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THE BELL SYSTEM TECHNICAL JOURNAL
Vol. 56, No. 10, December 1977
Printed in U.S.A.

WT4 Millimeter Waveguide System:

Waveguide Design and Fabrication

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(Manuscript received April 7, 1977)

The WT4 transmission line is a 60 mm diameter string of circular waveguide sections composed of 9 m long dielectric-lined and 4.4 m long helix waveguide sections, with dielectric-lined waveguide comprising approximately 99 percent of the transmission line. The dielectric-lined waveguide is manufactured from steel tubing whose geometric distortions are controlled on a power spectral density basis. The steel tubing is processed into waveguide by the application of copper and dielectric layers along its inner bore and by the attachment of flanges at its ends. The materials system and processes were chosen for extremely low ohmic losses, minimum geometric distortions, and high long-term reliability. The helix waveguide is formed from a closely spaced array of helically wound wires cast into an epoxy system, which is in turn enclosed in a steel jacket. The key design features of this helix waveguide are (i) the specially prepared iron-loaded epoxy which provides ohmic dissipation to spurious mode energy and (ii) the precision temperature control applied to the curing of the epoxy to assure minimum geometry distortion.

I. INTRODUCTION

The waveguide medium is composed of a string of 60 mm internal diameter, 9 m long, flanged dielectric-lined and 4.4 m long helix waveguide sections. Dielectric-lined waveguide consists of a copper-plated steel tube, the inner surface of which is lined with a thin dielectric layer. Helix waveguide consists of a steel tube encompassing an insulated copper wire which is helically wound and is cast within the steel tubing with an epoxy. Dielectric-lined waveguide was selected to be the principal transmission medium, comprising approximately 99 percent of the total waveguide length. The remainder of the transmission medium consists of helix waveguide sections deployed at 800 m intervals.

In this paper the factors leading to the choice of dielectric-lined waveguide as the principal waveguide medium will be reviewed. In addition, the designs and fabrication techniques associated with each type of waveguide will be discussed.

II. CHOICE OF DIELECTRIC-LINED WAVEGUIDE AS THE PRINCIPAL TRANSMISSION MEDIUM

Multiwavelength diameter TE_{01} circular waveguide has two classes of loss.[1,2] The first is that which would exist for a pure TE_{01} wave guided by a perfect right circular cylinder having a wall surface with finite dissipation. The second is due to the scattering of TE_{01} energy into other modes as a result of geometric imperfections in the waveguide surface. This second component can be calculated from the normal mode propagation constants, coupling coefficients, and the geometry of the waveguide.[3] Practically speaking, the type of geometric distortion that contributes the largest amount of loss is curvature of the waveguide axis.[4]

Waveguide curvature affects propagation differently in dielectric waveguide than in helix waveguide. For example, a waveguide route bend is typically constructed to have linearly varying curvature profiles at the input and output sections of the bend and a constant radius of curvature in the central section. For such a bend, it can be shown[5] that the increase in loss relative to a straight waveguide is given by a summation of terms; each of these terms is proportional to the absolute magnitude of the difference in attenuation coefficients between the TE_{01} mode and one of the spurious modes to which the TE_{01} mode is coupled when the waveguide axis is curved. Dielectric-lined waveguide is characterized by low differential attenuation constants; helix waveguide, by high differential constants. Hence, dielectric-lined waveguide has lower route bend losses than helix waveguide.

Another example which demonstrates the more tolerant behavior of dielectric-lined waveguide to curvature is that associated with unintentional curvature introduced in waveguide manufacture and installation. Although first-order average curvature losses are related to the power spectral density (PSD) of the curvature for both types of waveguide, the relationship is different for each type. In the case of dielectric-lined waveguide there is only a limited band of mechanical frequencies which gives rise to first-order mode conversion losses.[6,7] This band is from ⅓ to 1 ½ cycle/meter (c/m) for 60-mm waveguide as illustrated in Fig. 1. Helix waveguide, however, responds to a much larger mechanical frequency band,[8] including the high magnitude of the low-frequency curvature associated with installation.[9,10] The processes de-

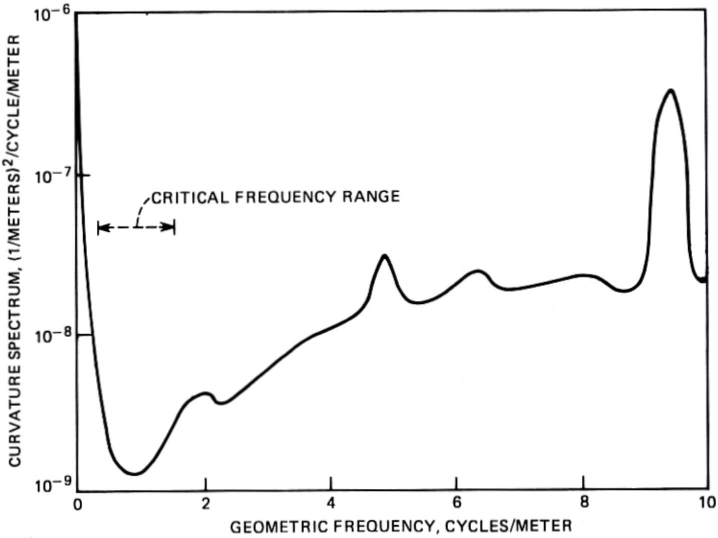


Fig. 1—Curvature spectrum of installed 60-mm waveguide.

veloped for the manufacture and installation of waveguide resulted in curvature PSDs which were lower in the ⅓ to 1 ½ c/m range than in the balance of the band. Thus, to minimize curvature losses, dielectric-lined waveguide was selected for the majority of the medium.

At the outset of the project, these advantages were recognized. However, it was also recognized that some helix waveguide would have to be deployed in order to limit the amount of reconverted spurious-mode energy and its attendant transmission distortion. Initially a 90%/10% mixture of dielectric-lined/helix waveguide was believed to be reasonable. However, improvements in the curvature of installed waveguide reduced spurious mode levels, permitting the use of less helix. The ratio was changed to 99%/1%.

The choice of waveguide system described above led to a decision to concentrate heavy effort on achieving a dielectric waveguide design which had an extremely low curvature spectrum over the limited mechanical frequency band. The helix design concentrated on the efficient absorption of the spurious modes rather than on achieving ultra-low TE_{01} helix loss.

III. DIELECTRIC-LINED WAVEGUIDE

3.1 General Considerations

The configuration of dielectric-lined waveguide is shown in Fig. 2. The principal structural element consists of a 60-mm internal diameter steel

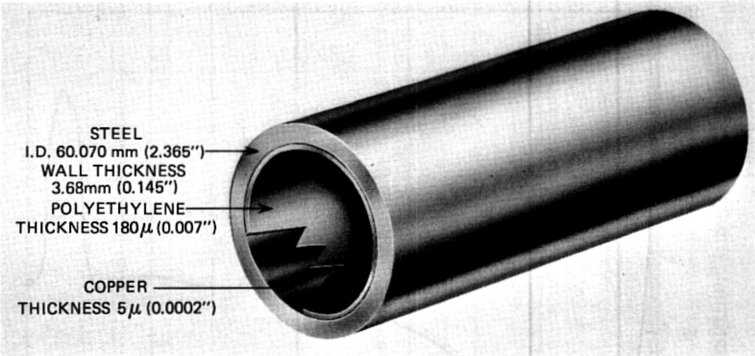


Fig. 2—Dielectric-lined waveguide configurations.

tube. The inner surface of the steel tube is plated with copper to which a thin layer of polyethylene is subsequently bonded.

This particular design was intended to provide an approximate balance of the heat and mode conversion components of loss over the 40 to 110 GHz frequency band, as shown in Fig. 3. (The loss at high and low ends of the bands are not made exactly equal since system balance requires lower transmission line loss at the high end of the band in view of the poorer solid state device performance at high frequencies.) In addition, the design had to be compatible with manufacturing technology, reliability objectives, and the installation techniques which were being developed in parallel with the waveguide. Finally, the overall program had to be carried out economically so waveguide costs would compare favorably to other technologies in new high-capacity routes.

The steel tube shown in Fig. 2 was chosen for waveguide manufacture. Other materials such as copper and aluminum were ruled out on the basis of technical performance and economics. It was found that steel tubing could be made to have extremely low power spectral densities over the critical mechanical frequency regions, not only for curvature, but also for diameter, ellipticity, and other forms of geometric distortion. It also provided rigidity and strength, making the waveguide medium difficult to damage. It lent itself to plating techniques and is dimensionally stable. Finally the use of steel was completely compatible with welding techniques, thereby permitting the use of welded flanges to facilitate the joining of contiguous waveguide sections.

The use of copper as a conducting surface over the steel substrate was based primarily on achieving low ohmic loss, while at the same time achieving a high degree of reliability. The two metallic elements with the highest conductivity are silver and copper, with copper having a conductivity of 0.97 that of silver. Offsetting this slight advantage of silver is the fact that silver is more vulnerable to sulfide attack from the

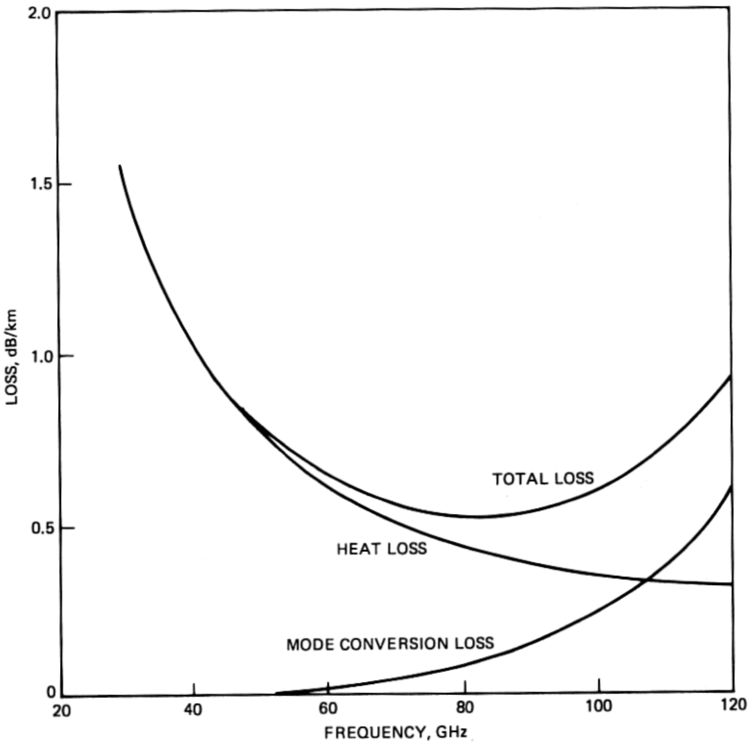


Fig. 3—Waveguide loss components.

atmosphere than copper. Thus the possibility of attack during manufacture and storage prior to installation weighed heavily against choosing silver. Finally, copper could be directly deposited in a dense, high-purity layer on the steel surface by electrolytic means.

The purpose of the dielectric liner is to break the degeneracy between the TE_{01} and curvature coupled TM_{11} modes. In idealized waveguide having infinitely conducting metallic walls, both the TE_{01} and TM_{11} modes have identical propagation constants. In waveguides with metallic walls having finite conductivity, the attenuation portions of the propagation constant for the two modes are different, but the phase portions of the propagation constants are almost equal. This situation makes simple copper-walled waveguide intolerant to bends. Low-loss propagation in bends can be achieved if the phase constants of the TE_{01} and TM_{11} modes are significantly different. One method of achieving the desired separation of the phase constants of these two modes is by application of a dielectric liner to the conducting wall. This liner has a pronounced effect on the propagation constant of the TM_{11} mode and a much lesser effect on the propagation constant of the TE_{01} mode.[11,12,13]

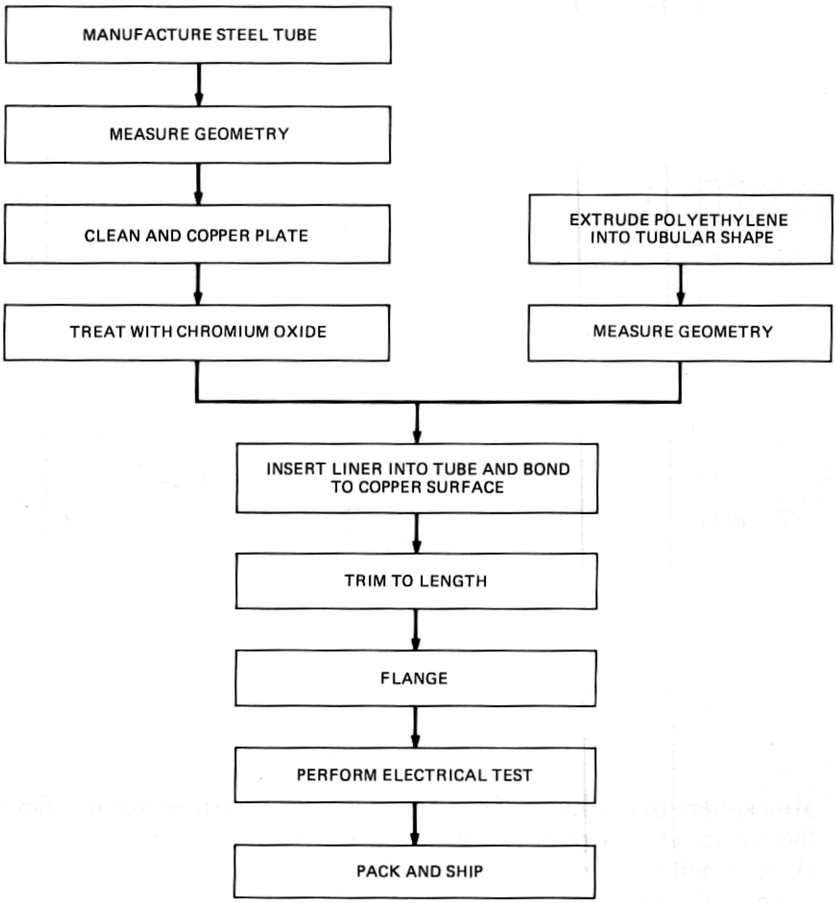


Fig. 4—Manufacturing process for dielectric-lined waveguide.

The choice of polyethylene for the dielectric liner was made for a variety of reasons. First, when free of all additives except antioxidants, polyethylene has an extremely low loss tangent over the 40 to 110 GHz band. Second, the particular polyethylene composition used in waveguide is one that had been used for many years in Bell System submarine cable applications; the submarine cable experience had shown that this particular composition was extremely stable chemically, even when bonded to copper for long periods of time. Third, polyethylene liner material could be made into prefabricated thin-walled tubing using modified commercially available extrusion techniques.

The foregoing discussion has reviewed, in general terms, the choice of waveguide configuration for dielectric-lined waveguide. In the paragraphs that follow, attention will be focused on specific elements of the

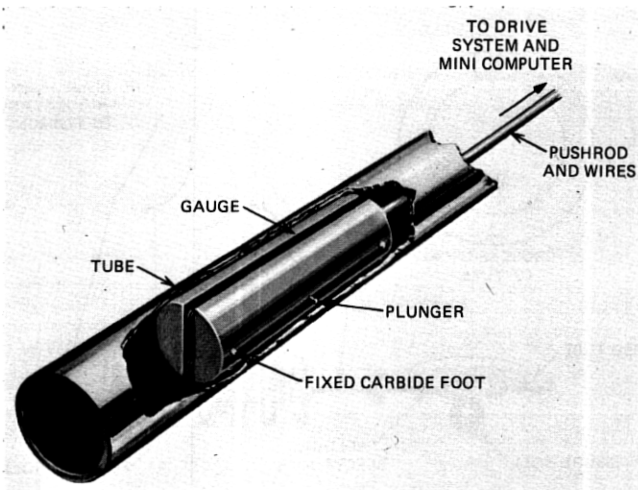


Fig. 5—Mouse.

dielectric waveguide design. To facilitate this discussion, reference is made to Fig. 4, which depicts the manufacturing process. Each of the key elements of the process will be reviewed along with performance data achieved for each of the processes.

3.2 Steel tubing

A number of commercially available steel tubing processes were analyzed to determine their suitability for waveguide. This evaluation consisted of having 2 inch or 51 mm diameter steel tubes fabricated at commercial facilities under scrutiny of Bell System engineering personnel, and measuring the resultant internal curvature and diameter with a gauge called a mouse (Fig. 5).[14] The output of the mouse was converted into curvature and diameter PSDs.

In this exploratory phase, it was soon recognized that each particular process had its own characteristic signature. It was also noticed that various periodicities revealed by the PSD plots could be related to periodic anomalies introduced by different components of the machinery that manufactured the steel tubes.

Of several commercial steel tube manufacturing methods investigated, one had significantly lower curvature PSD in the critical $\frac{1}{3}$ to $1\frac{1}{2}$ c/m range. This method, illustrated in Fig. 6, is the drawn-over-mandrel process (DOM). Flat steel strip is formed into a cylinder and welded longitudinally to form a tube. After a full anneal, the tubes are cold-drawn over a mandrel. They are then roller-straightened twice. Except for the double straightening, this is a standard commercial process.[15]

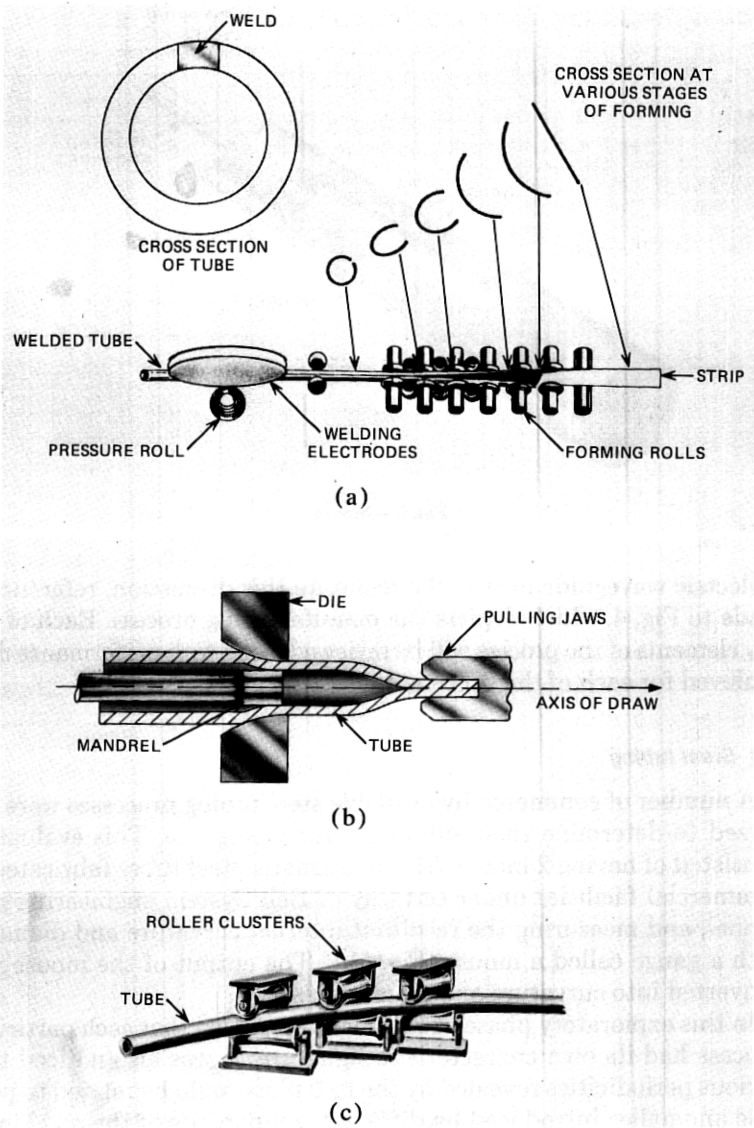


Fig. 6—Manufacturing process for steel tube. (a) Tube forming and welding. (b) Cold drawing. (c) Roller straightening.

To make waveguide-quality tubing, equipment tolerances were tightened and operating parameters were carefully controlled.

The types of tubing material that were considered were rimmed and aluminum-killed low carbon steel. Aluminum-killed was selected instead of rimmed to avoid impurity blow-out problems that could have occurred in the high-vacuum electron beam welding of the flanges to the tubes. (Flanging will be discussed later.) Steel having a 0.1 percent carbon content (1010 steel) was selected because it could be easily formed and cold drawn, would maintain long-term dimensional stability, was readily plateable, and is relatively free of martensite formation during the flange welding operation. Experiments on the drawing operation focused on the sensitivity of tube geometry to changes in operating conditions. A 3-milliradian misalignment of the draw and die axes produced tubes with long curvature bows of 200-meter radius. The tubes also had slightly higher curvature PSD in the 0 to 10 c/m range than tubes with aligned axes. No effect on curvature was seen when the axes were offset up to 3 mm. Tubes that were drawn on chain benches loaded to greater than 80 percent of drawing capacity had curvature spikes corresponding to the length of the chain links. These geometric distortions were controlled by carefully aligning a bench with sufficient drawing capacity. In addition, the maintenance of tight tolerances in the draw bench tooling is essential to achieving a round tube with the proper final diameter.

The final processing step for steel tubing is the straightening operation. Simply stated, the machine operates by imparting both longitudinal and rotary motion to the tube, with the center roll cluster offset from the imaginary straight line path extending between the end roll clusters. In this manner a beam bending action is provided. The degree of center roll cluster displacement relative to the end rolls is such that a straight section of tubing passing through the machine is deformed elastically and hence remains straight, while a curved section is bent beyond its elastic limit and springs back to a straight configuration after passing through the machine.

Roller straightener configurations other than the six roll cluster, which is shown in Fig. 6, were studied. The six roll cluster was found to be most desirable because the tube was supported on opposing sides at each cluster. The squeezing action of the opposing rolls substantially reduced the ellipticity of the drawn tubes.

The double roller straightening was primarily responsible for the low curvature PSD in the mechanical frequency range of ⅓ to 1 ½ c/m. However, due to high stresses at the contact area, a helical deformation at 9 c/m was introduced. Engineers at Western Electric Engineering Research Center designed contoured rolls that increased the roll-tube contact area, thus reducing the contact stresses and the resultant PSD spike at 9 c/m. Further reductions in the level of the spike were achieved by altering the temper of the tube by eliminating the prestraightening anneal and by improving drawn straightness and roundness. The curvature PSD of the tubes, both before and after straightening, is shown in Fig. 7.

Steel tubing development started with the objective of producing

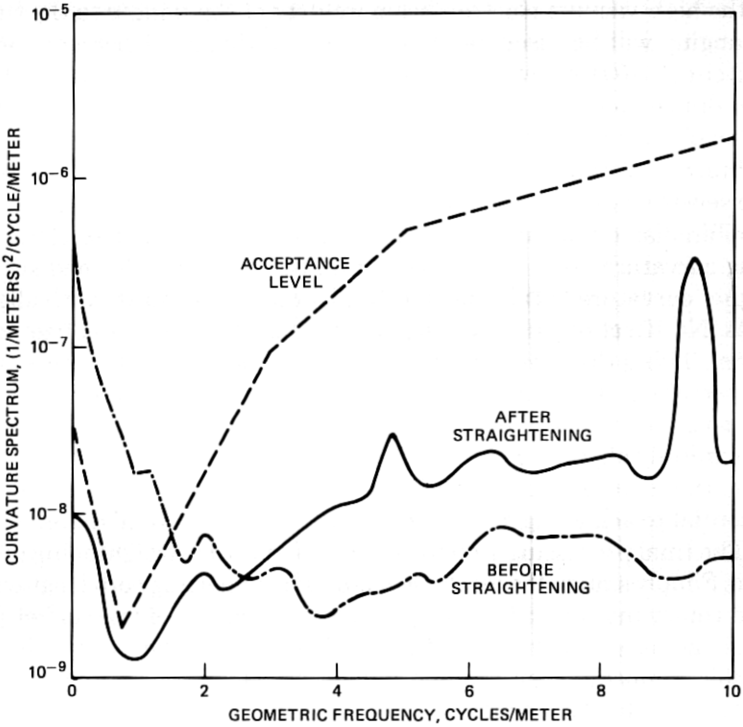


Fig. 7—Steel tubing curvature.

51-mm internal diameter tubes that were 5 meters long. For 51-mm tubing, the critical mechanical frequency band associated with curvature was from ½ to 2 c/m. It was found that curvature could readily be controlled not only in this band, but even at lower mechanical frequencies corresponding to ⅓ c/m. Indeed with the low curvatures that were being obtained, it was found that most of the losses were ohmic, not mode conversion, and that the repeater spacing was limited by waveguide ohmic losses at the lower frequencies. By increasing the inner diameter to 60 mm, these ohmic losses were reduced. Since the 60 mm tubes still had low curvature PSD levels in the now critical ⅓ to 1 ½ c/m range, the losses were brought into balance resulting ultimately in a repeater spacing of 50–60 km for the commercial 38–104.5 GHz system instead of the initial objective of 33 km.[16] Experiments showed that the tubing length could be increased to 9 meters—the maximum length that could then be processed—without sacrificing quality. This resulted in fewer joints and reduced construction costs. Thus 60-mm, 9-meter-long dielectric tubes were used in the field evaluation test. Subsequent experiments have demonstrated that 10 ½-meter-long tubes can be produced without loss of quality.

The tube-forming operation leave residual stresses in the tubes in both the circumferential and longitudinal directions. Experiments indicated that the stress relief expected over the lifetime of the tube would result in negligible distortions.

The steel tubes used in the field evaluation test were manufactured by Babcock & Wilcox Co., Alliance, Ohio, in cooperation with Bell System personnel. All tubes produced were inspected at the mill by Western Electric engineers. The inspection consisted of "mouse" measurements of curvature and diameter. An on-line computer was used to compute the curvature PSD. The acceptance rate was 70 percent.

After copper plating, samples of the tubes were measured with the rotary-head mouse for more detailed analyses of geometry.[17,18] A summary of the geometry spectra of the principal components of distortion achieved for the final 60-mm waveguide used in the field evaluation test is shown in Fig. 8. In this figure the different circular harmonic components of geometric distortion are presented in terms of power spectral density functions. It can be seen, that the zero foil (Fig. 8a) objective is easily met with a large margin. On the other hand, the other distortion components (Fig. 8b, c, d) exceed the objective at certain mechanical frequencies. Allowances for these higher spectral responses have been made in the administration of the overall loss budget and geometry specifications for the steel tube.

3.3 Copper plating

Copper plating was required to deposit a highly conductive layer on the inner surface of the steel tube. The objectives in the plating development were to: (*i*) achieve the highest possible conductivity, (*ii*) provide a uniform layer of copper, and (*iii*) present a reliable bond to the steel substrate and be receptive to the polyethylene layer.

At the outset of the program, various methods for plating were considered. These included electroless plating, the use of a nickel layer followed by an electrolytically deposited acid copper layer, etc. The results of scanning electron microscope studies, coupled with the desirability of achieving the plating with a single electrolyte, favored the use of the alkaline copper cyanide electrolytic chemistry applied with the setup shown in Fig. 9. This particular system yielded a copper plating performance that exceeded our original objectives. It has been found that the ratio of measured loss to theoretical loss for this plating is given by the following empirical equation:[19]

$$\frac{\alpha_{\text{meas}}}{\alpha_{\text{theory}}} = 1 + 0.2\left(\frac{f}{100}\right)^{1.5}$$

where f is the electrical frequency in GHz. It is emphasized that the above

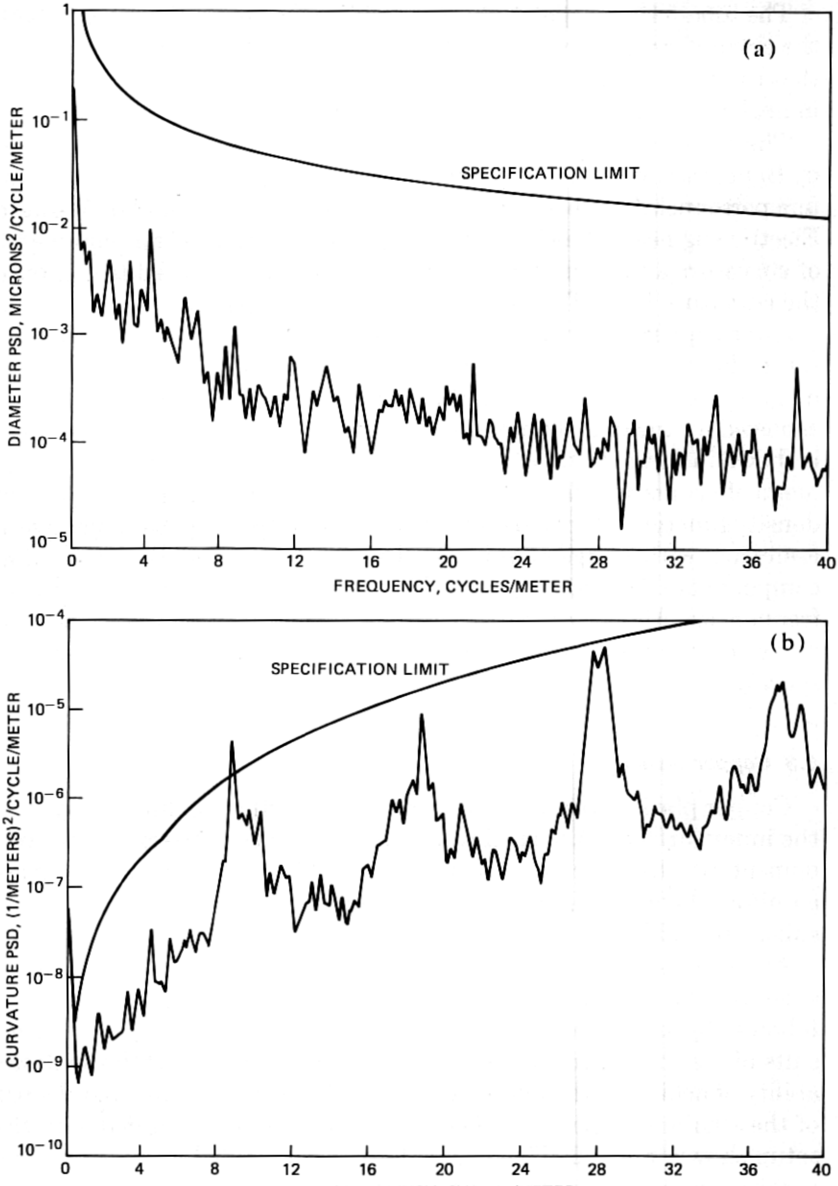
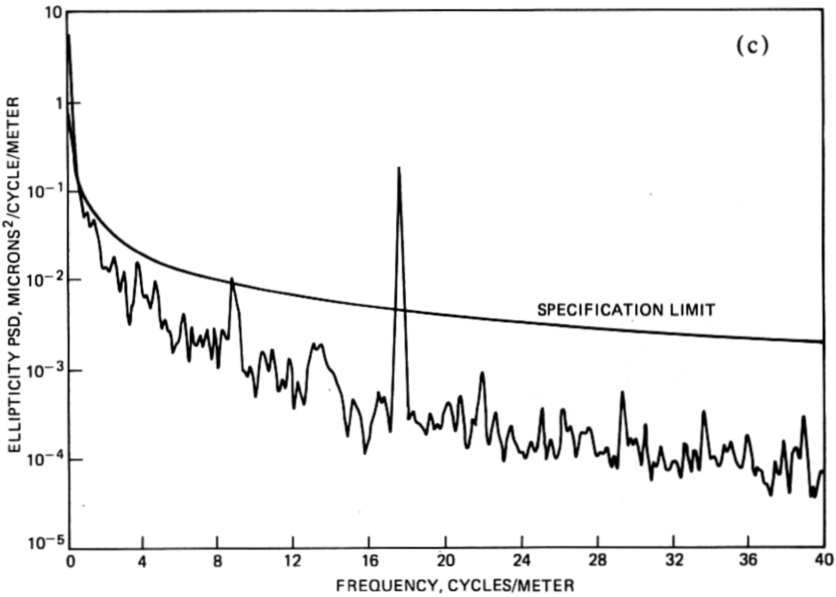
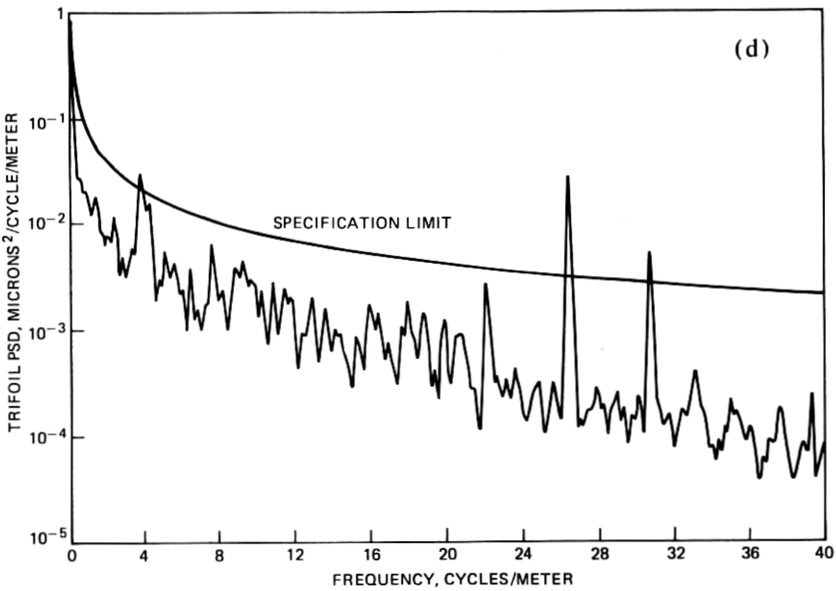


Fig. 8—Measured geometry spectra of dielectric-lined waveguide: (a) diameter, (b) curvature, and on opposite page (c) ellipticity, (d) trifoil.

equation translates to a loss that is only 6 percent higher than theoretical at 40 GHz. Further, this loss was achieved on a production basis, and has been found to be completely stable over a three-year testing period.





In addition to achieving high conductivity, the peculiar needs of the waveguide system led to the selection of additional plating requirements. Copper, even at the lowest frequency used in the system (40 GHz), has a skin depth of approximately ⅓ micron. Since only about 5 skin depths are needed to support propagation inside the waveguide, 2 microns of

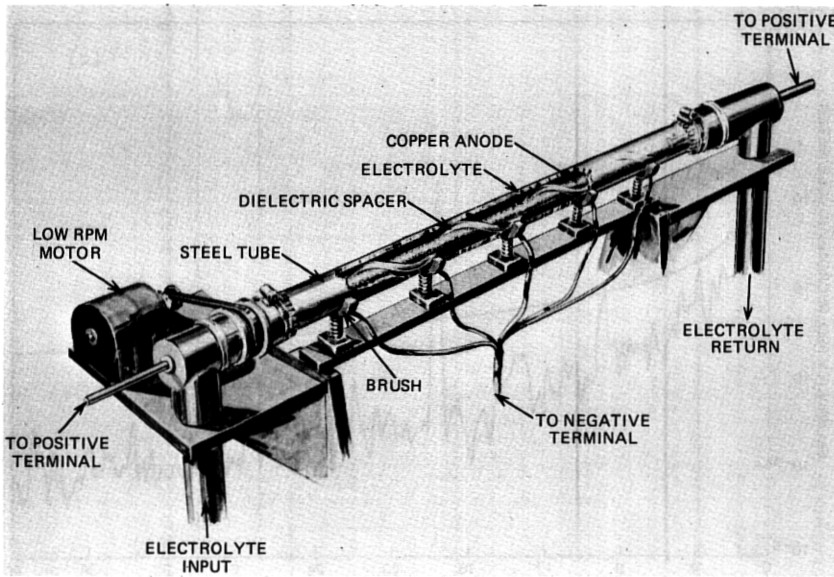


Fig. 9—Copper plating system.

plating would meet this requirements. Nevertheless, a plating thickness of approximately 5 microns was deemed to be optimal. With this thickness, the plating was for the most part free of porosity and was found to be adequate to cover most of the microscopic imperfections in the steel substrate. Thicker platings, such as the 15-micron coating used at the outset of the program, actually degraded the quality of the waveguide product. This degradation arose because the rotation applied to the tube to ensure a circumferentially uniform coating of copper, when combined with the gravitational sag of the anode and its helical dielectric support, resulted in an unacceptably high level of periodic diameter distortion. This periodicity was minimized by the use of a thinner plating and a slower tube rotation.

3.4 Chromium oxide layer

The previously described copper plating, when exposed to the atmosphere prior to being lined with polyethylene, will develop a very thin surface layer of cuprous oxide. Polyethylene, when bonded to this surface layer, can readily be delaminated at the ends of the waveguide tube in the presence of moisture. The electrolytic application of a thin chromium oxide layer to the copper surface prevents atmospheric attack and the formation of a copper oxide surface layer; when used in conjunction with the other elements of the bonding system, it contributes to a highly reliable bond. The chromium oxide layer, being very thin (~20 Å), does

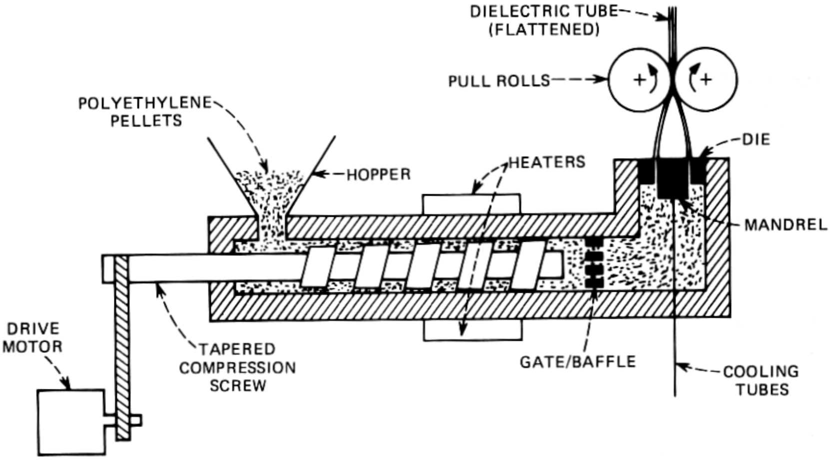


Fig. 10—Dielectric extruder.

not have to be included in the ohmic loss calculations applicable to a cylindrically stratified medium.

3.5 Dielectric lining

The dielectric material used for the manufacture of dielectric tubing is manufactured in pellet form; it contains 0.06 percent ethyl 330 antioxidant. The particular composition used has a density of 0.92 g/cm^3 and a melt index of 0.2. The transformation of pelletized polyethylene into homogeneous precision thin-walled tubing was accomplished by a commercial vendor using a heavy-duty extruder with a specially designed adjustable cross head. The very low melt index of the material required that the liquification of the pelletized material be carried out at higher-than-normal temperatures, with extensive mechanical shearing of pelletized material. The extruder system is shown schematically in Fig. 10.

During its passage through the extruder, a portion of the ethyl 330 oxidant is expended due to the combination of dissolved oxygen and high melt temperature; however, maintaining the maximum extruder temperature at or below 200°C allowed a sufficient amount of antioxidant to be present for the high-temperature copper-to-polyethylene bonding operation.

One of the major elements of the dielectric tubing program was associated with producing thin-walled tubing that satisfied the geometric PSD requirements. The most troublesome geometric component proved to be small periodic changes in thickness that occurred over entire circumferential zones as a function of length along the dielectric tube. This type of distortion, if present, generates TE_{on} modes which are not attenuated by the helix mode filters. Following the experience gained in the steel tubing program, periodic pulsations associated with the dielectric processing machinery were identified and suppressed. With the machinery optimized, these thickness periodicities have a PSD which is shown in Fig. 11.

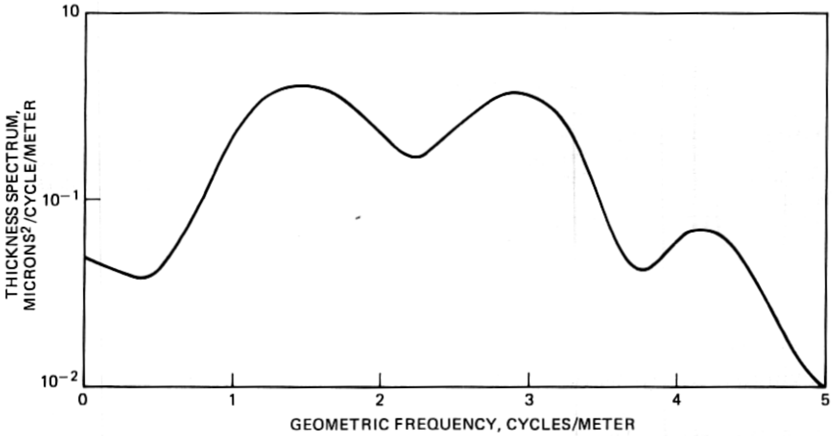


Fig. 11—PSD of dielectric tubing thickness.

The final version of the gauging used to measure dielectric tubing geometry is shown in Fig. 12. The measurement is carried out by longitudinally slitting samples of dielectric tubing and passing these samples through an array of eight pairs of differential air gauges. Changes in dielectric thickness give rise to changes in sensor pressure. These pressure changes are converted to voltage changes, which, after computer processing, yield the PSD of the thickness of dielectric tubing.

The dielectric liner thickness of 180 microns was chosen after the following parameters were analyzed: (*i*) differential phase and attenuation constants of the TM_{11} mode relative to the TE_{01} mode and their effects on route bend and installation losses; (*ii*) TE_{01} ohmic loss due to the current enhancement effect caused by the presence of the dielectric; (*iii*) TE_{01} loss due to dielectric loss tangent effects; (*iv*) sensitivity to mode conversion effects due to dielectric thickness distortions; and (*v*) liner tubing manufacturability. The above analysis had shown that there is a fairly broad choice of nominal liner thickness (from approximately 150 to 200 microns) which would be compatible with system objectives; the thickness of 180 microns was chosen because it appeared to be not only close to the midpoint of the broad optimum range, but also because it presented fewer difficulties in the liner manufacturing and subsequent bonding operations.

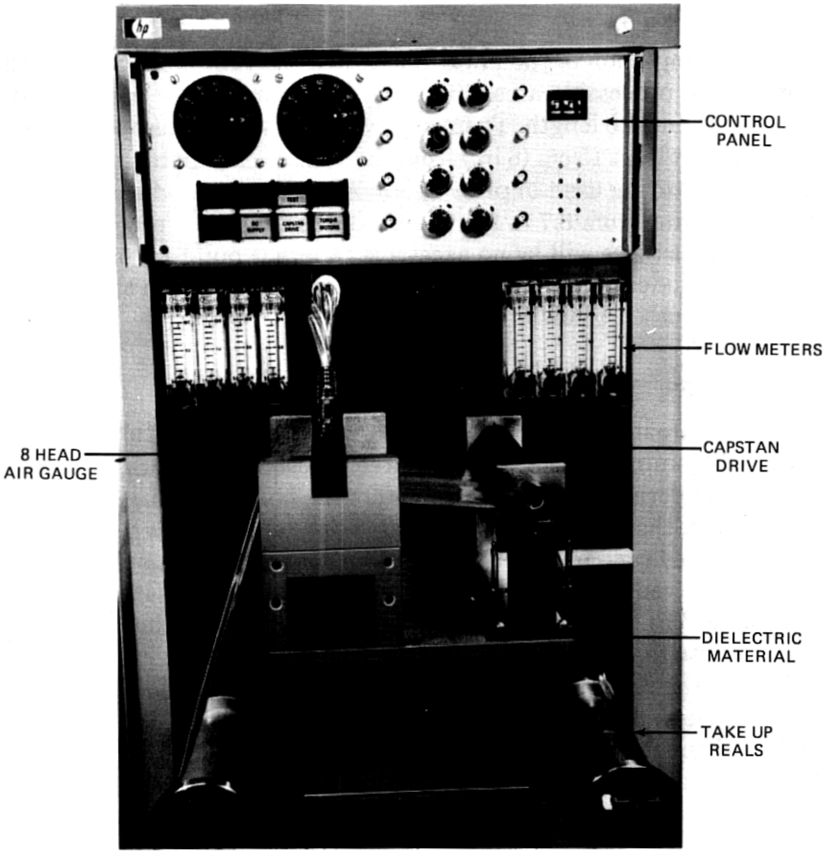


Fig. 12—Dielectric thickness gauge.

3.6 Dielectric bonding

The details of the dielectric bonding philosophy have been reported elsewhere.[20] Accordingly, only the following brief summary is included in this paper. The previously described liner tubing is subjected to a corona discharge prebond treatment at the regions corresponding to the ends of the tubing; this treatment enhances the bondability of the liner. The liner tubing is introduced into the copper-plated and chromated steel tube. The annular region between the outer surface of the dielectric liner and the inner surface of the plated steel tube is evacuated, and high-purity nitrogen is introduced inside the dielectric liner tubing. The assembly is raised to a temperature of 300°C, effecting a high-strength bond between the dielectric and metallic tubes. This system meets all requirements—low ohmic loss, bond integrity even in the presence of moisture and temperature cycling, and manufacturability.

3.7 *Trim to length*

After completion of the lining operation, the tube is moved into the mechanical processing area where the first operation is trimming the waveguide ends to length. There are two purposes for this operation: (*i*) to remove at least 15 cm (6 in.) from the ends to eliminate the effects of internal fixturing used in prior operations, (*ii*) to introduce a random length varying from 8.7 to 9 m from tube to tube. The random length ensures that there will be no excessive coherent build-up of energy in the TE_{on} modes due to diameter distortions arising from the flanging system discussed below.

3.8 *Flanging*

Flanges are incorporated at the ends of the waveguide tubes to facilitate field joining by welding. The large precision reference surfaces of the flanges permit accurate alignment of the bores of contiguous tubes. In addition, they provide high thermal impedances to the heat flowing from the field weld toward the liner. The details of the coupling design as they evolved over the course of the waveguide project are treated elsewhere.[21] In this paper, attention will be focused only on those items which relate to waveguide manufacture.

During the course of the program three methods for joining flanges to the waveguide tubing were considered: (*i*) threading both the tube ends and the flange with an adhesive intermediate layer, (*ii*) adhesive bonding without threading, and (*iii*) electron beam welding. The first two approaches offered no long-term cost or performance advantages relative to electron beam welding; moreover, they both involved the introduction of an additional material—adhesive—whose long-term behavior under prolonged shear stress would have to be evaluated. Accordingly, electron beam welding was selected for waveguide application.

Two different approaches for fabrication of flanges and assembly to the tube prior to electron beam welding were considered. In the first method, a precision-finished machined flange was to be applied to a machined surface at each end of each section of waveguide tubing. The tolerances associated with the flange and waveguide machining would assure that proper flange alignment would be obtained after electron beam welding. The second method utilized rough flange forgings which were premachined on a numerically controlled lathe to almost final dimensions, then electron beam welded to the tube, and finish-machined to final dimensions after welding by referencing the machining operation to the waveguide bore. Both methods utilize full circumferential welds at the front face and rear portion of the flange as shown in Fig. 13. Both methods required that an expandable mandrel be inserted into the bore

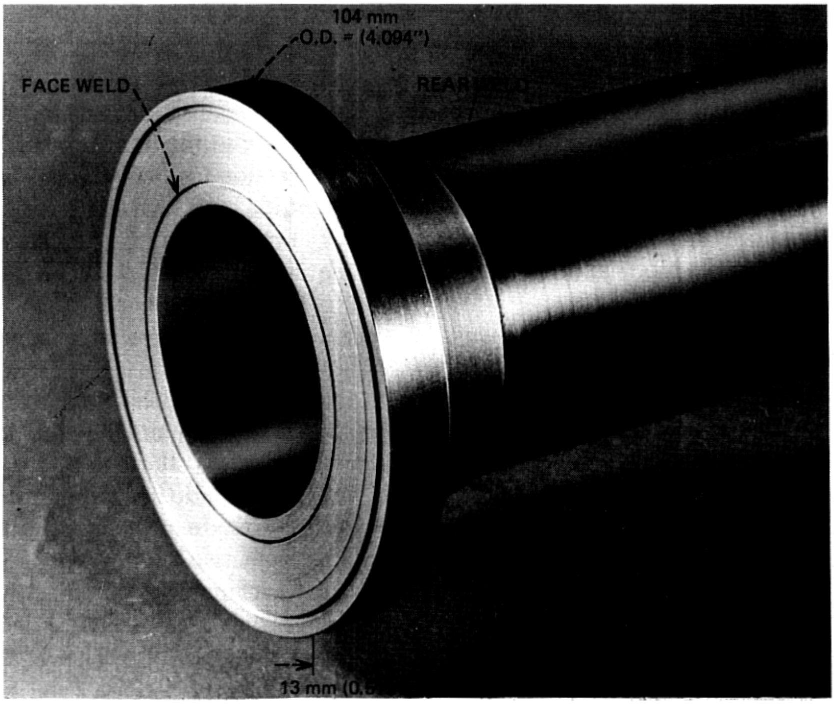


Fig. 13—Flanged end of waveguide.

of the waveguide to maintain precision alignment of the tube axis. The second method was selected since it provided better alignment tolerances.

After locating the flanges at the ends of the tube in accordance with the scheme described above, the tube ends with appropriate fixturing are inserted in a specially designed high-vacuum electron beam chamber where partial-penetration circumferential welds are applied at the face and rear of the flange. After inspection of the welds, the flanged waveguide end is fitted over a precision expandable mandrel on the lathe. Measurements indicated that for all practical purposes the mandrel axis, which was referenced to the dielectric liner, coincided with the electrical axis of the waveguide. The face of the flange is cut to the required squareness, the end of the tube which protrudes beyond the flange face is removed, and the outer diameter of the flange is cut to final dimension concentric with inner bore. The final inspection of the finished flanges showed concentricity of 50 microns, perpendicularity of 0.064 μrad and parallelism of back and front faces of 25 microns.

These tolerances yielded a tube-to-tube tilt alignment in straight waveguide sections of about 0.2 mrad rms. With 9-m waveguide lengths, this corresponds to a random component of tilt loss of 0.02 dB/km at 110 GHz. For offsets, the losses are significantly lower.

IV. HELIX WAVEGUIDE

4.1 General considerations

The dielectric waveguide described above has been designed for low mode conversion loss due to both manufacture and installation. Nevertheless, there is a certain level of mode conversion loss which must be expected, and it is the purpose of helix waveguide to absorb some of the resultant spurious mode energy, and thereby limit its reconversion back to the TE_{01} mode and the transmission degradation which results from this reconversion.

It has been previously shown that over the mechanical frequency band of approximately $\frac{1}{3}$ to $1\frac{1}{2}$ c/m, the highest level of curvature spectral density for installed waveguide occurs at the lower edge of the band. This particular mechanical spectral zone corresponds to TM_{11} and TE_{12} mode conversion at the higher electrical frequencies. At these electrical frequencies, the TM_{11} dielectric-lined waveguide mode has a field distribution which most closely resembles the TE_{11} mode in the lossy-wall helix waveguide described below. The TE_{12} dielectric lined waveguide mode resembles its TE_{12} counterpart in helix waveguide. To significantly attenuate the TM_{11} and TE_{12} modes generated by dielectric lined waveguide, it is essential to have a helix waveguide design that has high TE_{11} and TE_{12} mode losses.

In order to design a helix waveguide that meets the above requirement, the so-called wall impedance representation of waveguide has been used in theoretical modeling studies. Briefly, waveguide propagation is represented in terms of obliquely incident plane waves impinging on a reflecting and/or absorbing surface.[22,23] Thus it is customary to define two surface impedances, $Z_z = -E_z/H_\phi$ and $Z_\phi = E_\phi/H_z$; the former represents wave components having electrical fields parallel to the plane of incidence, and the latter perpendicular to the plane of incidence.

Theoretically at 110 GHz a waveguide with a longitudinal wall impedance $Z_z \approx 50\ \Omega$ will maximize the loss per unit length of the TE_{11} and TE_{12} helix modes (and by extension the TM_{11} and TE_{12} dielectric modes). A practical manufacturable configuration which provides a longitudinal impedance approximating this ideal impedance is a helix waveguide formed from closely spaced insulated wires, directly backed by a lossy material having an impedance $\sqrt{\mu/\epsilon}$ between 50 and 100 Ω.

During the course of the WT4 program, a number of lossy materials were developed and evaluated. One family of materials, carbon-coated glass, had an impedance of approximately $75 + j30\ \Omega$; another family of materials, ferrous metal particles suspended in an epoxy, had an impedance of approximately 85 Ω. Helix waveguide using these materials has the attenuation coefficients shown in Fig. 14.

Both materials described above met the electrical objectives for helix

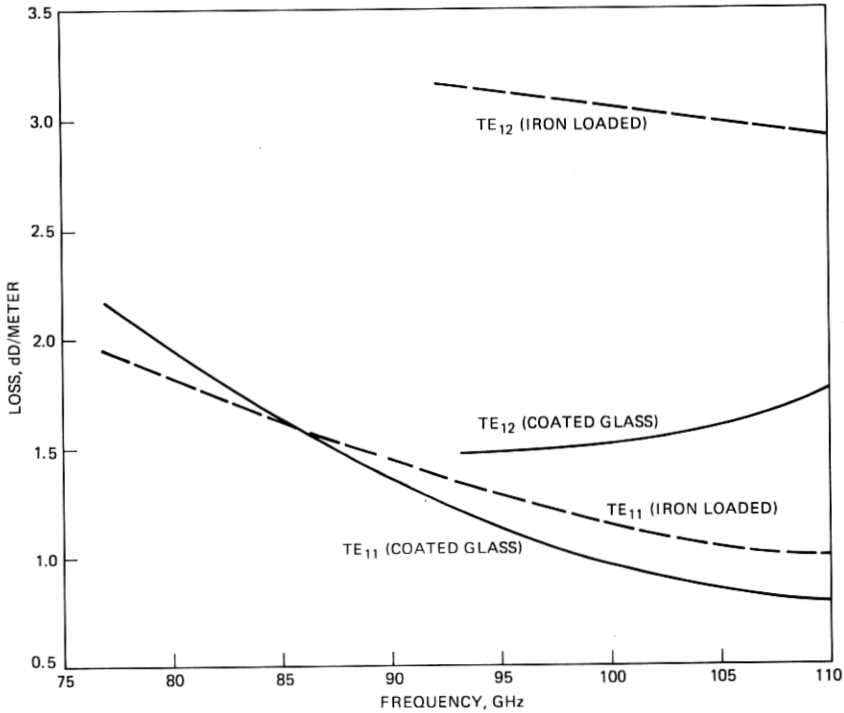


Fig. 14—Measured loss of TE_{11} and TE_{12} modes in helix waveguide.

waveguide. The coated glass material, because of its early development, was used in the field evaluation test. However, during the course of the program, the coated glass material exhibited the following shortcomings: (*i*) the rf resistivity of the coated glass strands exhibited a high degree of variability, leading to the rejection of many batches of glass; (*ii*) the individual glass filaments forming the strands exhibited breaks, which on many occasions caused the helix processing machinery to jam. For these reasons, the use of carbon-loaded glass material in helix waveguide fabrication was abandoned after the field evaluation test. The iron-loaded epoxy system described below has been selected for future waveguide applications.

4.2 Helix process

Iron-loaded epoxy helix waveguide has the finished nominal dimensions shown in Fig. 15. This waveguide can be seen to consist of a helical layer of insulated copper wire impregnated with a conformal low-loss epoxy dielectric. This is followed by a high-loss iron-loaded epoxy layer. The entire spectrum of electrical materials is contained in a flanged steel

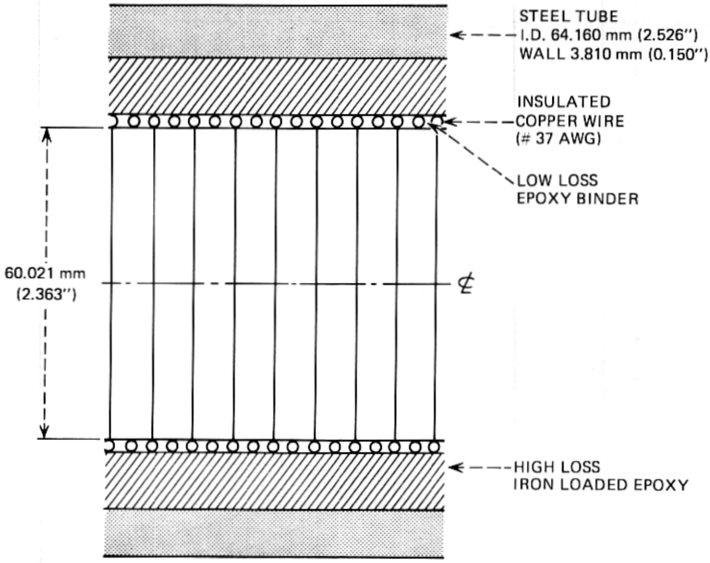


Fig. 15—Helix cross-sectional geometry.

jacket. In this structure, the insulated wire provides circumferential conductivity required for the propagation of the TE_{01} mode. The low-loss epoxy surrounding the helical wires serves as a barrier blocking the flow of high-loss iron-loaded epoxy to the interstices of the wires during the fabrication process; this layer is necessary for low TE_{01} loss. The high-loss iron-loaded epoxy has a wave impedance of approximately 85 Ω and serves to absorb spurious mode energy in accordance with the objectives depicted in Fig. 14. The steel tubing serves as the mechanical strength member of the waveguide. Finally, the flanges permit the welded joining of contiguous sections of either helix or dielectric-lined waveguide.

The basic helix process flow shown in Fig. 16 will now be briefly reviewed. Steel tubes are manufactured to straightness requirements of best commercial tolerance. This steel tube is degreased and flanged via the electron beam welding process described for dielectric waveguide.

In parallel with the steel tubing preparation, a mandrel is cleaned, coated with a mold release agent, and then coated with a thin layer of low-loss epoxy. While still wet with low-loss epoxy, the mandrel is covered with a helical wrap of insulating wire and the low-loss epoxy oozes through the interstices between the wires. The excess low-loss epoxy is wiped conformal to the wire layer and the epoxy is allowed to gel (complete curing is undesirable, because a poor bond would result between the low-loss and iron-loaded high-loss epoxy layers). This mandrel is loaded into the prepared flanged steel tubing, and special pressure fittings are applied at both ends of the assembly.

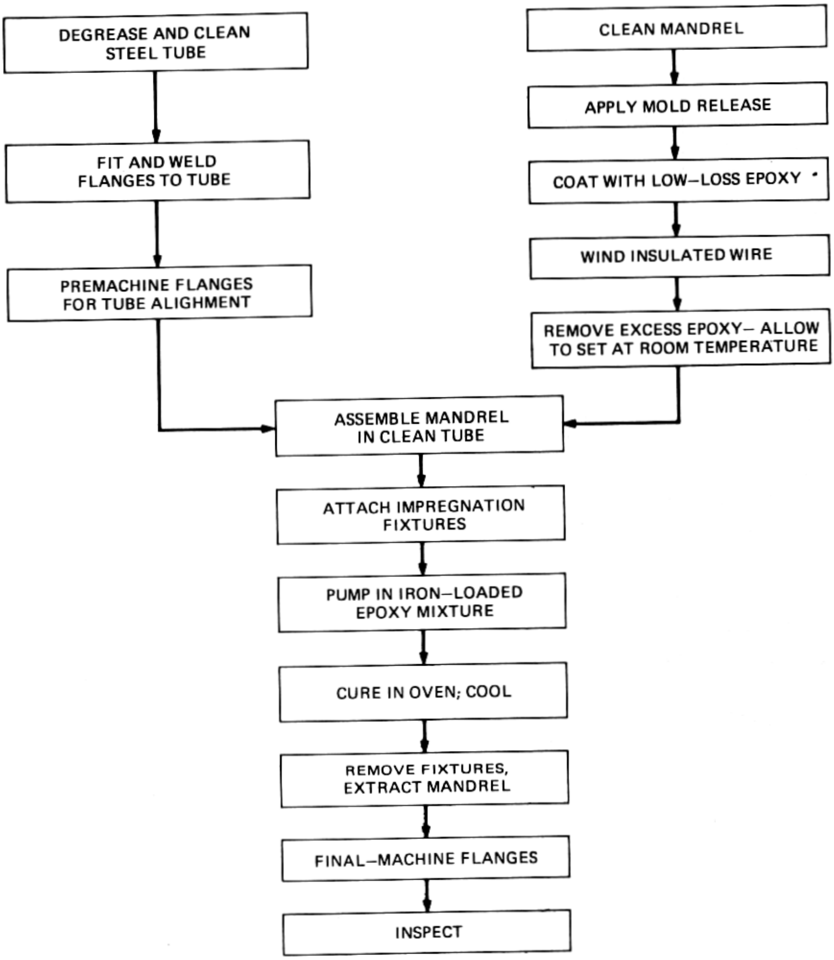


Fig. 16—Helix processing sequence.

A vacuum is applied to one end of the assembly and a heated mixture of iron-loaded epoxy is injected under pressure to the opposite end. When the entire annular region between the wire-loaded mandrel and the steel jacket is filled with iron-loaded epoxy, the pressure fittings at both ends of the tube are sealed off and the entire assembly is placed in an oven to cure under pressure and temperature conditions shown in Fig. 17. In this process both the pressure and temperature parameters have been found to be extremely important in terms of assuring an acceptable final geometry. In the case of pressure, only the initial pressure is set by the epoxy injection machinery. The remaining portion of the pressure curve is determined by the heating and curing stages of the epoxy. In the case of temperature, it has been found to be absolutely imperative to

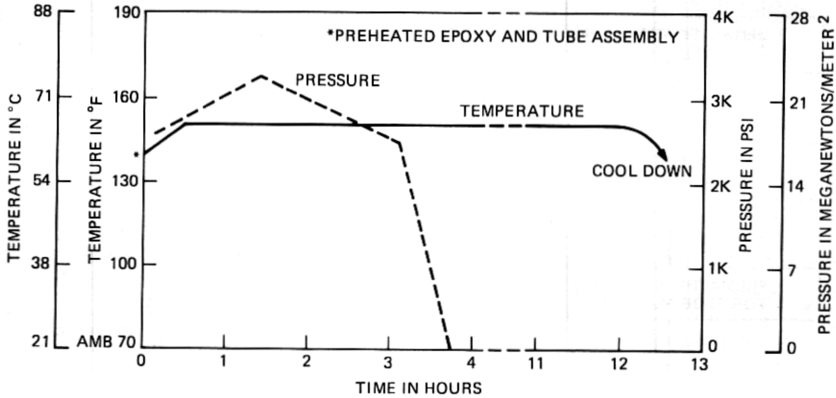


Fig. 17—Iron-loaded epoxy cure cycle.

maintain every portion of the tube within 3⅓°C; if two portions of the waveguide have different time-temperature profiles, significant geometrical distortions result.

Following the epoxy cure, the mandrel is extracted from the assembly. The flanges are finish-machined in a manner similar to that used for dielectric-lined waveguide.

V. SUMMARY

This paper has reviewed the design philosophies and fabrication implementation of both the dielectric-lined and helix waveguide. Both types of waveguide have received extensive electrical testing and accelerated age stressing. Both have been shown to be readily manufacturable and durable, and can be expected to retain their properties over the typical 40-year life of underground transmission media.

VI. ACKNOWLEDGMENTS

The developments cited in this paper are the results of a large number of contributions at both Bell Laboratories and Western Electric Co. In particular, the authors would like to make note of the contributions by the Western Electric Engineering Research Center for the dielectric-lined waveguide manufacturing process, and to members of the Bell Laboratories materials research laboratories for their consultations during the course of the program.

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