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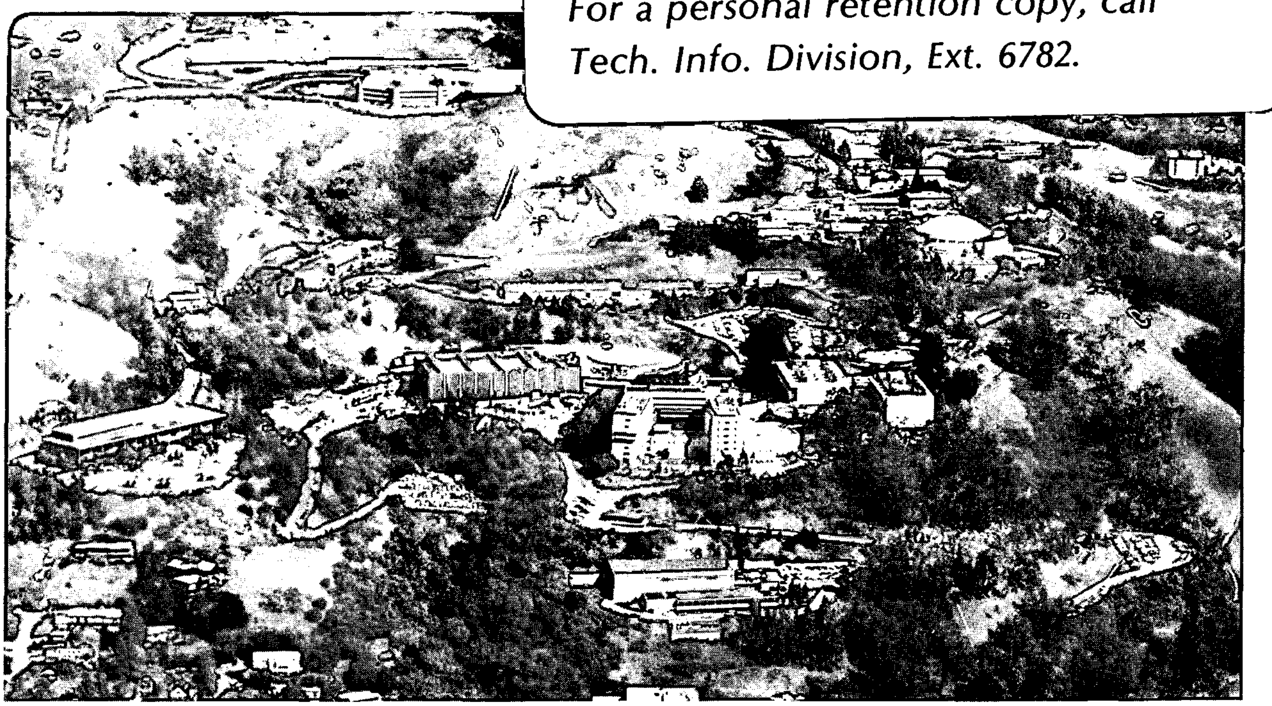

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FABRICATION AND TESTING OF THE FLEXIBLE TRANSMISSION LINE TO THE TFTR NEUTRAL BEAM ION SOURCES

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The four Neutral Beam Injectors (NBI) on the TFTR Tokamak Test Cell (TTC) floor require twelve transmission lines to carry arc and filament power to the twelve ion sources from the basement. Also, the Neutral Beam Test Cell (NBTC) requires three lines but on the same floor through a wall. The same basic specifications apply: (1) center bundle operates at 120 kV with respect to the outer cables, (2) filament circuits at 6000 A, (3) arc circuits at 3000 A, (4) gradient grid, (5) accel grids in a quadrupole configuration, (6) multi wire control cable, (7) SF_6 environment, (7) flexible, (8) 36" centerline bend radius and (9) hi-pot to 200 kV.

Background

The requirements for the transmission lines have been described in a previous paper.[1] A design was selected and a prototype section without the actual connectors and flanges was fabricated, assembled and electrically tested in 1979. In the spring of 1982, LBL was asked to fabricate and test the design on a full-scale mockup, after which production would follow.

Mockup Testing and Results

A mockup (Figs. 1 and 2) was installed, reproducing the conditions between the bottom of the ion source enclosure and through the floor penetration to the lower flange. A cart on rails formed to a curvature of 410" radius duplicated the ± 5° (± 36") travel of the ion source enclosure with the top end of the cable bundle. The floor penetration was offset by the proper 23", and the lower end flange anchored the lower end of the cable as designed. Force gages were used to measure the horizontal forces required to move the swing of the cable bundle.

Test results[2] indicated that the lateral force required to swing the transmission line horizontally was approximately 220 lbs. at 36" with the outer jacket installed (Fig. 3). The surprise was the load (80#) at the neutral position. This was attributed to the compressing and storing of the length of the outer jacket necessary for the end positions but which became excess at the neutral position. The shortening of the length also decreased the internal volume with a resultant rise in pressure (Fig. 4).

Mechanical Design

The assembly and installation of the line proved to be labor intensive and unsatisfactory in that there was no way to check the internal final configuration. A new design was developed to keep the cable bundle centered and without sag inside the jacket, allowed full inspection throughout assembly and was very flexible. The electrical requirements were met.[3,4]

The key element in the redesign is the spacer guide which basically is an electrical standoff as shown in Fig. 5. This is a very large injection molding using a thermoplastic polyester (PBT - Celanex 3300) reinforced with 30% fiberglass with properties as in Table 1. Although acetal (Delrin) would have been better electrically, it proved to be a process problem because of the large size and total material weight. The PBT provided the best combination of properties, fabrication ease and cost. In hi-potting the space guide, the electrical breakdown was in the air at 110 kV; with SF_6 at 240 kV, the limit of the equipment for two hours with a drain of .5 μA. When the latter test was repeated with the parts not cleaned but as received from the molder, the drain increased to 5 μA. The unit cost of the part was $36 each including tooling cost or $10.46 without tooling.

Table 1. Thermoplastic Polyester Resin, 30% Glass Reinforced, Celanex 3300

Underwriters Laboratories Ratings

RATING OR PROPERTY (.120 thickness)	UNITS	3300
Temperature Indicates		
Electrical	°C	130
Mechanical w/Impact	°C	130
Mechanical w/o Impact	°C	140
Arc Resistance	seconds	125
Comparative Tracking Index	volts	500
Hot Wire Ignition	seconds	93
High Amp Arc Ignition	seconds	99
High Voltage Track Rate	in/min	0.5
Flammability @ 1/32" UL94	-	HB
Color Recognition	-	All

Typical Properties

PROPERTY	ASTM METHOD	UNITS	3300
PHYSICAL			
Specific Gravity	D792	-	1.54
Water Absorption			
24 hr. immersion	D570	%	0.07
MECHANICAL, 73°F			
Tensile Strength at Break	D638	psi	19,500
Elongation at Break	D638	%	2
Flexural Modulus	D790	10^6 psi	1.2
Flexural Stress at Break	D790	psi	28,000
Izod Impact Strength			
Notched	D256	ft-lb/in.	1.7
Rockwell Hardness	D785	M Scale	90
Coefficient of Dynamic Friction			
Against Self	D1894	-	0.16
Against Metals	D1894	-	0.12
THERMAL			
Melting Point	Fisher-Johns	°F	442
Heat Deflection Temp.			
@ 66 psi	D648	°F	442
@ 264 psi	D648	°F	403
Flammability			
@1/32"	UL94	-	HB
ELECTRICAL			
Volume Resistivity	D257	ohm-cm	10^{16}
Dielectric Strength			
Short Term @ 0.125"	D149	volts/mil	560
Dielectric Constant			
@ 100 Hz	D150	-	3.7
Dissipation Factor			
@ 100 Hz	D150	-	0.0015

Prior to the final production design, a prototype was fabricated using Lucite in order to check the strength and rigidity of the part as well as the electrical potential holding capability. The part was marginally rigid as originally designed, but we found that critical azimuthal slots could be decreased to half their lengths without compromising the electrical holding properties. This change was sufficient to increase the rigidity to the desired level. In addition to its main job of keeping the critical cable bundle centered within the outer jacket, the spacer guide also carried the outer conductors in slotted holes in its periphery. The slotted holes made possible the snapping in of the cables from the outside instead of threading the cable all the way through from one end of the transmission line to the other. The outer cables were installed in sinusoidal fashion, alternating from one spacer guide to the next (see Fig. 8). This storage of excess lengths made possible the short radius bends which call for great differences between the outer cables and the inner cables.

During the mock-up testing, we found that the central cable bundle changed in cross section from round to elliptical. The taping of the bundle did not stop the change in cross section. To resolve the question as to whether the force would cause any problems with the spacer guide, a test ring of Lucite with an inner diameter the same as the spacer guide was fabricated. The ring was then cut into two halves, then glued together, thus creating weakened joints. Four of these were slipped over the cable bundles and the bundle was then bent to a 36" center radius. The elliptical shape was contained by the ring satisfactorily.

The SF_6 envelope itself was a small development in that there were no commercial equivalents available. Samples of various flexible ducts were tested, but none were leaktight enough to hold 6 psig internal pressures. Rubber hose manufacturers whose products are generally heavy and stiff (1) were not interested in small quantity special items or (2) did not have long enough mandrels. American Rubber Mfg. Co. was interested and developed a lightweight flexible jacket which held 6 psig for more than 195 hours, meeting the requirements very satisfactorily.

This outer jacket was also subjected to a vacuum pumping test, at 5" Hg; the middle of a 8' length went elliptical, 20 1/4" x 27 1/4" from its original 24 3/8" diameter. Vacuum pumping prior to the introduction of SF_6 is not a recommended procedure since the longest lines will be 52' long, and the vacuum loading on the spacer-guides will be severe.

The floor penetration requirements were revised after the initial review to provide radiation shielding and fire barrier between the TTC and the basement where all the utilities and services are located. The floor penetration sub-assembly resolved into 30" of hi-density polyethylene for radiation shielding and 9" of silicone GE RTV 850 for fire protection as shown in Fig. 6. The subassembly was successfully tested by PPPL for 3 hours at 2000°F.[5]

Assembly

The assembly of the line proceeds sequentially at two stations: Station #1 where the center bundle of 58 cables is laid up and assembled and Station #2 where the spacer guides, outer cables and SF_6 jacket are assembled to the center bundle. At Station #1 (see Fig. 7) the cables are laid up according to a predetermined quadrupole pattern to minimize the inductance. The cross section of the cable bundle was found to change from circular to elliptical when bent, and there were suspicions that the quadrupole configuration could be lost if those cables were not restrained. Consequently, the conductors were strapped with thermosetting fiberglass tape in the required grouping of four's and laid in properly as shown in Fig. 10. The entire bundle is strapped with thermosetting fiberglass tape with a single layer of mylar between the tape and the cables to allow some shearing motion between cables in a bend.

At Station #2 the spacer guides are installed with approximately 2" gaps between guides and the outer cables woven in with alternating pitch (Fig. 8) pattern instead of a straight line. The pattern allows for some flexibility in the cables which enables the transfer line to make extremely small radius bends (see Fig. 11). The assembly is then lifted off the workbench and track and crawlers placed underneath. The assembly is lowered onto the crawlers. The full length of SF_6 jackets with tracks (see Fig. 9) is placed in tandem in line with the cable assembly, and the cable assembly is easily towed by hand into the SF_6 jacket. The jacket and cable assembly is then rolled 180° until the tracks and crawlers are at the top and free of the weight of the cable assembly. The tracks and crawlers are then pulled out, and the assembly is then completed for hi-potting.

Electrical Testing

Electrical testing of the assembled transmission line was performed prior to crating for shipment. Each end of the line was fitted with a mating corona shield over the cable terminations, then fitted with a plastic bagging to contain the SF_6 (see Fig. 12). The supply lead from the testing power supply was introduced through the bag at one end to the cable bundle. At the opposite end, a ground lead was brought out to a meter to read the current drain. The line was purged with SF_6 2 times and SF_6 was allowed to flow through for 1 shift to insure high purity. During the testing, the SF_6 was maintained at 4" H_2O pressure. Test curves for the first 3 lines (52' and 42') are shown in Fig. 13. The hi-potting was carried to 175 kV with drain current of 20-43 μA for the 52' and 185 kV and 14 μA for the 42'.[6] The breakdown is usually at the pressure isolation plate which supports the connector assembly where the cables terminate, although the pressure isolation plate had been successfully hi-potted to 214 kV with 2-3 μA drain.

Summary and Acknowledgment

The flexible transmission line has been an unusually challenging engineering development. All requirements have been met or exceeded with lower overall cost than initially estimated. The authors gratefully acknowledge the contributions of the Mechanical Shops and the Liaison Group. We especially appreciate the willing cooperation of Jupiter Engineering in undertaking the injection molding of the spacer-guides and American Rubber Mfg. Co. in developing and fabricating the light-weight flexible jacket. This work was performed under the U.S. Department of Energy Contract DE-AC02-76 CHO 3073 for PPPL and DE-AC03-76-SF0-0098 for LBL.

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[6] Test report. Electrical - LBL unpublished report by E. Fong, 1983.

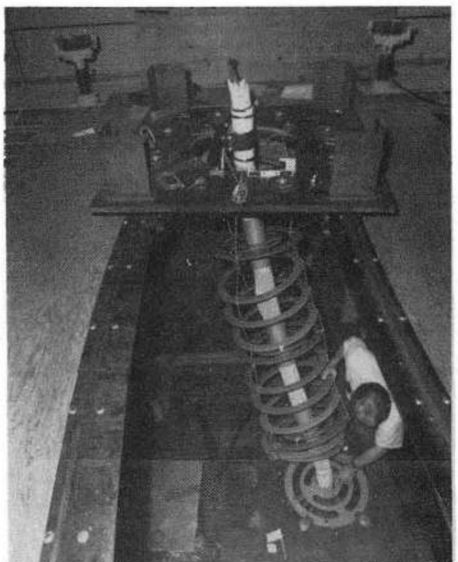

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Fig. 1 Transmission Line, Original Design, in Mock-Up Test Facility. Positioned at -36"

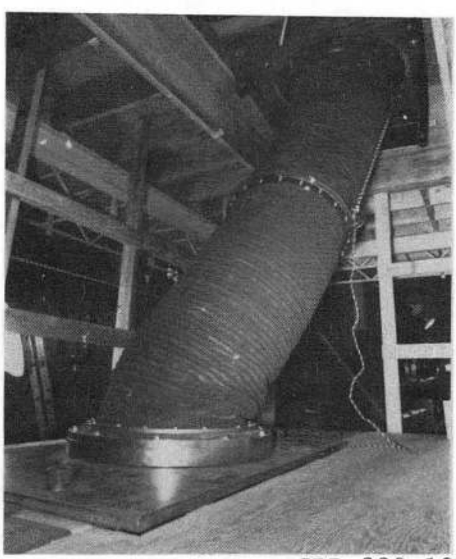

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Fig. 2 Original Outer Jacket in -36" Position. Note Buckling and Loss of Circularity at Lower Flange

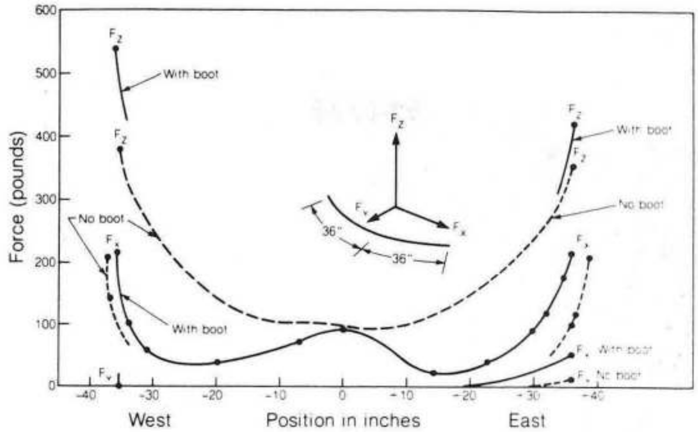

Fig. 3 Transmission Line Mechanical Forces with 3-1/2" Excess Length of Center Cable Bundle and PPPL-Supplied Outer Jacket

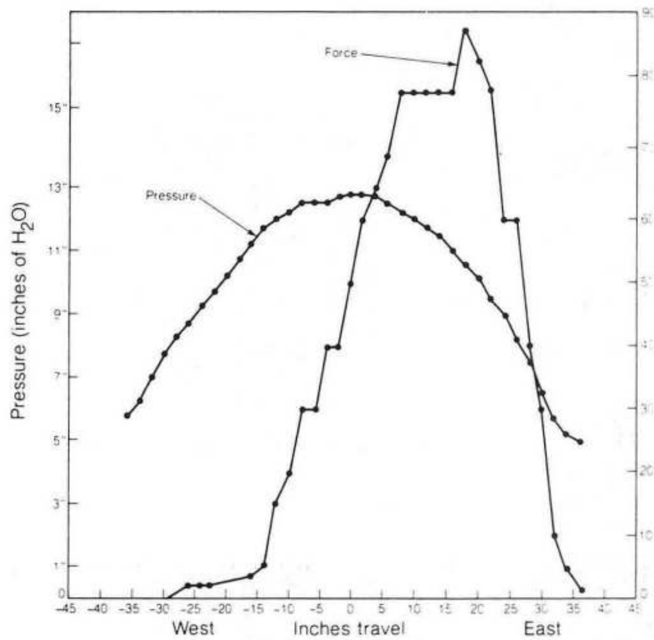

Fig. 4 Outer Jacket Mechanical Forces Pressurized with Nitrogen at 6" H_2 Pressure

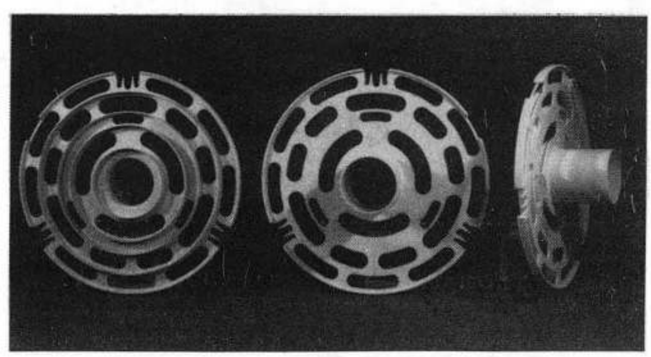

Fig. 5 Spacer Guide CBB 839-8570

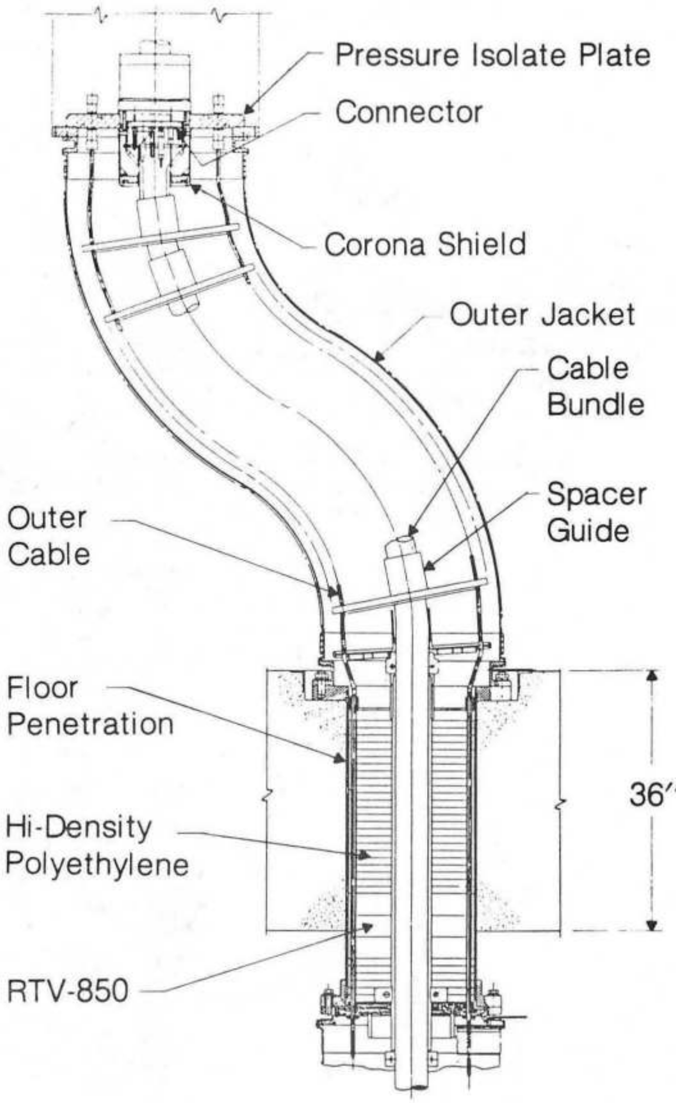

Fig. 6 Transmission Line with Connector and Floor Penetration Assembly

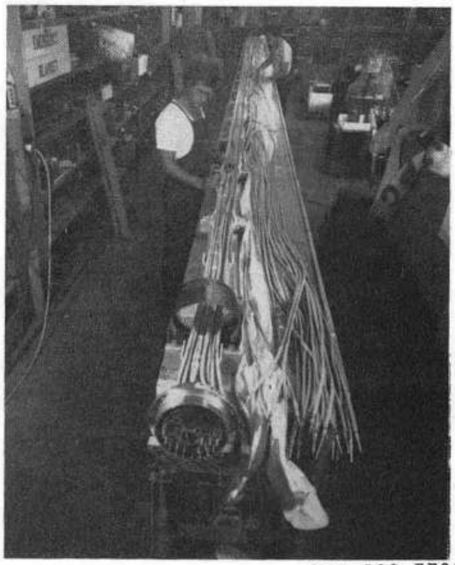

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Fig. 7 Station 1, Assembly of Center Cable Bundle

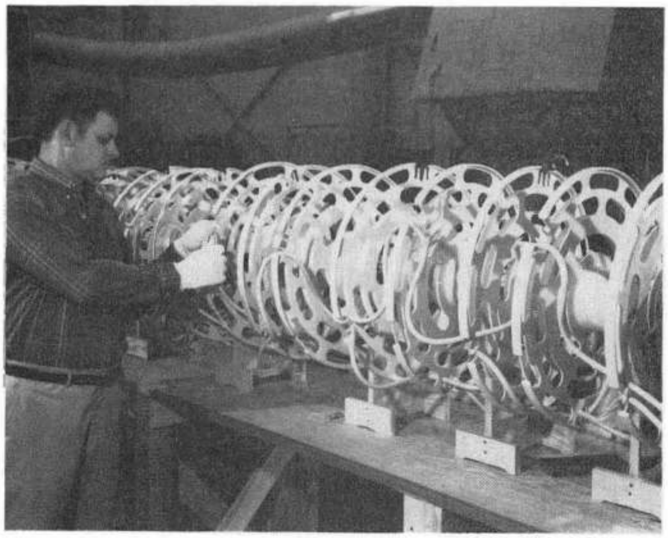

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Fig. 8 Station 2, Assembly of Spacer Guides, Outer Conducters and Outer Jacket

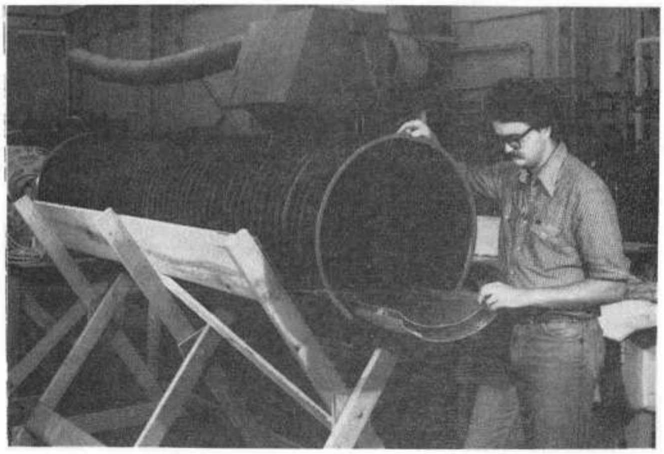

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Fig. 9 Station 2, Assembly of Cable Assembly into Outer Jacket. Track and Cable Assembly Carrier in Place

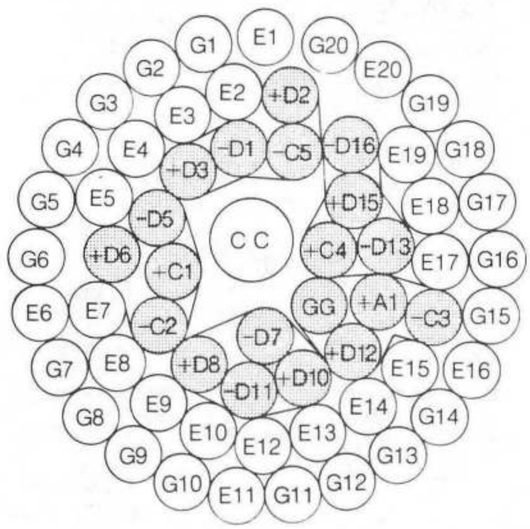

Fig. 10 Center Cable Bundle Layout with Quadrupole Grouping

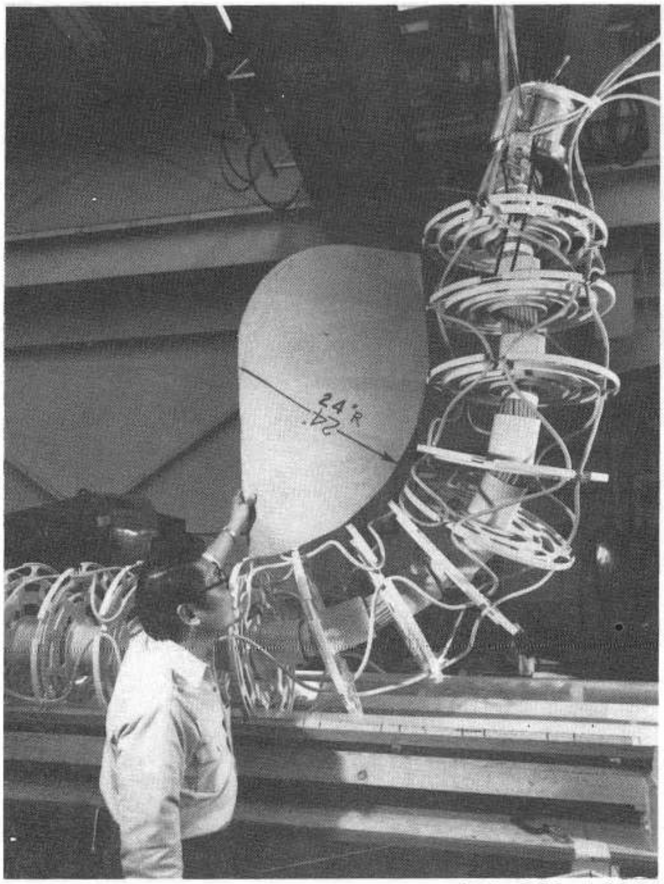

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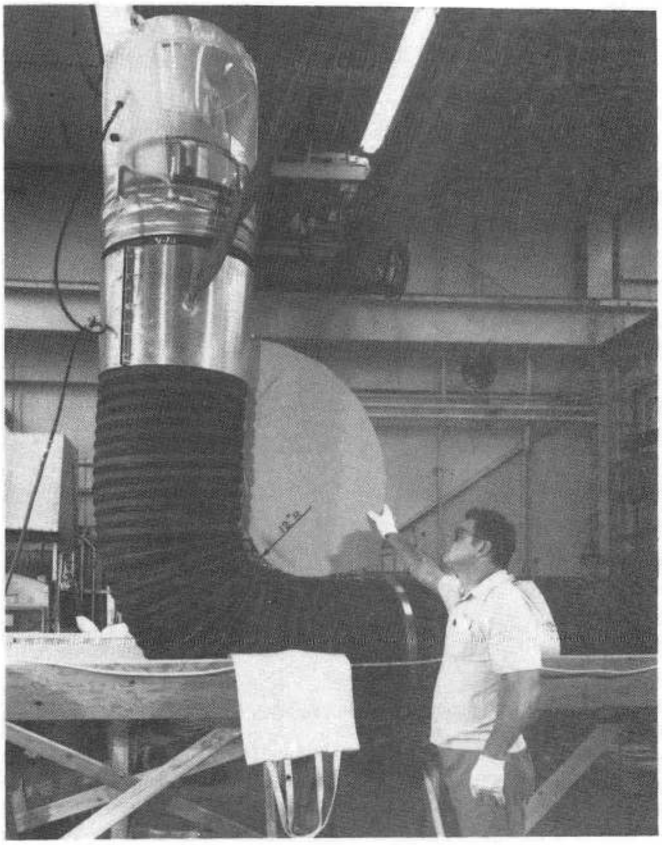
Fig. 11 Cable Assembly in 90° Bend, Outer Jacket Removed



CBB 839-8578

Fig. 12 Completed Transmission Line with Temporary End Closure for SF_6 for Electrical Testing

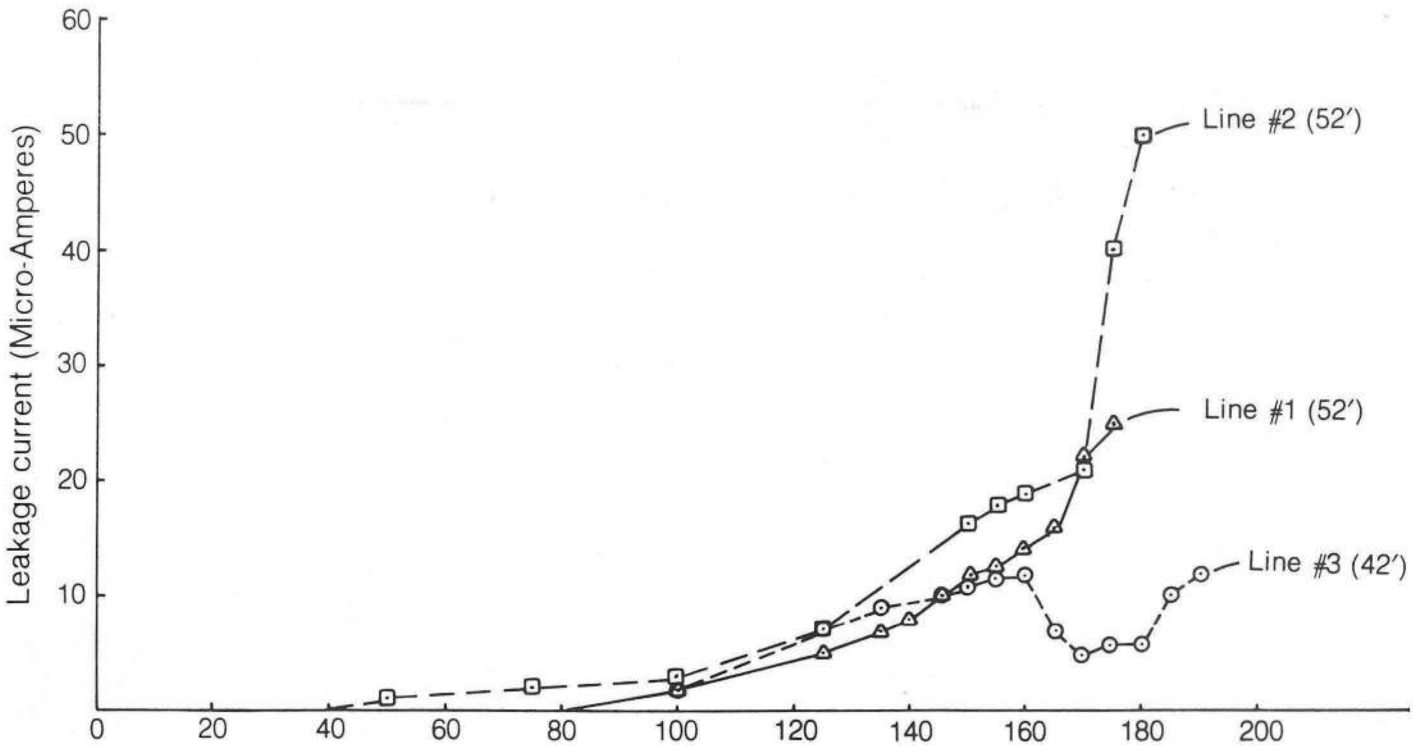


Fig. 13 Hi-Pot Testing of NBTC Lines (3)

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