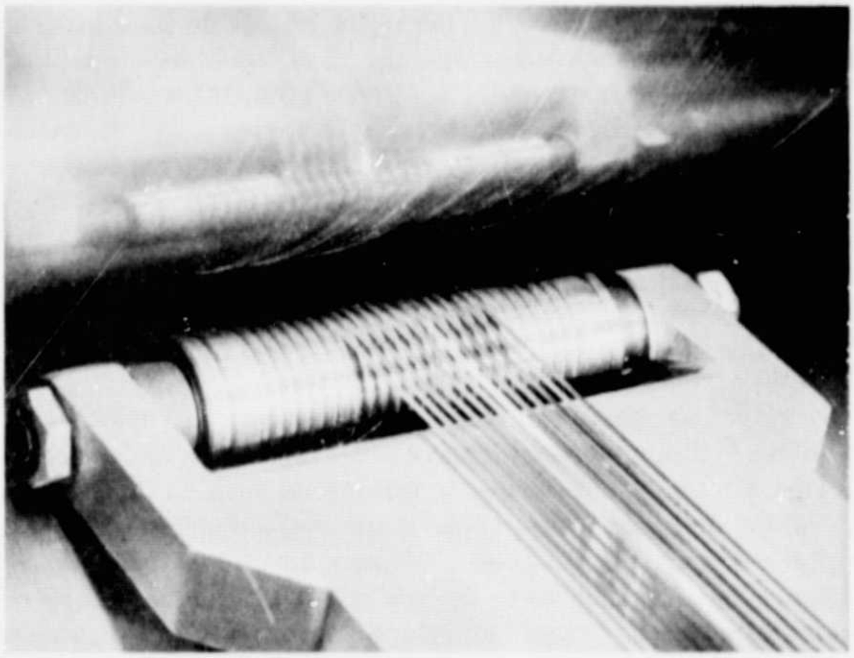


Figure 16. Close-up view of a grooved guide roller for flat conductors in MSFC laminator.

6. Laminating the Flat Cable. The heart of any FCC laminating machine is the station for joining the various cable components (flat conductors, insulating film, and adhesive). The methods used for joining differ widely as illustrated basically in the examples which follow:

(a) Films and conductors are placed in proper orientation in a laminating press. Pressure is applied, then heat, then cooling. Finally, the pressure is released.

This is the customary method for laminating short runs of flexible printed circuits. For continuous length cables, rollers are used.

(b) Films and conductors are joined and pressed together between hot rollers.

(c) Same process as in (b) above, except that film and conductors are preheated to increase the laminating speed.

(d) Films and conductors are preheated and joined together between cold rollers.

(e) Films and conductors are joined and heated between hot rollers and then immediately quenched between cold rollers.

a. Heat and Quench Method. This is a good method for high volume production of FCC. Because components are heated before reaching the cold-quench lamination cylinders, production speeds of about 30.5 meters (100 feet) per minute are attainable.

Application of radiant energy to the adhesive is the most desirable technique for heating tapes since only the adhesive layer needs to be heated. The plastic substrate (Mylar or any thermoplastic material) should be kept as cool as possible to prevent weakening and subsequent tape stretching under tension. To achieve this desirable situation in practice, the adhesive film must be opaque so that it can absorb the radiant energy before the substrate is seriously weakened by heat. The adhesive layer of a naturally transparent tape can sometimes be made opaque by adding heat absorbent matter to the adhesive. Studies at MSFC have indicated that Kapton/FEP and Mylar/polyester adhesive are two tapes which could be effectively heated in this manner. TFE/FEP, however, will absorb only a slight amount of the energy which is passing through the material, and thus is not suitable [5]. If the tape is transparent and the adhesive cannot be sufficiently heated, a "shoe" can be laid against the substrate for support and for heat reflection. The reflected heat is then directed back from the shoe to the adhesive. Although this technique heats the adhesive, it is not desirable since it also heats the plastic layer. In actual practice, the high transparency and small mass of the adhesive layer make it very difficult to heat this layer more than the substrate film.

b. Simultaneous Application of Heat and Pressure. With MSFC's equipment, the bonding process occurs completely at the nipline of electrically-heated laminating rollers (Figures 6, 7, and 17). Oil cylinders apply the necessary pressure to the rollers to press the heated conductors and tapes together, and complete solidification of the adhesive occurs later in the process. Because heat and pressure are applied simultaneously by a single set of rollers and the bonding takes place only at the nipline, this fabrication technique is relatively slow. It is capable of handling up to about 6.1 m (20 ft) per minute, depending on the type of adhesive. In other words, heat transfer limits the speed. Consequently, although relatively simple and inexpensive, this method is suitable primarily for experimental or low production purposes, rather than large volume production of FCC.

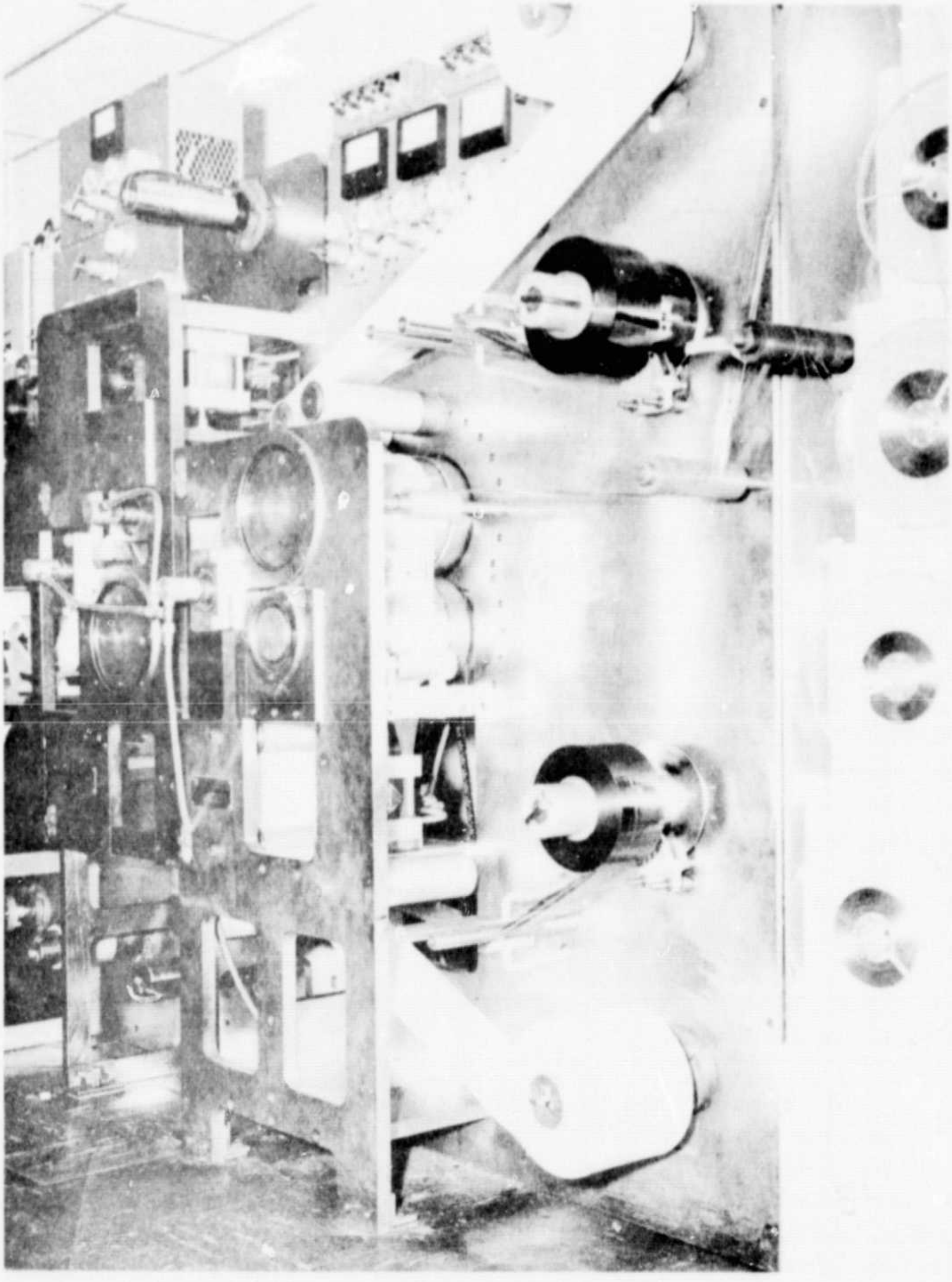


Figure 17. Close-up view of MSFC laminator showing hot rollers and other pressing devices.

A short remark on production quantity may be in order at this point. If a hot roller laminator is adjusted to run 3 m at (10 ft) per minute, it would produce 1463 m (4800 ft) of finished FCC during an 8-hour workday. Since warmup time, along with temperature, pressure and speed adjustments, are required for setting up the operating initially, it becomes economically desirable to make long runs of one type cable in a continuous operation (the only interruptions being for splicing conductors and tapes). On this basis, it may be reasonably assumed that the machine will produce FCC for 20 hours each day. This amounts to a production capability of about 3658 m (12,000 ft) per day.

The MSFC FCC Laminator is an experimental machine having only 25.4 cm (10-in.) reels carrying about 457 m (1500 ft) of flat wire, 0.1-mm (0.004-in.) thick. Of course, this setup means that considerable time is lost in splicing. A more efficient operation could be obtained by using larger supply reels for the wire and insulating film.

7. Edge Trimming. After the insulating tapes and conductors have been bonded together, only one fabrication step remains, the cable edges must be trimmed. Uniformity of margin is critical since the cable is sometimes located in a termination tool using the edges as reference. For this reason, the margins should be equal, so that the cable can be laid on either side in the tool.

Rotating circular scissors (a standard commercial item) are used for the trimming operation. The speed of the rotating blades should be equal to or greater than the speed of the cable (Figure 18).

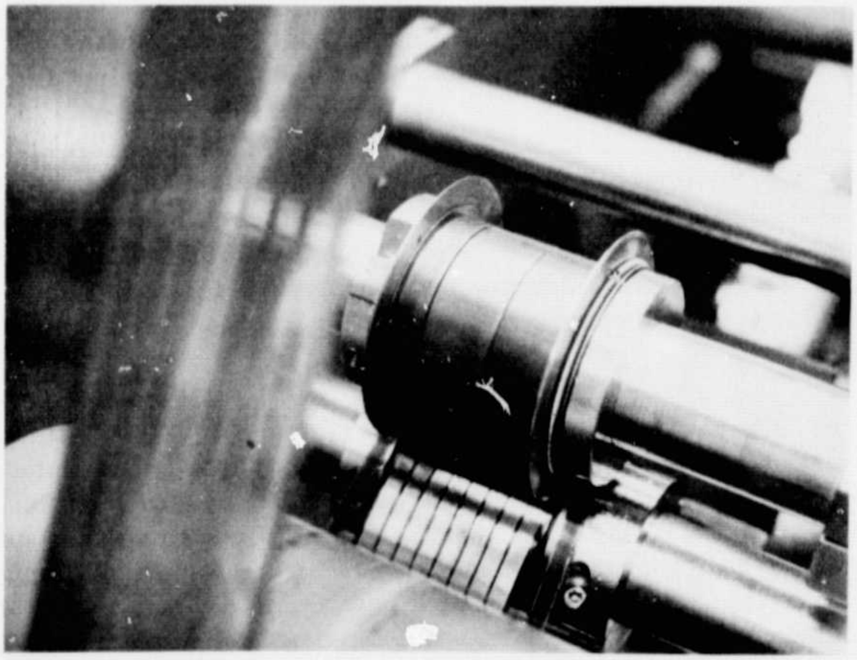


Figure 18. Two-bladed edge trimming unit on MSFC laminator.

To control the lateral position of the cable relative to the cutters, some type of automatic sensing and alignment system is needed. If the cable insulation is transparent or translucent, a photo-optical detection system (a photocell and light beam) can be used. In this system, the light beam is adjusted to pass through the film so that about half of the beam is intercepted by the outer edge of the outer conductor. The balance of the light energy is directed onto the photocell, thus establishing a certain baseline signal level. As the FCC moves through the edge sensor during actual production runs, any lateral deviations of the outer conductor causes a change in light intensity at the photocell. This creates an electrical signal which is detected and sent through a servo system to properly reposition the cable.

Obviously, a photo-optical detector will not work with opaque film, but for this situation, electromagnetic sensors can be used. The hysteresis type sensor, which incorporates a coil emitting a high frequency electromagnetic field, is positioned under the edge of the outer conductor. This high frequency field induces eddy currents in the outer copper conductor. These eddy currents, in turn, develop a countermagnetic field which influences the coefficient of self-induction of the coil. Thus, if the film being trimmed should wander laterally, an electrical signal will be developed in the coil. This signal can be detected and used in an electromechanical servo system to reposition the film.

To trim shielded FCC, the system must employ a sensor capable of detecting the outer conductor through the shield foil. Since the shield foil is usually much thinner, 0.013 to 0.025 mm thick (1/2 to 1 mil thick) than the conductor, 0.076 to 0.152 mm thick (3 to 6 mils thick) it is still possible to detect the conductor edge.

8. Cable Testing. In order to assure that the manufacturing process produces cable of the desired high quality, certain tests must be performed on the finished laminate. These include examinations for moisture resistance, flex life, and ease of cable end stripping. Two unique tests developed at MSFC are designed to measure conductor center spacing and detect flaws in the insulation.

a. Measuring Conductor Spacing. The need for accurate conductor spacing in flat conductor cables calls for appropriate inspection methods and equipment. The standard method of measuring the conductor positions in a cable is to use a toolmaker's microscope. The cable is moved across the field of view by a calibrated spindle during measurement. Results must be tabulated and plotted. This technique is highly accurate, but represents a large equipment investment and is rather tedious for large volume inspection work.

A much more convenient, less costly, and time-saving method exists which provides an accurate, visual presentation of the conductor spacing errors. The method is based on optical interferometric effects and produces a pattern called moiré, which is accurate and easy to interpret. The only requirement is that the FCC be translucent. The moiré pattern is produced when a cable to be tested is superimposed over a standard cable in front of a light source, and a slight angle is introduced between the two cables. The angle and irregularities of the resulting moiré pattern can be interpreted as conductor spacing errors in the cable under test. As a general rule, if the moiré pattern is formed straight and is square to the conductors of the standard cable (as in Figure 19.c), the center-to-center spacings of the two cables are equal. However, if the moiré pattern is slanted across the standard cable (as in Figure 19.d and Figures 20.a, 20.b, and 20.c), the center spacings are different. The slant angle of the moiré pattern can be measured and used to calculate the conductor center spacing of the cable under test. Additional information can be obtained by further examination of the moiré effect. For example, irregularities in the pattern (as in Figure 20.c) indicate some very specific problems with the conductors:

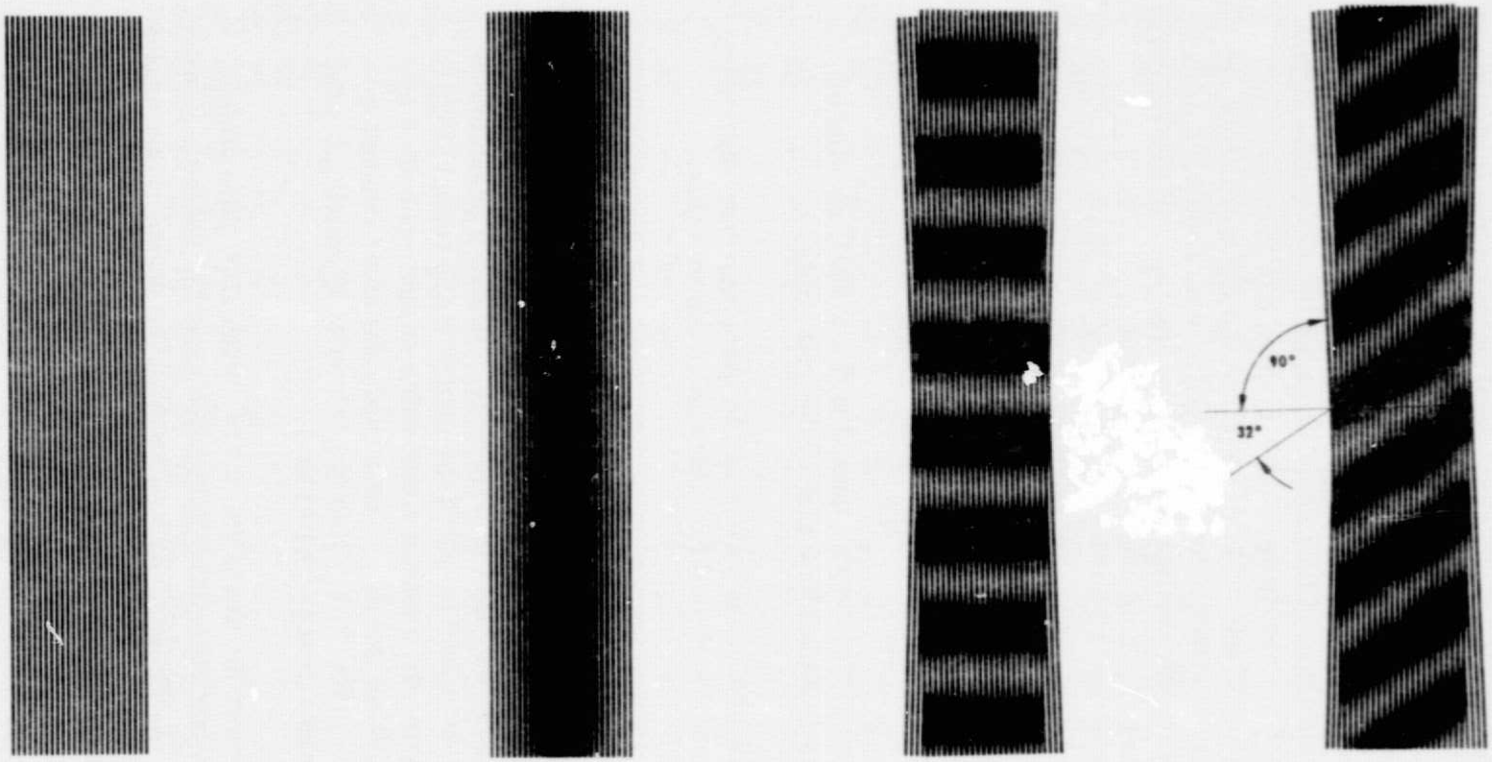
- The slant angle of the moiré indicates the overall spacing of the conductors is wider than that of the test cable.

- The rhomboids are much shifted at the margins, thus suggesting extra large spacing of the conductors near the margins.

- Minor irregularities exist across the cable.

Moiré patterns produced by the interferometric method can be used to measure accurately the center-to-center spacing of conductors in flat cable. This technique, illustrated in Figure 21, utilizes a precision grid (Figure 21.b) as the standard to which the cables being tested (Figure 21.a) are compared. Figure 21.c shows a test cable superimposed on a standard grid and the resulting moiré. The center-to-center conductor spacing of the test cable is given by the line of horizontal symmetry for the moire' pattern, in this case 1.9 mm (0.075 in.).

Test equipment for using the moiré method is quite simple, consisting essentially of a box containing light bulbs mounted behind a frosted glass panel (Figure 22). A standard cable along with the moiré slant angles and their corresponding conductor center spacings are fixed on the glass. After the test cable has been laid on the standard cable, it is rotated to the desired angle to produce a moiré pattern. The angle of this pattern is



(a)

STANDARD CABLE
25 CONDUCTORS
10 MIL WIDE
75 MIL CENTER SPACING
PLOTTED WITH TAPE
CONTROLLER GERBER X-Y
PLOTTER. COPIED AS A
NEGATIVE

(b)

A TEST CABLE WITH 78 MIL
CENTER SPACING IS SUPER-
INPOSED OVER A STANDARD
CABLE WITH 78 MIL CENTER
SPACING FORMING A BEAT FRE-
QUENCY OF 24 CONDUCTORS

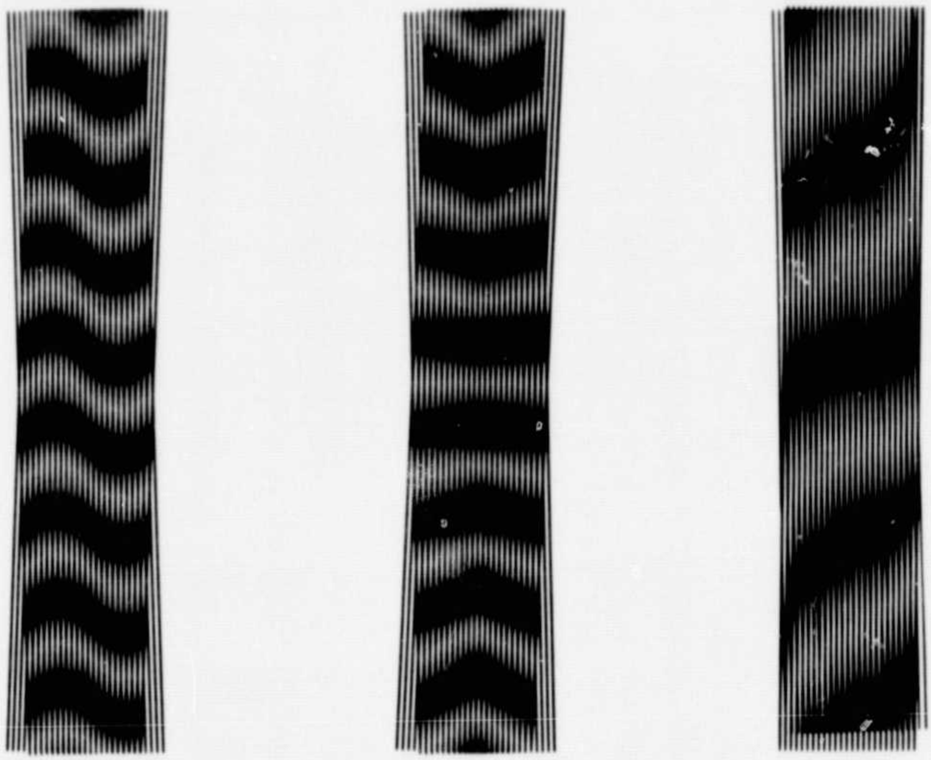
(c)

TWO STANDARD CABLES OF
IDENTICAL DIMENSION ARE
SUPERIMPOSED AT $\alpha = 3½°$.
THE MOIRÉ PATTERNS ARE
SQUARE TO THE CONDUCTORS
AND EQUALLY SPACED AND
TOTALLY UNIFORM. THE TWO
CABLES ARE IDENTICAL
STANDARDS

(d)

2 STANDARD CABLES
C_1 = 75 MIL AND C_2 =
78 MIL CENTER SPACING
ARE SUPERIMPOSED AT
$\alpha = 3.7°$. THE MOIRÉ
SLANT ANGLE $\beta = 32°$.

Figure 19. Typical moire′patterns for measuring irregularities in conductor spacing in FCC.



(a)

THE SINE WAVE MOIRÉ IS FORMED BY A STANDARD CABLE WITH C_1 = 75 MIL AND A TEST CABLE HAVING A SPACING WHICH CHANGES LINEARLY FROM THE CENTER TO THE MARGINS FROM 75 MIL TO 78 MIL. THE CABLE ANGLE $\alpha = 3.6°$.

(b)

THE CHEVRON MOIRÉ PATTERN IS FORMED BY TWO IDENTICAL CABLES HAVING A LINEARLY CHANGING SPACING OF 75 TO 78 MIL FROM THE CENTER TOWARDS THE MARGINS. CABLE ANGLE $\alpha = 3.6°$.

(c)

COMMON MOIRÉ PATTERN, ILLUSTRATING A COMBINATION OF IRREGULARITIES IN FCC UNDER TEST.

Figure 20. Typical moiré patterns for measuring irregularities in conductor spacing in FCC.

matched with its counterpart on the glass, and the associated center spacing is located. Analysis of moiré patterns is a fast, accurate, and inexpensive way of analyzing conductor center spacing.

A comprehensive description of the moire' pattern technique for measuring conductor spacing in FCC may be found in NASA TMX-53843 (June 1969 "Measuring the Conductor Spacing in Flat Conductor Cables").

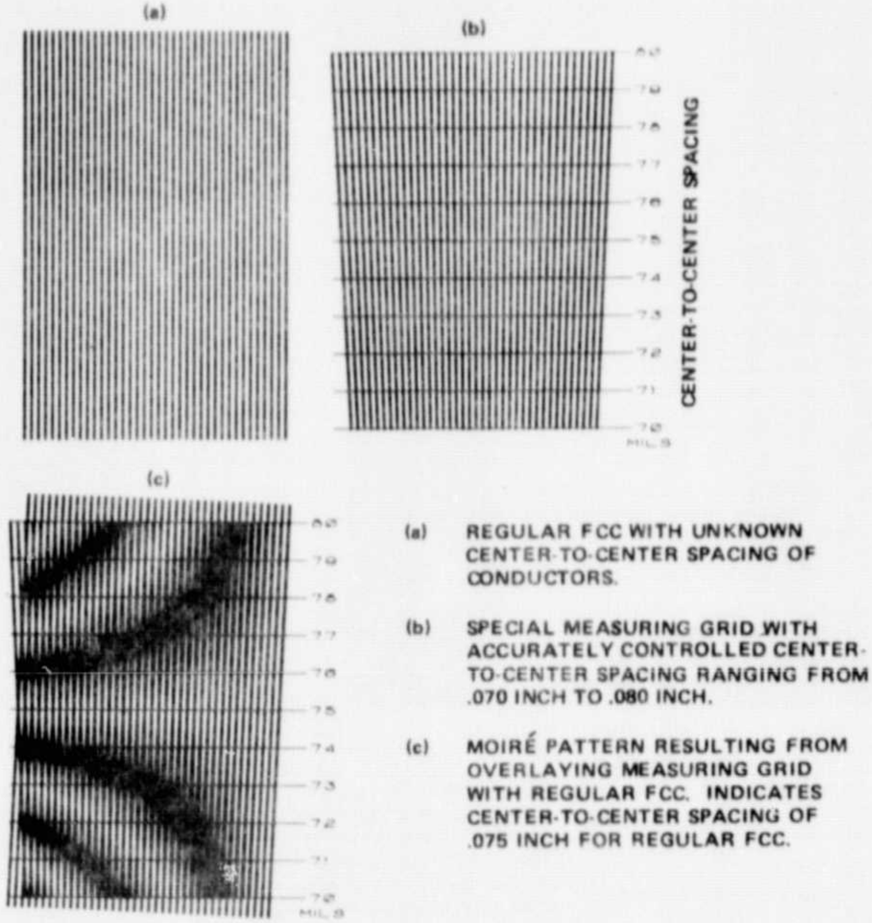


Figure 21. Moiré technique for measuring center-to-center spacing of conductors in FCC.

b. High-Voltage FCC-Insulation Flaw Tester (For Laminated Cable). This equipment (shown in Figure 23) is very similar to the High Voltage FCC Film Tester described earlier [6]. Material flaws in the completed cable are detected through the use of the dielectric strength characteristic of the insulation. The conductors at one end of the cable are attached to the rewind reel, and are electrically connected to the high voltage source by a jumper wire. The other high voltage lead is connected to the two center rollers, which are kept in good mechanical contact with the FCC as it is rewound. As the cable passes in "S" form over two grounded metal rollers, the voltage is applied for testing the insulation. When an insulation flaw

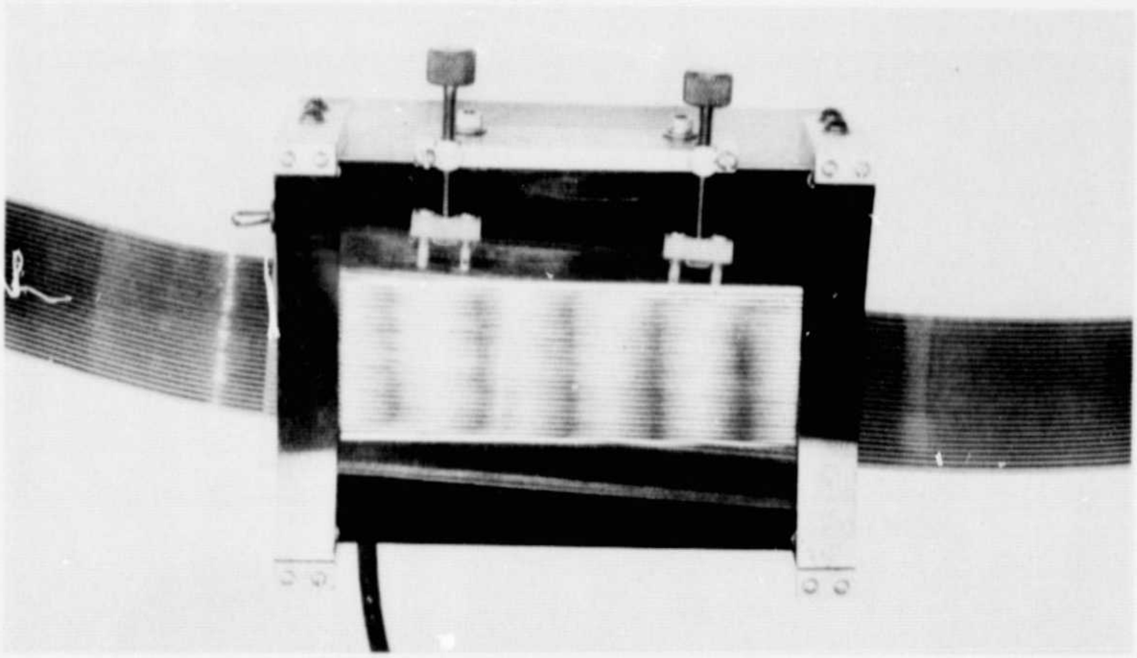


Figure 22. Moire' tester for measuring conductor spacing and irregularities in FCC.

moves over the grounded roller, the high voltage on the conductor closest to the flaw will arc to one of the grounded test rollers, depending on which side of the cable the flaw is on. When this happens, the drive motor automatically cuts off and a buzzer and light warning are actuated. The motor is then driven enough to move the insulation flaw out from the rollers. The flaw is then marked on the cable for later removal and the test continues.

B. Woven Cable

Commercial weaving techniques and equipment which have been highly perfected by the textile industry are used to make woven cable. The conductors are usually placed in the warp direction and interwoven with selected filler and/or warp materials which space, insulate, and bind the warp conductors in place. Conductors may be preinsulated prior to being woven together, or the completed cable can be impregnated against moisture, using a material such as silicone.

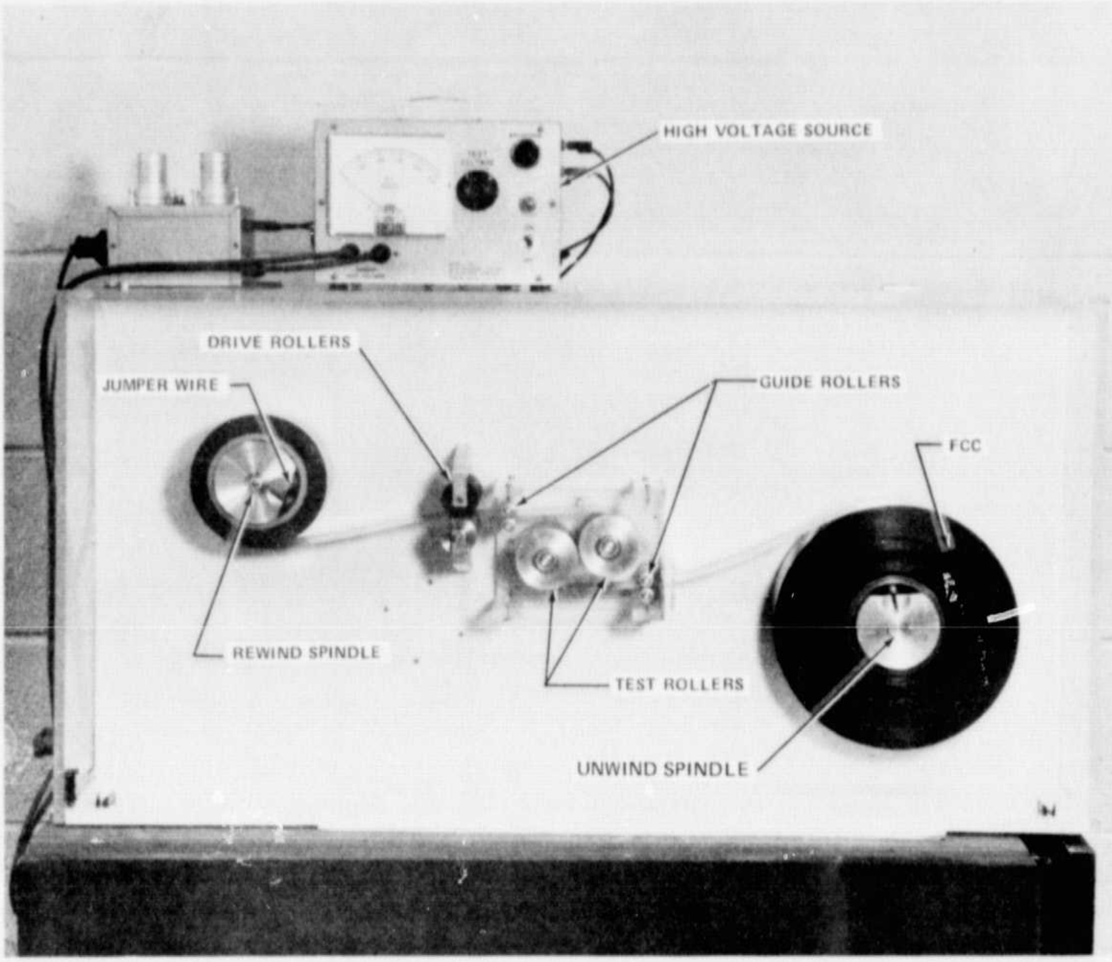


Figure 23. High voltage flaw tester for FCC insulation.

The application of weaving techniques to the fabrication of FCC has excellent potential. Weaving is an old, well-developed, inexpensive process, which utilizes highly mechanized equipment. Conductors can be accurately spaced, the woven cable never delaminates due to excessive heat and vacuum, and neighboring conductors never short out unless the weaving fiber melts. Furthermore, this process is adaptable to an endless variety of high-flexibility cable constructions.

1. Weaving Patterns. Three textile patterns commonly used in the construction of flat woven cabling are plain weave, cross-shot weave, and twill weave.

a. Plain Weave. Figure 24 illustrates this simple and commonly used textile construction, which can be applied to flat cable fabrication. Cams operate the heddles, forming an opening of the warp threads to allow the shuttle carrying the fill thread (weft) to pass between and interlace with the warp threads. After the fill thread is moved into position, the cams change the position of the warp threads and another fill thread is moved into place to form the weave.

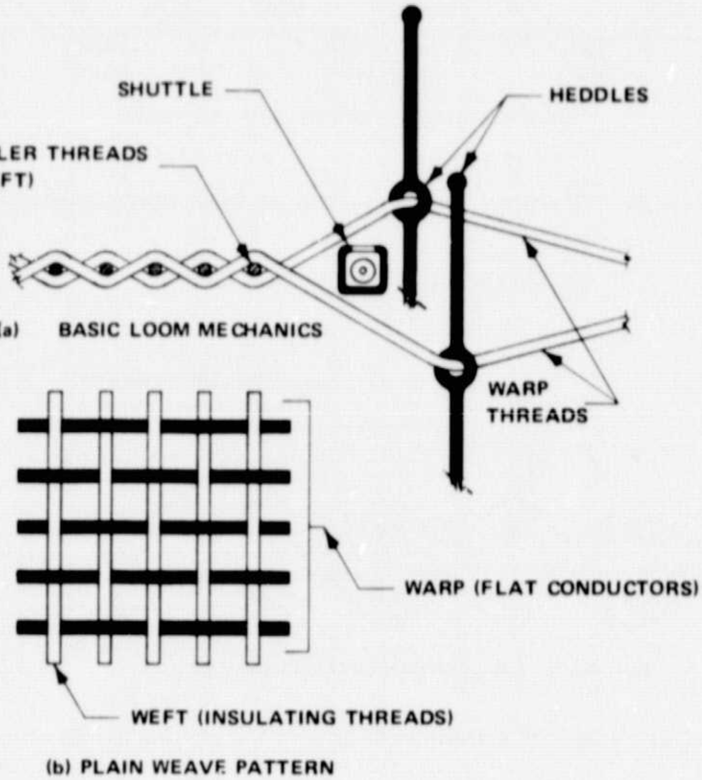


Figure 24. Production of a textile plain weave.

Figure 25 depicts the construction of a flat conductor cable using a plain (conventional) weave. A single shuttle is used to lay the filling fiber across the width of the cable. While the plain weave has the potential of slightly distorting the conductors due to the force of the heddles, it has the advantage of high speed fabrication.

b. Cross-Shot Weave. Figure 26 depicts the construction of a flat conductor cable using a cross-shot weave. The cross-shot weave employs two shuttles running in opposite directions, one above the conductor and one

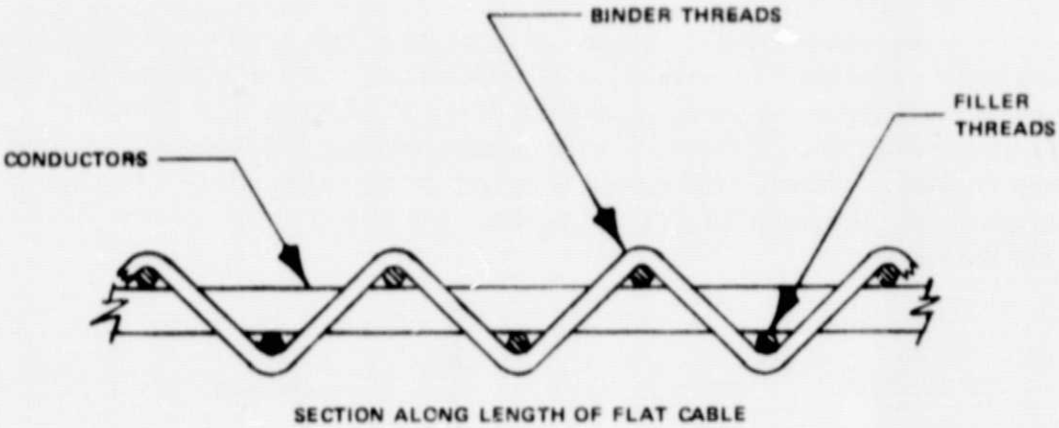


Figure 25. Typical construction of FCC using plain weave.

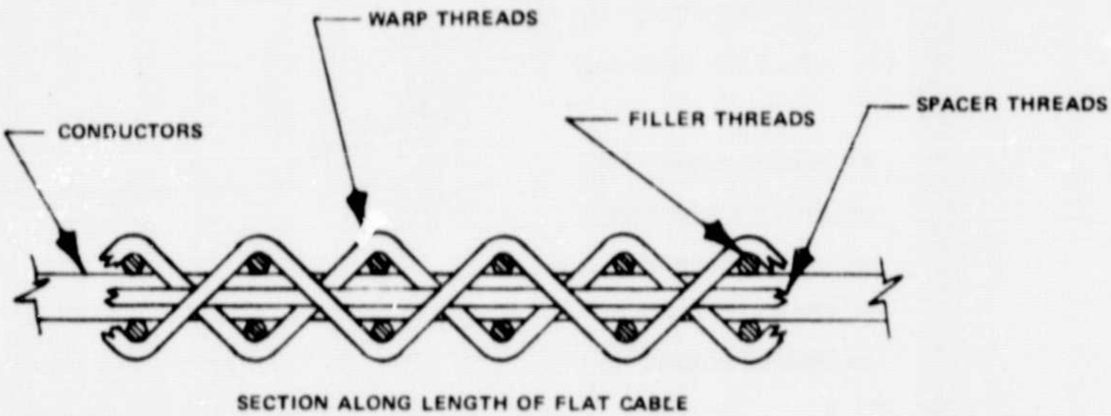


Figure 26. Typical construction of FCC using cross-shot weave.

below. The conductors are drawn directly through the loom (in the warp direction) and are not subjected to distortion by movement through the heddles. The dielectric warp threads are alternately lifted and depressed by the heddles to interconnect the top and bottom fillers.

c. Twill Weave. In the twill weave, (Figure 27) conductors are woven on a two-up and two-down alternating and shifting pattern and in this way are held in position by the fill theads. It is unnecessary to use binder threads between conductors since the conductors themselves interlace with the fill threads. Because of the absence of warp fibers, cable stripping and termination are simplified.

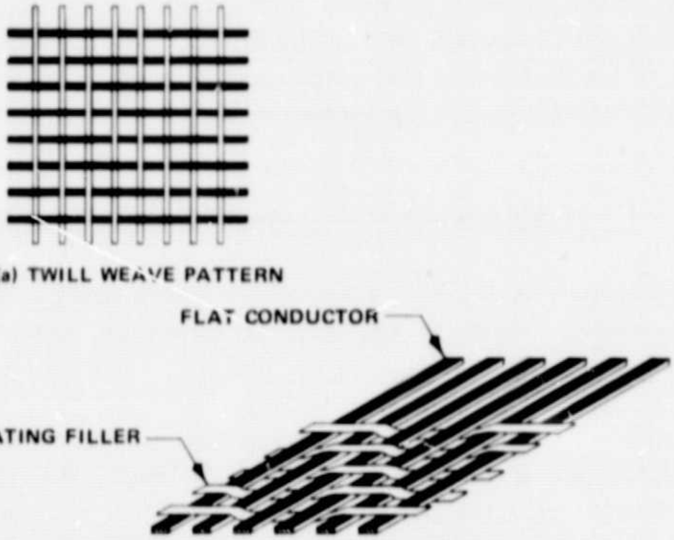


Figure 27. Typical construction of FCC using the twill weave.

2. Construction Variations. The weaving technique is adaptable to a wide variety of special constructions such as:

(a) Strain relief tabs can be woven into the cables.

(b) Accordian folds, with strain relief threads at each fold, can be woven for drawer applications.

(c) Pneumatic or hydraulic tubing and electrical conductors can be combined.

(d) Conductors with different sizes, insulations, and with or without shielding can be combined.

(e) Cables can be branched in the weaving process.

(f) Lengthwise webs can be woven in the cable to allow folding a wide cable for passage through narrow spaces, for use in separating conductors, and to provide a convenient means for mounting the cable. As described by Ross (Patent No. 3,495,025), holes can be formed in a thermoplastic web by heating, and fasteners can be passed through the web [7].

(g) Cable can be fabricated in multiple layers.

The versatility of the weaving process provides the possibility for fabricating many different types of special cable. However, this is in direct opposition to the concept of standardizing and reducing the number of cable types. It also magnifys the problem of terminating cables to standard FCC connectors.

C. Cable with Preinsulated Conductors

There are several cable constructions which use preinsulated conductors: high-density laminated cables, woven cables, bonded cables and others.

In the case of high-density laminated cables, the conductors are located in very close proximity and must be preinsulated to reduce electrical leakage. In woven cable, the weave serves primarily to correctly space conductors and to provide mechanical support, rather than for wire insulation. Unless the woven cable will be encapsulated when complete, preinsulation of conductors is essential. During bonding, individually insulated conductors are glued or fused together. The most common methods of applying preinsulation are described below.

1. Tower Coating. The desired insulation thickness is obtained by multiple coatings from solution, with oven curing after each pass. Using MSFC equipment (illustrated diagrammatically in Figure 28), a system of rollers moves the conductor (at a speed of 5 to 10 meters/min) through the insulation bath, blades evenly distribute the insulation over both flat sides of the wire, then additional rollers apply insulation to the wire edges. Insulation thickness can be controlled by the speed with which the conductors are drawn from the liquid, by the viscosity of the liquid, and by special wiper blades which can be adjusted for thickness control. To assure efficient solvent removal during curing, only about 0.003 mm (0.1 mil) of insulation is applied during each coating. After coating, the wire moves through the curing tower (6 meters tall) which is equipped with infrared heat source, passing first through a section heated to about 180°C (356°F) and then through a section heated to 370°C (700°F). This infrared heating prevents insulation blistering because it heats the wire directly, thus causing the insulation to dry from the inside outward. The speed of this operation could be increased if the curing tower was higher. Speed and tower height are controlled by the time needed to remove tackiness from the insulation so the coated wire does not stick to the Teflon coated rollers at the top of the curing tower. The entire coating and curing process is then repeated, if necessary, until the desired insulation thickness is obtained. Application of liquid insulation to

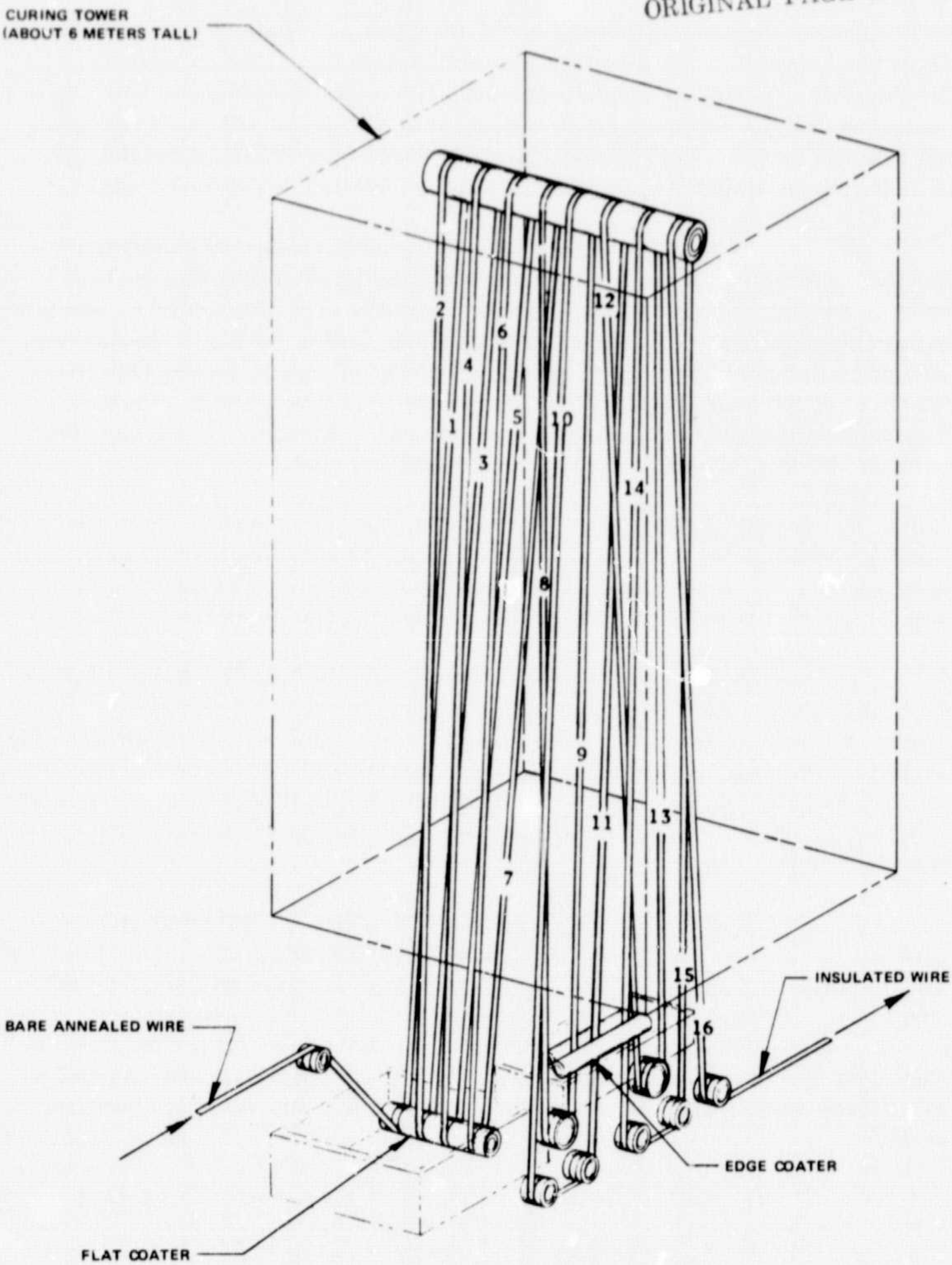


Figure 28. Schematic of tower coating equipment for insulating flat conductors.

the conductor edge surfaces can pose a problem. Because of surface tension, the coating material has a tendency to accumulate on the major surfaces of the flat wire, leaving the edges exposed. The edge rollers of the MSFC tower coating apparatus are intended to correct this situation. Other ways of dealing with the problem include coating round wires then rolling them flat, or by using metal sizing dies to assure complete coating of conductor edges.

2. Tape Wrapping. This is a very reliable method of ensuring consistent insulation thickness, since the thickness is established in the tape prior to insulation application. The tape consists of a film coated on one side with a thermoplastic (e.g., Kapton coated with Teflon FEP). This tape is wrapped around the conductor, using an overlap of approximately two-thirds the width of the tape (Figure 29). The wrapped conductor is then heated, thus causing the FEP to fuse and seal the wrapped system. If desired, the tape may be further sealed by over-coating the system.

3. Vacuum Deposition. In this technique, the conductor is coated by passing it repeatedly through a vacuum chamber containing vaporized insulation material. There is the alternate vacuum chamber technique of sputtering. Vacuum deposition is also used to apply metallic shielding to FCC.

4. Electrostatic Painting. Basically, an electrical'y charged insulation material is dissolved in an appropriate solvent and sprayed onto a conductor which is oppositely charged so that the droplets will be attracted to the surface. The resulting coat is uniform and paint loss is very low. This process can also be performed with insulating material in powder form rather than in a solution, whereby the conductors are heated so that the powder will stick and melt.

5. Fluidized Bed Coating. In this technique, the hot conductors (either single or in flat cable array) are guided through a so-called "fluidized bed" of insulation powder. The insulation powder is agitated from the underside of the container by a series of air jets to form a dense suspension. The powder melts and adheres to the surface of the hot conductors, thus forming a uniform coating. If the process is repeated, the melted insulation powder will fill the spaces between the conductors to form a finished flat conductor cable.

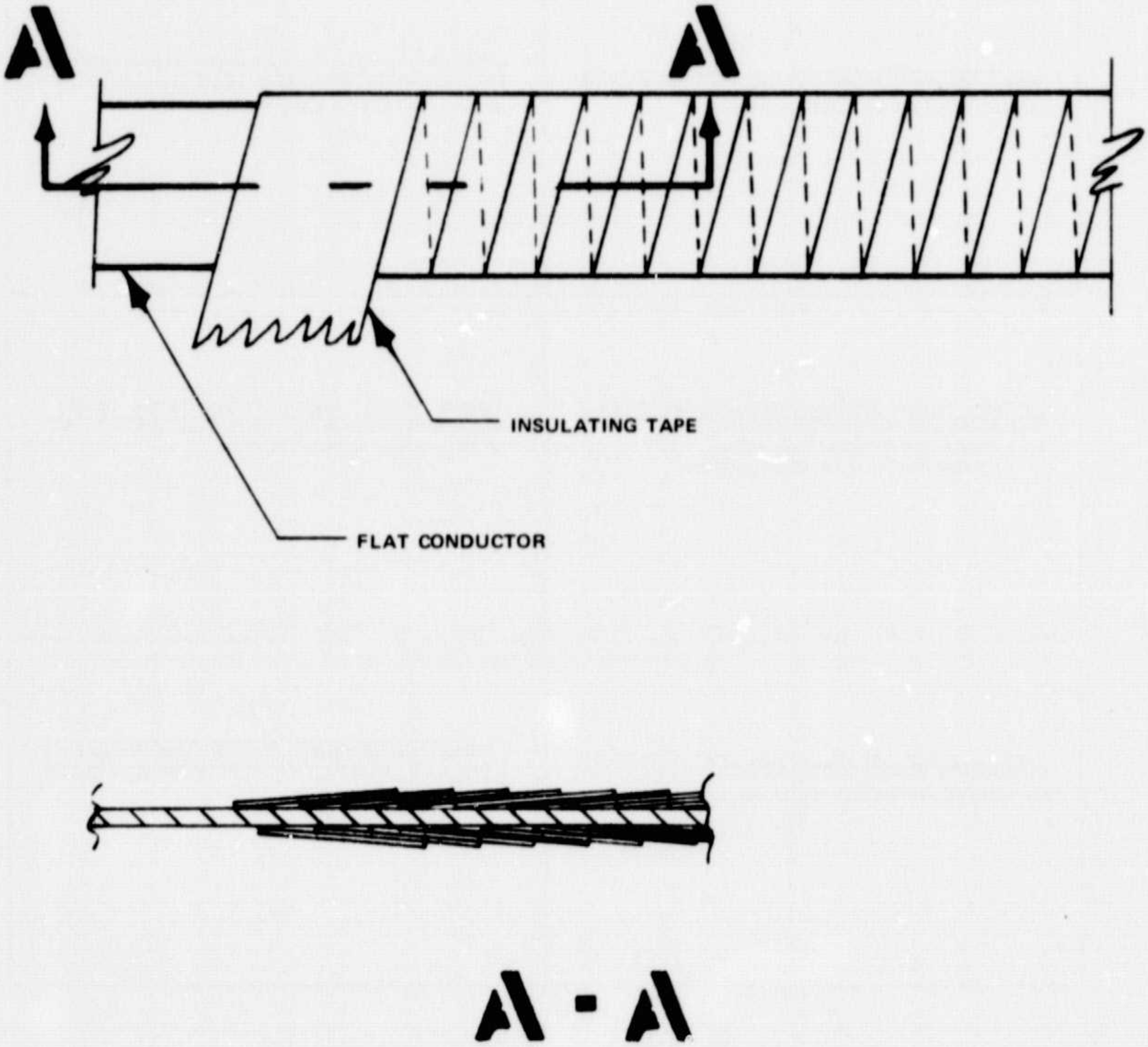


Figure 29. Tape-wrapped flat conductor.

D. Etched Cable

Etched cable is another widely used type of FCC. It is produced by etching conductors from a foil-clad substrate and then covering this cable core with a top insulating layer. By using the "continuous" etcher, lengths of cable in excess of 300 feet can be processed. The major steps involved in producing etched cable are illustrated in Figure 30.

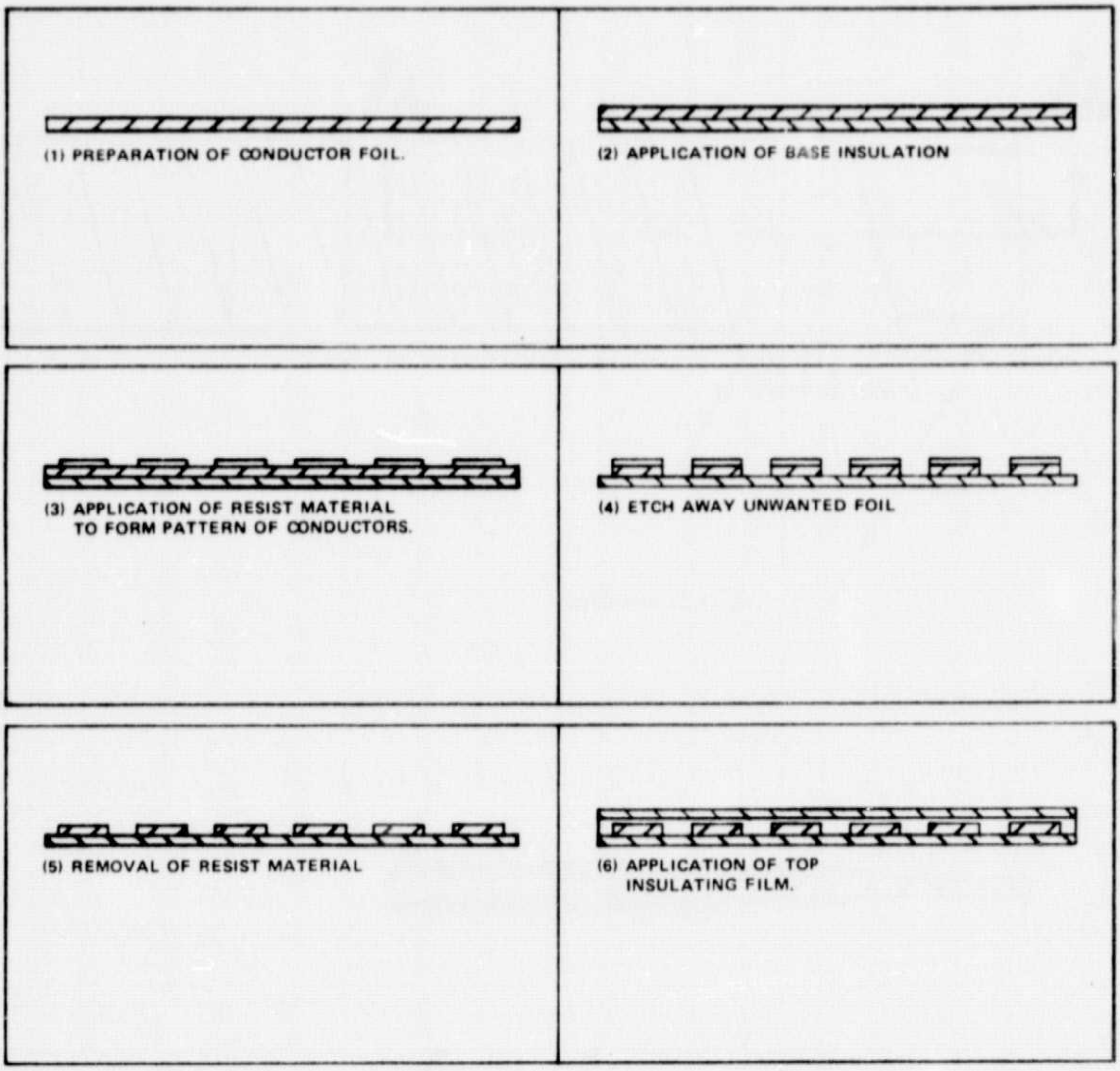


Figure 30. General steps in producing etched cable.

According to manufacturers, etched cable enjoys certain advantages over other forms of FCC:

- Closer tolerances permit smaller gaps between conductors. This reduces the size of cable needed for a particular current carrying capacity.

- With conductors permanently bonded to the bottom insulation layer, conductors cannot shift or "swim" during lamination of the top layer, a potential problem with conventional lamination.

- Because only one adhesive layer at most will be needed, the thickness of the completed cable is less than that of laminated cable. Weight savings, space savings, and higher flex life result from thinner cable.

- High temperature processing (i.e., dip and flow soldering, welding) is not limited by an adhesive layer between conductors and base substrate.

- Conductor areas can accept high contact pressure, as there is no thermoplastic between conductors and base insulation which can cold-flow.

- With at least one layer of insulation free of adhesive, chemical stripping is simplified.

- As described by Gordon (Patent No. 3,547,718), if a release agent is applied at spaced transverse areas prior to application of a resinous top film, exposed contact areas can be formed for termination [8]. The subsequent task of stripping is thereby eliminated.

On the other hand, the production of continuous etched cable involves several more steps and is more expensive than lamination. Thick conductors pose an etching problem when small center spacing is required. Although rounded conductor corners would be desirable, only square corners at best are possible with this fabrication process.

E. Extruded Cable

Thermoplastic as well as thermosetting materials are used in the production of extruded FCC. As the cable conductors are pulled through an extrusion die in proper geometric orientation, they are completely enveloped by plastic which is flowing under pressure. This forms a seamless tape in accordance with the profile of the die exit (Figure 31).

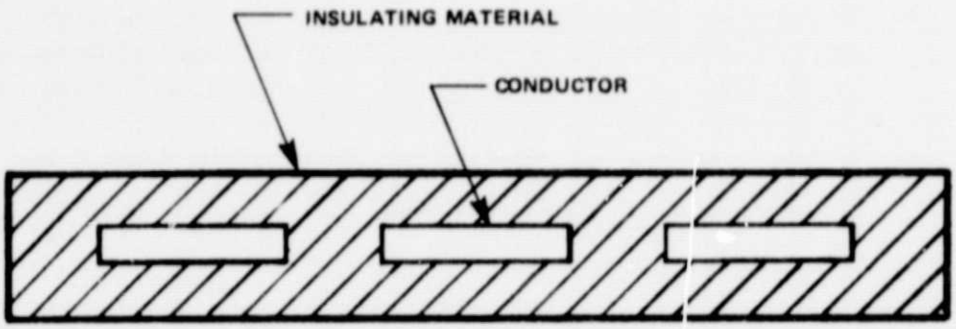


Figure 31. Typical cross-section of extruded FCC.

The extrusion process presents somewhat of a tolerance problem, owing to shrinkage during cooling or polymerization. In addition, most plastics used for extrusion require a greater insulation thickness than films used for lamination. This is caused either by the lower dielectric strength or by the mechanical softness or by both. Flat cables for computers require thicker insulation for specific characteristic impedances, expecially when there are several layers of cable in a harness assembly and shielding foils between cable layers should be eliminated.

Extrusion of FCC is a well established, high speed production process which results in a high quality cable. The cost of extruded FCC is quite low when one considers the high processing speeds of several hundred feet per minute. In fact, the cost of extruded FCC lies mostly in raw material costs rather than in labor and processing costs.

The limitation of extruded FCC lies mostly in the insulation material itself, since its tensile strength is only about 1/5 that of Kapton or Mylar. Thus, for cables of equal strength, the extruded FCC would have to be much thicker and, hence, much heavier. As a consequence, part of the basic advantage of FCC is lost when one uses extruded cable.

F. Additional Cable Types

1. Bonded. Bonded cable is made by joining two or more individually insulated wires with an adhesive, or by thermal fusion of the insulation. With the former technique, an adhesive is applied to the bonding area of the insulations, and the insulated wires are glued together within a guide or closing die. During heat fusion, the insulated wires are heated to a temperature approaching that at which the insulation was originally placed on the

conductor, thereby causing the insulation to flow. With pressure, the insulation joins together in a common configuration. However, as noted by Anderson and Perreault (Patent No. 3,537,927), the heat bonding technique is not without difficulties, especially when heated rollers or platens accomplish the fusion [9]. Temperature control is critical and the insulation material must reach a certain minimum temperature to enable adjacent wires to bond. However, if the material is excessively heated it will become quite soft and unduly deform, resulting in nonuniformly insulated wires or sticking to the heating device. Anderson and Perreault describe a technique in which the heating medium is a liquid. The hot liquid transfers heat to the plastic insulating material much faster than a metallic surface. Since the plastic can be heated to substantially the same temperature as the liquid heating medium, the temperature of the medium can be closely controlled within the bonding temperature range without fear of either under or overheating the plastic material.

One advantage of a flat bonded construction is that the plastic insulated single-conductors may be different colors.

2. <u>Milled</u>. In fabricating this type of FCC, a special milling cutter is used to remove unwanted copper from a foil-clad substrate.

During early FCC development work, MSFC experimented with this manufacturing technique. In one approach, the milling cutter was adjusted to remove all undesired copper from the foil-clad substrate, leaving only the predetermined conductor pattern. In another approach, the milling and etching processes were combined. A helical milling cutter was adjusted to remove about 10 percent of the undesired copper from a foil-clad substrate which had been presprayed with photo resist. The remaining copper was then removed by etching, thus leaving only the predetermined conductor pattern. In both cases, a top layer of insulation was applied by spray coating or lamination techniques.

The milling operation was performed using a 6.4-cm (2.5-in.) diameter helical milling cutter, ground and grooved to provide the appropriate lines and spacing for the cable conductors. This was positioned near a curved back-up surface or "cable shoe", as illustrated in Figure 32. Both the milling cutter and the cable shoe were positioned on the foil side of the cable material with the teeth of the milling cutter projecting through slots in the shoe. The cable material was pressed against the shoe by a back-up roller. In this manner, the depth of cut was determined by how far the teeth projected through the shoe and was not affected by variations in the thickness of the base material.

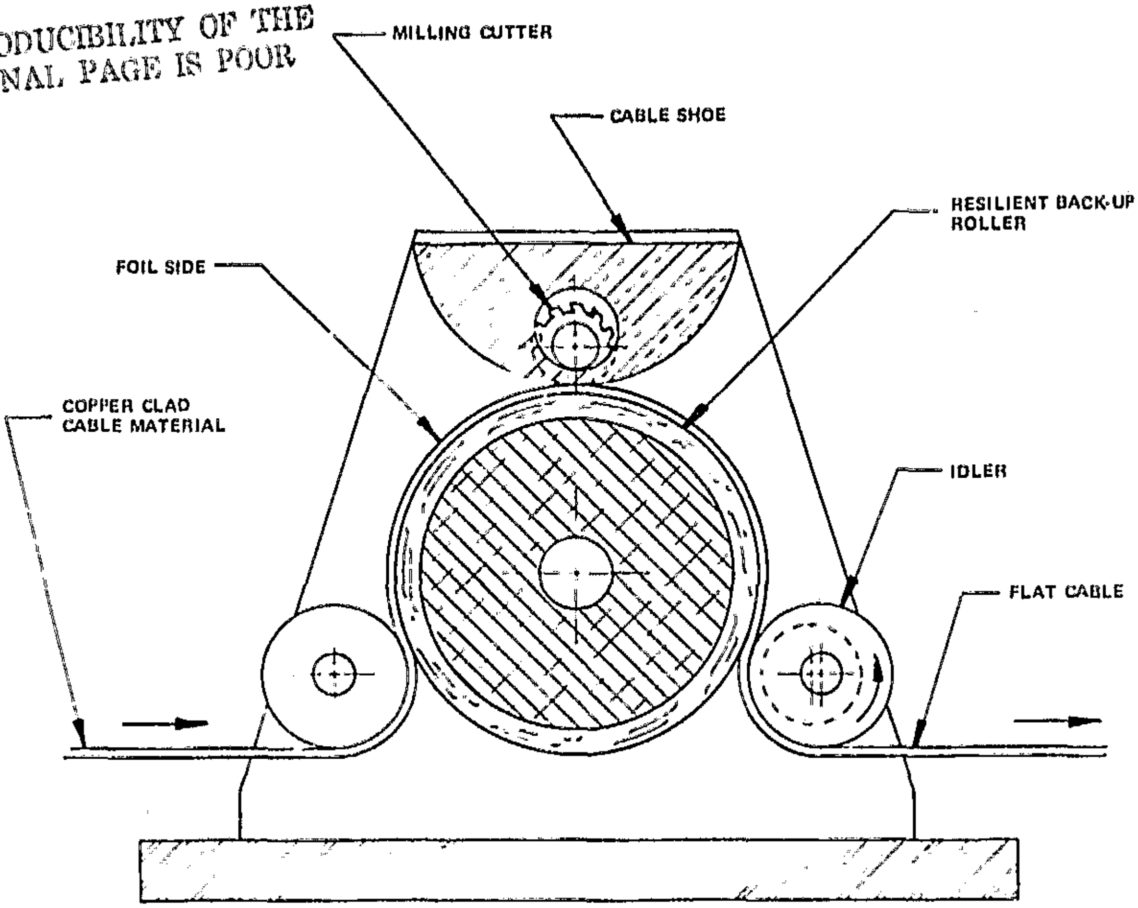


Figure 32. Milling process for making flat conductor cables.

3. Flat Molded. To produce flat molded cable, preformed conductors are arranged and held in a mold form into which insulating material is poured and then cured to form the cable structure. This process is limited to production of short cable lengths.

4. Multiple Spray Coated. In this method, illustrated in Figure 33, the conductors are properly spaced and pulled over a large diameter heated drum which is coated with Teflon (or a mold release agent). The plastic is sprayed against the drum forming the first layer of insulation on the conductors and in the spaces between the conductors. The cable then makes a similar pass over a second drum (so that the first layer of insulation is against the drum) where it receives another spray coating to completely insulate the conductors and tie them together mechanically.

Multiple spray coatings can be applied as necessary by winding the group of conductors several times around the drum in helical fashion. If longer drying or curing time is needed, only one coat should be applied at the beginning of the helix.

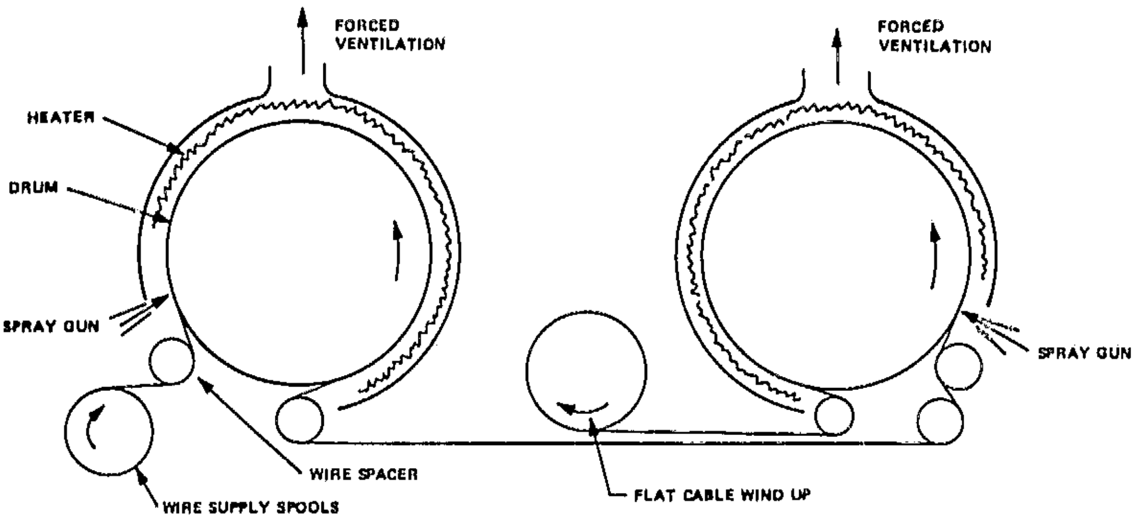


Figure 33. Making flat conductor cable by spray coating.

The liquid dielectric can also be applied by a soft roller coater or by a wiping blade arrangement (or by a combination of both). In this case, the margins of the cable may need mechanical trimming.

SECTION IV. FABRICATION OF SHIELDED CABLE

A. General

A separately applied shield is rarely needed for flat conductor cable. Often sensitive conductors can be physically separated from disturbing circuits, or the cable can be shielded by mounting to a grounded metal substrate or by grounding alternate conductors to electrically separate the sensitive ones. Conductors pairs can also be etched from double-sided, copper-clad films to form the zigzag pattern shown in Figure 34, a design which acts in a manner similar to twisted wires in reducing the effects of strong electromagnetic interference. Only a few critical situations will require shielding and, even then, the task of designing an effective system will be easier than designing a similar system for round wire cable. Because of the fixed geometry of FCC, electrical effects are consistent and shielding requirements can usually be predetermined. But, regardless of conditions, numerous techniques, materials, and designs are available for providing effective shielding.

Shielding is generally designated as loose or fixed. Loose shields are attached to the basic flat cable only at the termination point, whereas fixed shields are attached along the full length of the cable. Thin copper foils (solid or perforated) or fine wire mesh are often used as loose shields for standard FCC, and they can either be laminated to one or both sides, or wrapped around the cable. Shielding can be plated-on by vacuum or galvanic deposition. Insulated shielding thread can be woven around conductors, or a woven braid can be applied around the entire unshielded cable.

Shielding may be either a material of high electrical conductivity or it may be a ferromagnetic material of high permeability (for low-frequency magnetic fields), or both. These techniques and materials, and combinations of them, can be used to design shielding systems which effectively attenuate both electrostatic and electromagnetic interference.

Selection of an optimal shielded cable configuration is based on several considerations:

- Shielding effectiveness
- Cost and ease of cable fabrication (preparation for termination, including stripping).
- Cable flexibility.

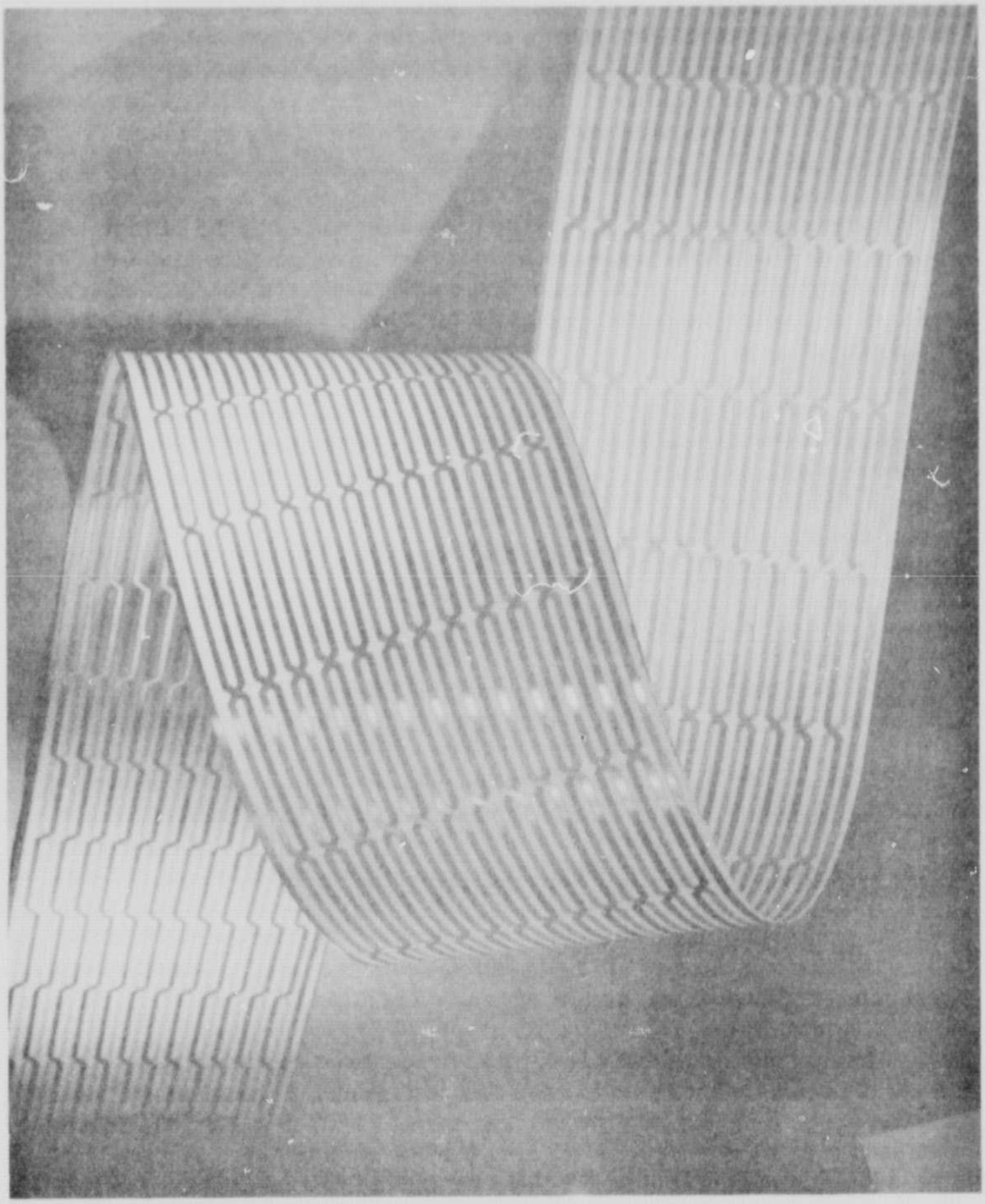


Figure 34. FCC etched in a zigzag pattern.

For maximum effectivity, the shielding system should be: (a) an electrically closed envelope, (b) fabricated of a combination of highly conductive and ferrogmagnetic materials, and (c) preferably solid and continuous in construction. However, configurations of this type are often difficult to fabricate and to strip. For example, while a thick, solid foil offers maximum shielding effectiveness, it also reduces cable flexibility and may be difficult to bond to the unshielded cable. Several alternatives can be selected, depending on specific program requirements. Improved flexibility of the solid foil construction can be obtained by attaching loose shield assemblies to the end of an unshielded cable, or by corrugating a totally laminated shielded cable. Improved flexibility can also be obtained by using perforated foil, wire mesh, or a wrapped tape.

Because shielding is rarely needed, work in this area has been limited primarily to development efforts. The remainder of this section is devoted to a description of some of these development configurations, the methods and problems encountered in fabrication, and the relative effectiveness of the different designs.

B. FCC with Loose Shield Assemblies

Loose preinsulated shield foils can be attached to an unshielded cable at the cable end through use of solder tabs. The foils can be insulated on one or both sides, and can be attached to one or both sides of the FCC. This type shield construction offers several advantages. Studies have shown that a solid foil provides greater shielding effectiveness at critical frequencies than a perforated foil; however, a solid foil laminated to the cable severely limits cable flexibility. The loose construction prevents this loss of flexibility, and consequently is a good choice for an application requiring cable flexing. In addition, the loose construction greatly simplifies the fabrication and stripping procedures. This type shield is used in the FCC bundles which cross the torque-sensitive gimbal system of the Skylab's ATM.

Rather late in the ATM program, it was discovered that there was not enough space to accommodate the required number of conventional round wires and it was further discovered that torque required to bend the round wire cables at the gimbals was too high for the existing servo system. The successful application of FCC for the ATM gimbal system avoided costly redesign, remanufacture, and program delay.

The typical loose shield assembly shown in Figure 35 is fabricated and attached to an unshielded FCC in the following manner. First, a thin copper foil, 0.013 mm (0.5 mil) thick is insulated on one or both sides, using any of various techniques such as lamination or tower coating. If one side of the foil is left bare, no stripping will be needed for attachment of the solder tab. However, to prevent short circuits, the insulation should extend out past the foil edges. If both sides of the foil are to be covered, an insulation must be selected which can be removed easily from the end of the thin copper foil to permit attachment of the solder tab.

The completed shield assembly, with exposed foil end, will need the addition of a solder tab. A copper tab of slightly heavier gauge than the shield foil is soldered to the end of each prepared shield assembly. These tabs provide mechanical reinforcement and minimize the danger of tearing the thin foils. The tab is shaped to fit the end of the FCC and to meet the two outside cable conductors. The cable end is then stripped and a shield-tab assembly is soldered to ground conductors on one side of the cable. The process is repeated for the remaining cable side.

C. FCC with Fixed Shields

Various shielded cable systems can be devised in which the shield is fixed to the full length of the cable. It may be electrically open, attached to the outer conductors, or continuous around the cable edges. The possible cable configurations are numerous, limited only by the imagination of the designer. A few of these shielded cable designs are considered below.

1. Open System. In this system, the edges of the cable are electrically open, with no contact between shield layers. The structure consists of a standard FCC to which are laminated two thin copper shield foils, each insulated on one side only. Figure 36 is an end view of this type cable.

As disclosed by electrical testing, this cable configuration is quite effective for attenuation of electrostatic interference if a solid conductive foil is used as the shield. Other configurations have been tried in which a copper screen shield provided openings to enable the required bond between the adjacent insulation layers. However, the openings may reduce the shielding effectiveness at critical frequencies.

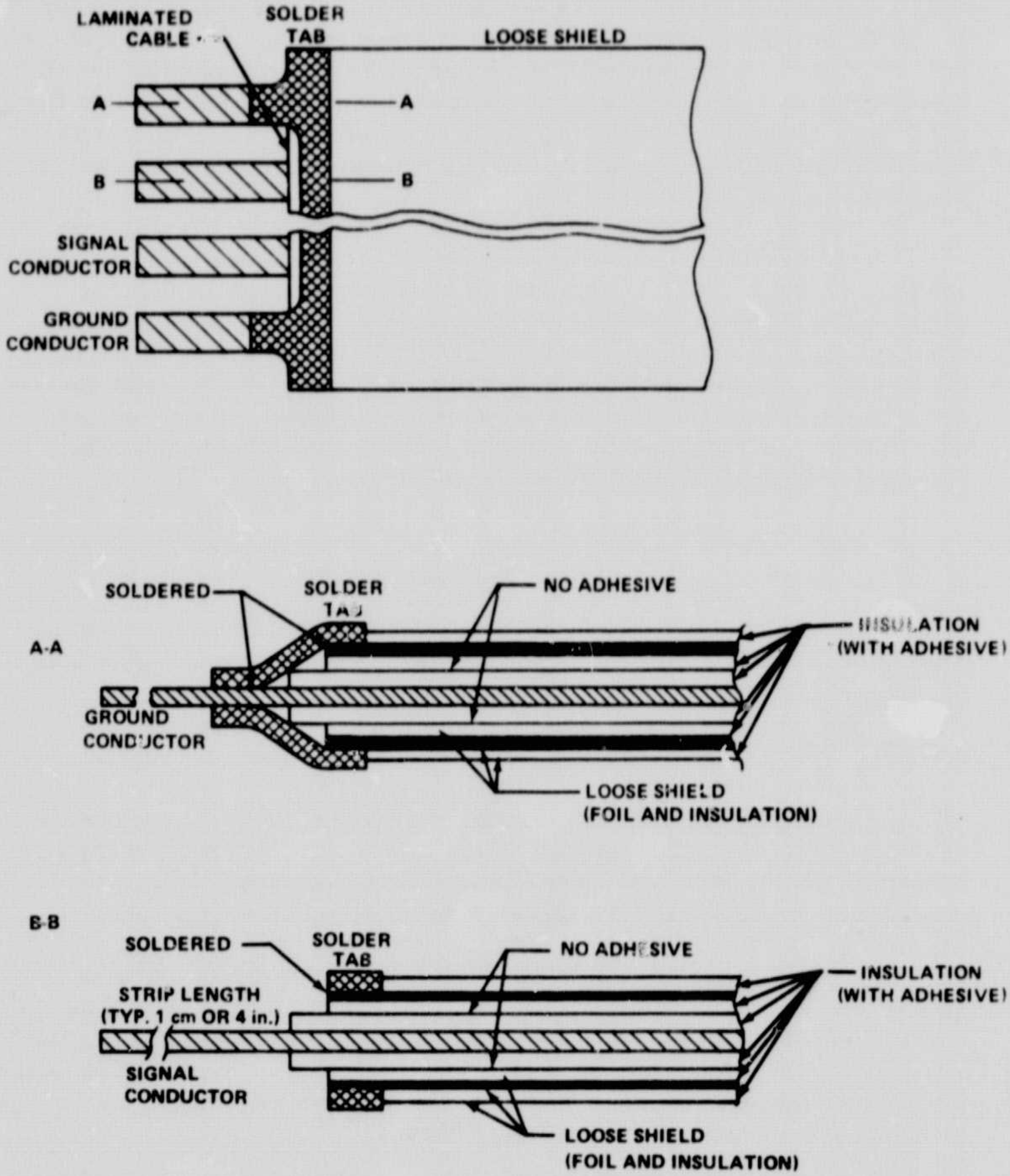


Figure 35. FCC with loose shields.

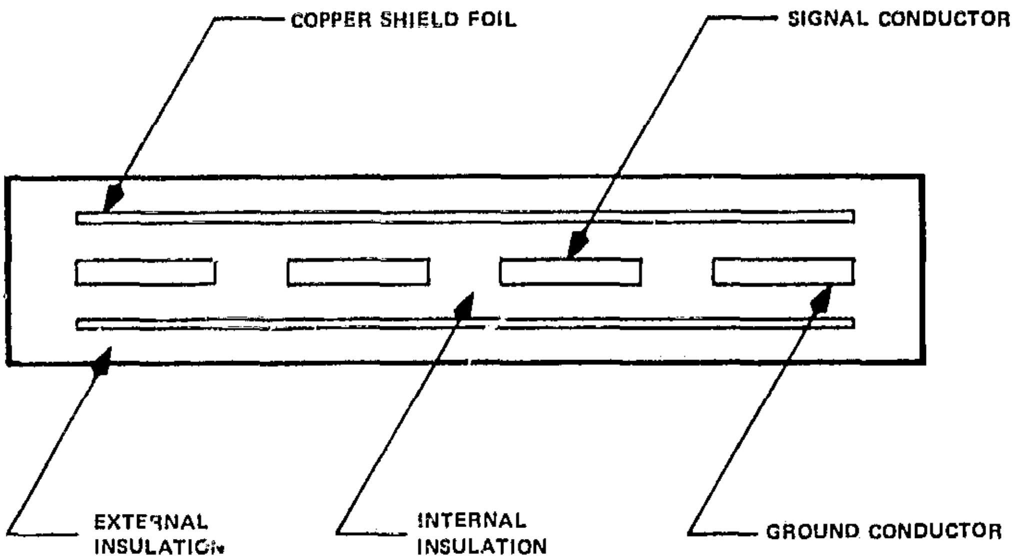


Figure 36. End view of shielded FCC with open shield system.

2. Closed System. Although the loose and open shields described earlier are sufficient for most requirements, a completely closed envelope will provide even better results and is essential for attenuation of low frequency magnetic fields. Various configurations have been designed in which shields are grounded to the edge conductors for the full length of the cable. Others have shields which do not make contact with any conductors, but rather are wrapped or woven around individual wires or the total cable to form a continuous envelope. To provide complete shielding effectiveness for both electrostatic and electromagnetic fields, a combination of high-conductivity and high-permeability materials must be used.

Figures 37 through 42 illustrate cable with shields grounded to edge conductors. In Figures 37, 38, and 39, shields have been laminated to standard unshielded cables. The configurations with the crimped-contact and roll-formed shield contacts would be the most difficult to fabricate on a production basis, and the most difficult to strip for cable termination. The third example would be fabricated essentially by adding two edge conductors to a standard FCC and laminating on a top and bottom foil with outside insulation.

Both Figures 40 and 41 theoretically could be fabricated in one pass through the laminating machine by adding to the standard FCC components either the roll formed shield assemblies with outer cable insulation or the round wires and foils with outer insulation.

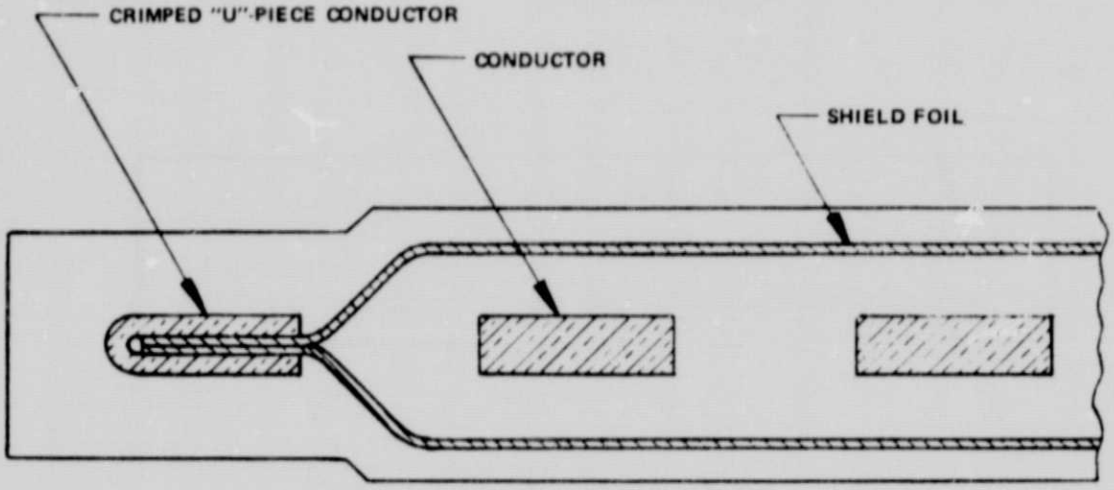


Figure 37. FCC with crimped-contact type shielding.

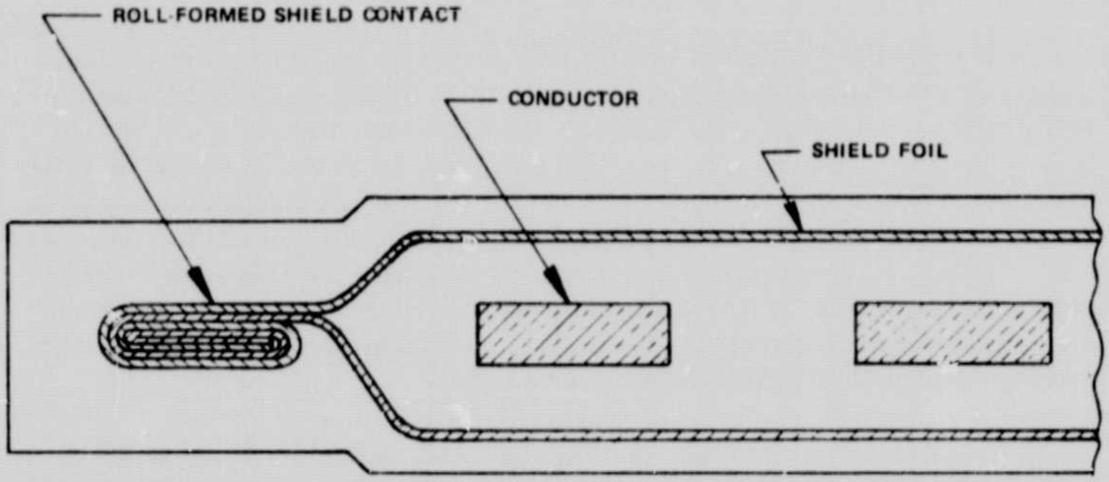


Figure 38. FCC with roll-formed shield contacts.

In Figure 42, a continuous shield has been deposited or spray coated directly on the unshielded FCC outer insulation and to the exposed edges of the outer conductors. A standard nonshielded FCC is trimmed of its margins clear to the edge of the first and last conductors. The trimming actually shaves off a small amount of the ground conductors to make them bare for vacuum of galvanic deposition or spray painting of the shield. After the shield is completed to the desired thickness (about 0.1 mil), application

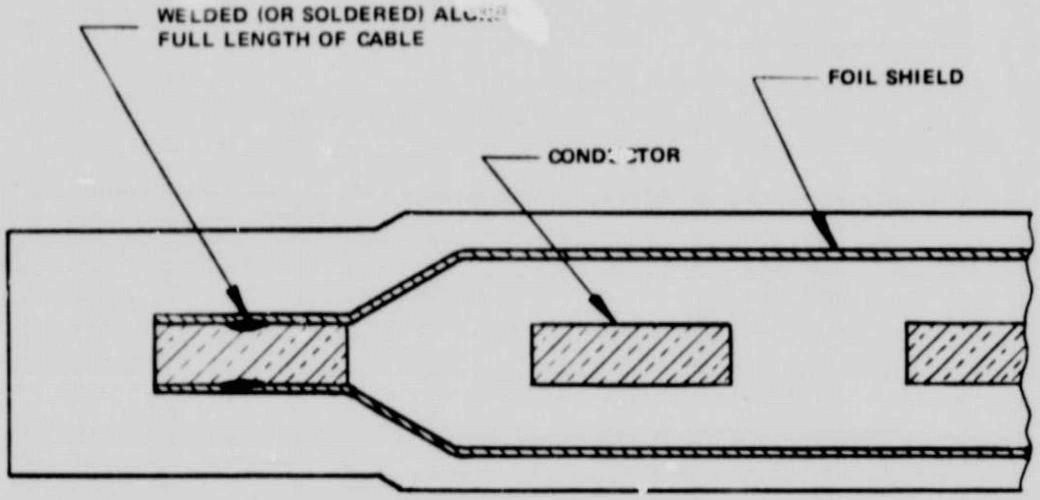


Figure 39. FCC with welded (or soldered) type shield contacts.

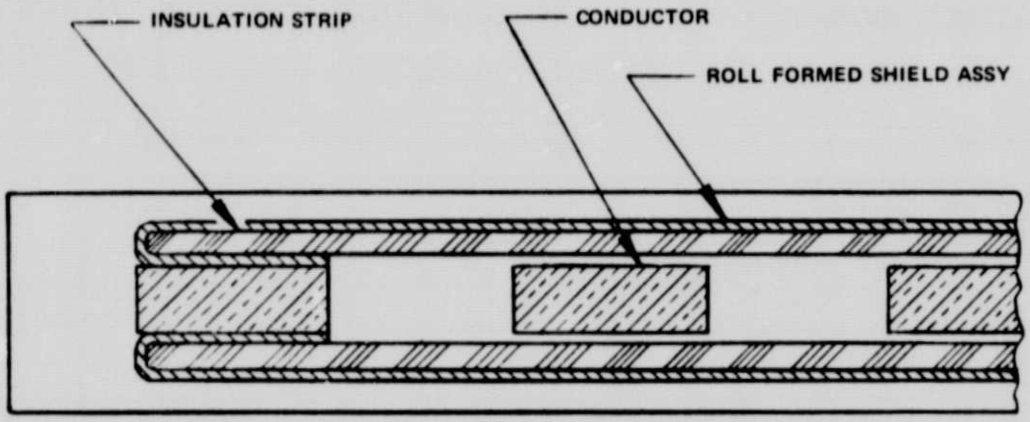


Figure 40. FCC with roll-formed shield assembly.

of the outer insulation layer can follow. The left half of Figure 42 depicts a shielded cable with the outer insulation applied by tower coating. In the right-half, outer insulation layers have been added by lamination. This method is very promising for complete shielding, as various deposition methods would permit use of many thin layers of alternate copper and high-permeability shielding materials. Shielded cable prepared by this technique is highly flexible, since only a very thin layer of plating is required for effective shielding.

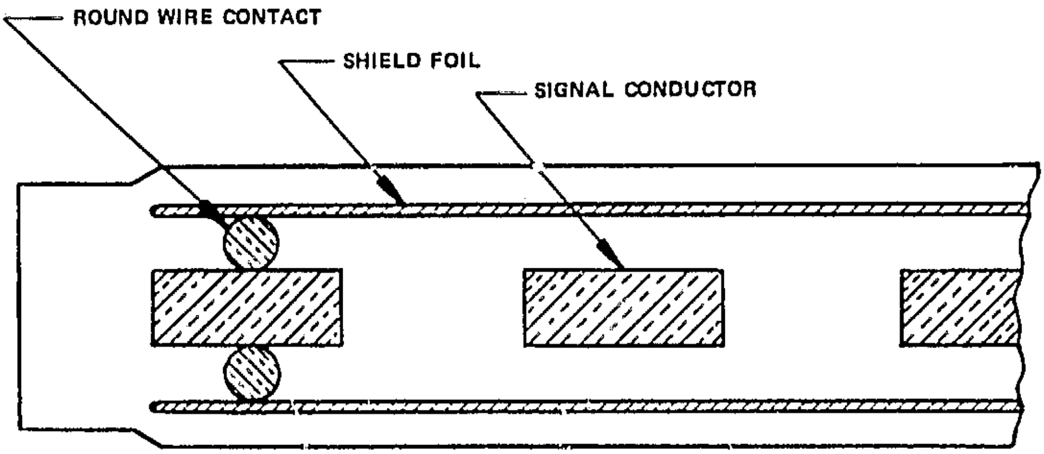


Figure 41. FCC with round-wire type shield contacts.

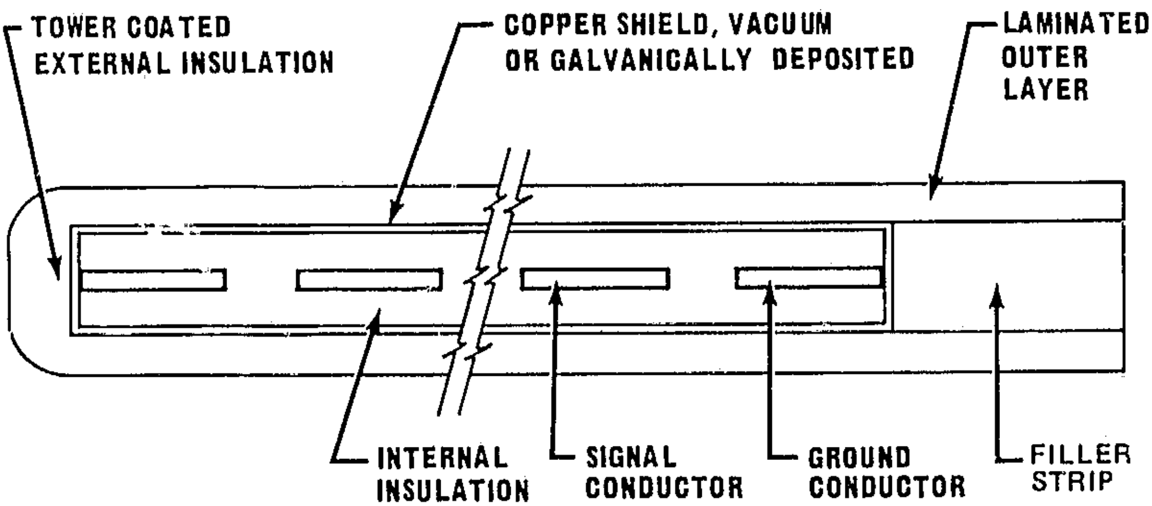


Figure 42. FCC with closed shield system (vacuum or galvanically deposited).

Figures 43, 44, and 45 are examples of continuous shields which are not attached to the ground conductors. Although flexibility is better than that of cables with laminated shield foils, these configurations are not as effective as others which have been considered earlier, because contact is not continuous along the shield envelope. Effectiveness could be improved by welding along the shield edges in a continuous manner.

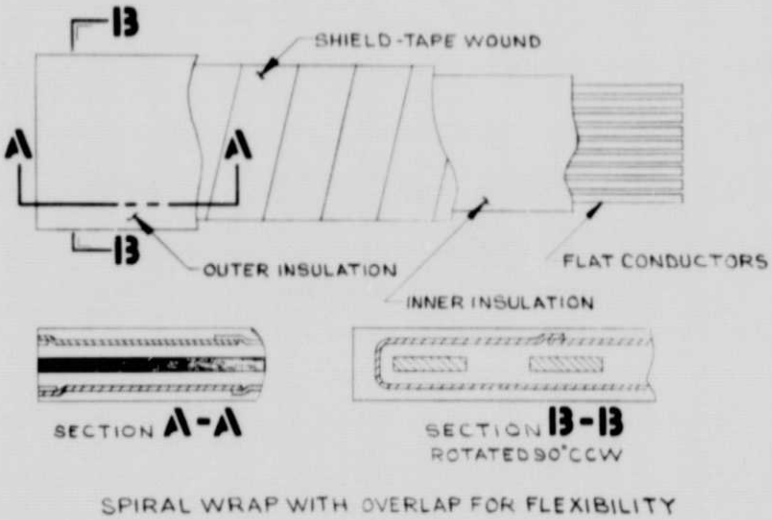


Figure 43. FCC with spirally wrapped continuous shield.

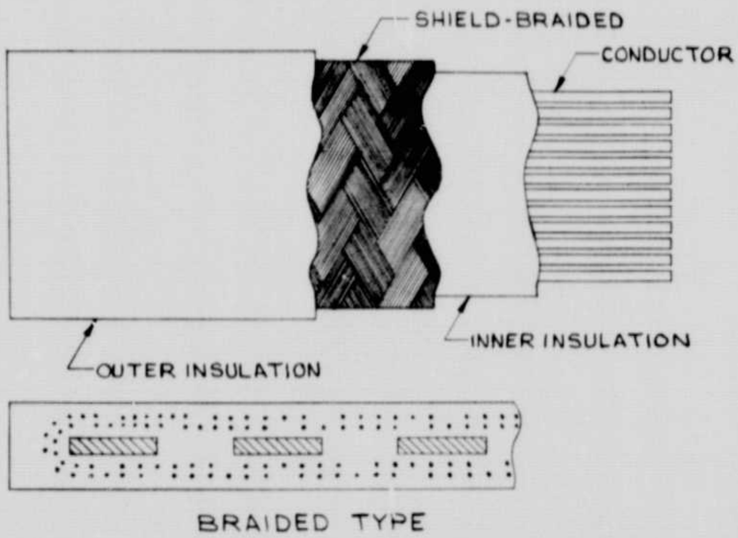


Figure 44. FCC with continuous braided type shield.

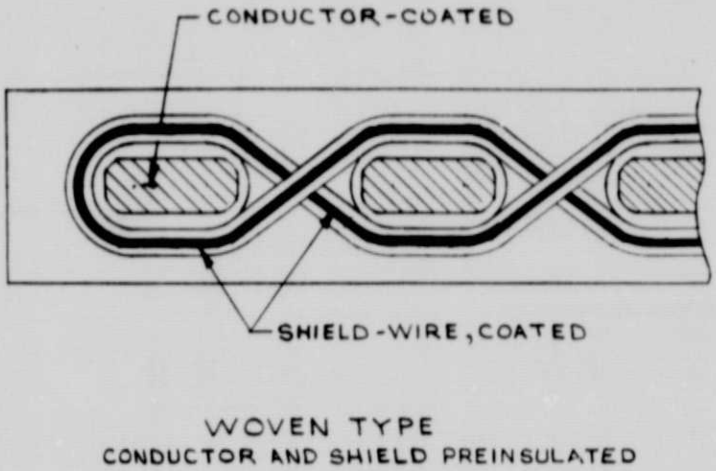


Figure 45. FCC with continuous woven-type shield (conductor and shield preinsulated).

SECTION V. CONCLUSION

Flat conductor cable evolved in response to the stringent requirements of the gigantic rocket and space vehicle programs beginning in the mid-1950's. During the early development phase, the FCC market was almost nonexistent. Since that time, the manufacture and marketing of FCC has grown into a multimillion dollar industry.

Interest in applying FCC is at an all time high, as more and more engineers and designers become acquainted with the potential advantages that FCC systems offer over conventional RWC systems. These advantages include: weight, space, and cost reductions; increased realiability; and uniformity of electrical characteristics.

However, these qualities do not happen magically, but result from careful planning and integration of the electrical interconnection system. In fact, the use of flat cable probably requires more careful planning than does a conventional round-wire interconnection system, but therein lies a major advantage. Since FCC systems cannot be readily altered, the designer is obligated to optimize in the beginning, thus avoiding many pitfalls which seem to characterize conventional round wire systems which are often added as an afterthought.

It is the objective of this document, to assist the FCC designer in his task by providing a general overview of current designs and fabrication methods/equipment along with a critical comparison of the relative advantages and disadvantages of each.

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APPROVAL

THE MANUFACTURE OF FLAT CONDUCTOR CABLE

By W. Angele

The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer.

This document has also been reviewed and approved for technical accuracy.

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