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WT4 Millimeter Waveguide System:

Waveguide Medium Manufacturing Process Research and Development

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The Western Electric Engineering Research Center (ERC) conducted the research and development effort necessary to establish the waveguide medium manufacturing process technology. The Forsgate Laboratory staff was involved in product design, process research and development, facility development, setting up a pilot plant, and gaining valuable manufacturing experience. The development of a low-loss transmission medium was a key part in establishing the overall WT4 system capabilities.

I. INTRODUCTION

1.1 Project objectives

Full-scale development of the WT4 millimeter waveguide system was authorized in 1969. Bell Laboratories, charged with overall system responsibility, requested that the Western Electric Company participate in a joint program to develop the waveguide medium technology. Western Electric involvement was deemed extremely important because it was impossible to separate the design and processing problems and because the overall system economics was tied directly to the manufacturing process capability of the medium.

The Western Electric Engineering Research Center (ERC) initiated project involvement late in 1969 and outlined the major objectives:

(*i*) To develop the manufacturing process technology for fabricating waveguide both economically and reliably,

(*ii*) To fabricate the waveguide for various Bell Labs evaluations and the field evaluation test.

With the major objectives defined, effort initially was directed toward solving the problems of organizing a staff and providing the space and facilities for conducting the research and development effort. The goal of a system trial planned for 1974 posed a formidable challenge for the ERC technical staff both in technology development as well as waveguide fabrication. The project would involve product design, process R&D, facility development, setting up a pilot plant, and gaining valuable experience in manufacturing. Essentially, the ERC had the responsibility of a Product Engineering Control Center (PECC) and was totally accountable for shipped product.

1.2 Organization

The overall waveguide effort was assigned to an assistant director at the ERC. The initial organization of a waveguide R&D staff involved the selection of personnel with both extensive academic experience and manufacturing process development from previous Western Electric plant experience. It was anticipated that the blending of both types of personnel would permit the developments to move at a more rapid pace.

An initial staff of 7 in 1969 grew to 27 by 1971. This period was directed toward highlighting the technical problems, setting up experimental facilities, and starting the initial research and development effort. By 1973, the staff increased to 42 with the addition of some personnel from the Western Electric–Kearny Works. The Kearny Works had been given the waveguide medium allocation through the planned field evaluation test. The period from 1973 included the final process development, pilot plant equipment development, and the preparation for pilot plant production. The addition of plant development engineers from Kearny was planned to provide an orderly transition of responsibility from development to high-volume manufacture.

1.3 Forsgate Laboratory considerations

The next step in the overall planning involved obtaining adequate and suitable space for the medium research and development. Initial space studies indicated that approximately 50,000 ft^2 of floor space would be required to provide for process research and development and waveguide fabrication. Considerations on space included:

Process flow	Waste disposal
Facility requirements	Support services
Personnel requirements	Transportation needs
Plant services	Duration of project
Building height	Geographic location

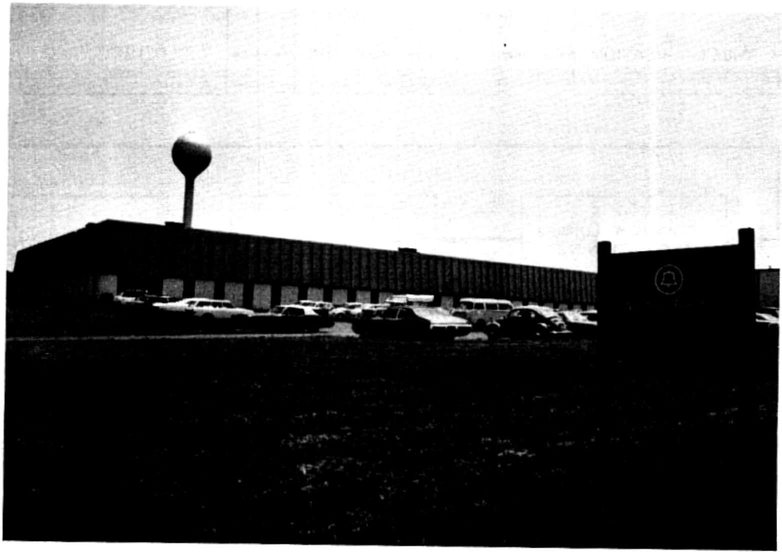

Fig. 1—Forsgate Laboratory.

Since space was not available at ERC, other alternatives were necessary. Investigations covered possible space at Western Electric locations such as Kearny and Baltimore. In addition, several leased facilities were also investigated. After considerable effort, it was determined that a leased site, approximately 18 miles from ERC in Monroe Township, New Jersey, offered the most flexibility relative to both project and geographic considerations.

The location designated as the Forsgate Laboratory was leased and initially occupied during mid-1970. The building as shown in Fig. 1 included only the basic structure which allowed for the layout of the facilities for the most reasonable processing sequence. The ultimate layout of 44,000 ft^2 allowed for separate helix and dielectric-lined waveguide areas and for a separate measurement area. While this space satisfied the processing needs, an additional 16,000 ft^2 was subsequently required for waveguide electrical testing, packaging for sheath insertion and shipment to the field. This space was leased from the Kearny Works.

II. TECHNICAL EFFORT

2.1 Overall dielectric waveguide processing

As noted in a previous article,[1,2] the waveguide system will use two types of waveguide, namely, helix and dielectric-lined. Since the dielectric-lined waveguide is to be used as the main transmission path ($\sim$99 percent), the major portion of the technical discussion will cover only

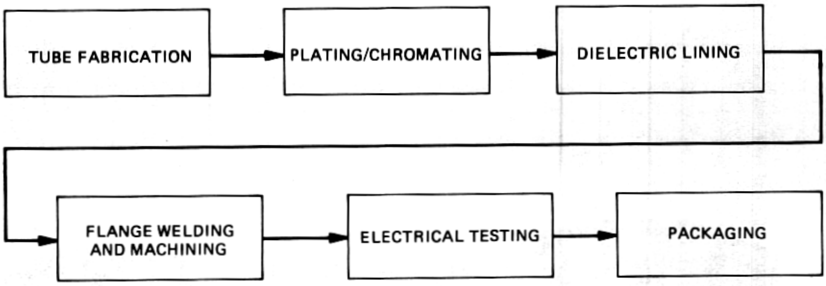

Fig. 2—Dielectric-lined waveguide processing.

developments in this area. The processing steps that evolved relative to dielectric-lined waveguide are outlined in Fig. 2.

At the start of the project, the major manufacturing processing problems included:

(*i*) Need for precision tube and measurement technology.
(*ii*) Need for precision copper plating and surface preparation.
(*iii*) Need for low loss/reliable dielectric lining process.
(*iv*) Need for low loss/reliable method for flange attachment and machining.

Considerable effort for each item shown in Fig. 2 has been expended relative to design, process, and facility feasibility. For example, the tube fabrication program advanced the state of the art of tubing manufacturing, yielding tubes of much higher geometric precision than available in the general trade. The in-house development of copper plating technology demonstrated the precise control over long lengths. The melt bonding process of dielectric lining included two stages of development. The first stage required the development of thin-walled precision dielectric tubing using low-loss pellets of high-purity polyethylene materials. The second stage required the development of a reliable method of bonding. Methods for flange attachment resulted in the selection of electron beam welding to provide low distortion, highly reliable fusion joints. The evolution of precision machining methods resulted in waveguide sections that exhibited very low mode conversion losses. This was mainly due to the excellent section-to-section tilt and offset alignment. The extensive development of mechanical and electrical measurement concepts resulted in facilities for on-site tube measurements and low-loss guide testing. The packaging effort resulted in concepts that provided for ease of waveguide shipment and installation. All of the Forsgate developments contributed to the successful processing of low-loss waveguide. Due to the space limitations, only two of the areas noted will be discussed. The main consideration in the subsequent

TUBE PARAMETERS	COMMERICAL TOLERANCE, mm	INITIAL SPECIFICATION, mm
Inside diameter	8.8×10^{-2}	1.3×10^{-2}
Ellipticity	3.5×10^{-1}	2.0×10^{-3}
Minimum radius of curvature	$2.1 \times 10^{+5}$	$7.6 \times 10^{+5}$

Fig. 3—Initial tube tolerances (51 mm).

technical discussion is to note the detailed method of technology research and development and the associated results.

2.2 Tube development

The need for a precision tube with extremely close control of curvature, diameter, ellipticity and other forms of geometric distortions is highlighted in another article of this issue.[2] Prior to the involvement of the ERC, it was recognized that domestic tube mills did not possess the technology to manufacture waveguide tubes with requirements as noted in Fig. 3.

ERC staff members visited various tube mills aimed at evaluating the tube-making capability as well as the technical capability of the tube fabricator. As a result, a tube fabricator was selected for on-site evaluations. An extensive analysis of the tube processing operations showed that the final operation of roller straightening was the most critical element in controlling the geometric tolerances. As a result, a roller straightener was completely overhauled, installed and dedicated solely for the waveguide project at the tube mill. Detailed studies on this facility showed that the roller shape was one of the dominant machine parameters controlling the final tube geometry.

In the straightening process as shown in Fig. 4, a tube passes through three sets of rollers rotating around its center line. The first and last set of rollers are in a fixed position with respect to the reference axis of the tube. The center pair of rollers is vertically offset from the reference axis. As the tube passes through the three sets of rollers, each element of the tube undergoes a complex pattern of bending stress reversals producing the desired straightening. During the process the tube is driven forward and turned by the rotation of the rollers which are at an angle to the tube axis.

As outlined, the rotary straightening operation has inherent difficulties that produce undesirable distortions in the cross-section of the tube. Conventional rollers, designed to work over a wide range of tubing sizes, do not distribute the load evenly over the contacted tubing, producing load concentrations at the tubing surface. The high load concentrations propogate through the tube wall producing a helical pattern of deformation on the inner surface of the tube.

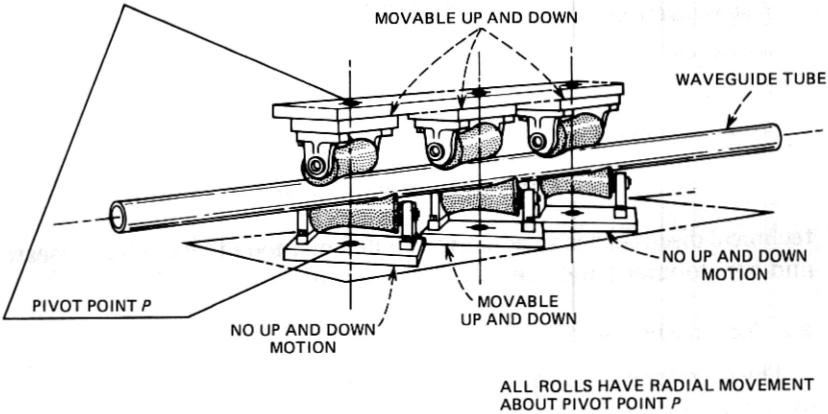

Fig. 4—Roller straightener.

The roller-tube interaction shown in Fig. 5 was studied by P. F. Lilienthal, ERC, in order to mathematically describe a roller geometry having a line of contact over which the applied load could be distributed. The objective of the effort was to develop a roller contour which would allow uniform load distribution over the length of the roller.

An examination of the geometry of the horizontal plane at distance z_0 from the center of the roller denotes the elliptical cross section of a tube having center coordinates of x_0,y_0,z_0. Tangent to this ellipse is the undetermined radius R of the corresponding roller cross section. The coordinates of the tangency point are x,y,z_0. The center of the elliptical tube section is located at

$$x_0 = R_1 + R_2 \tag{1}$$

$$y_0 = \frac{z_0}{\tan\theta}$$

The equation of the circular cross section of the roller at plane $z = z_0$ is

$$x^2 + y^2 = R^2 \tag{2}$$

and the corresponding expression for the ellipse is

$$\frac{(x - x_0)^2}{a^2} + \frac{(y - y_0)^2}{b^2} = 1 \tag{3}$$

where $a = R_1$ and $b = R_1/\sin\theta$. As is shown in Fig. 6, both the circle and the ellipse have a common tangent at point (x,y,z_0). Therefore,

$$\underset{\text{circle}}{\left.\frac{dy}{dx}\right|_{x,y,z_0}} = \underset{\text{ellipse}}{\left.\frac{dy}{dx}\right|_{x,y,z_0}} \tag{4}$$

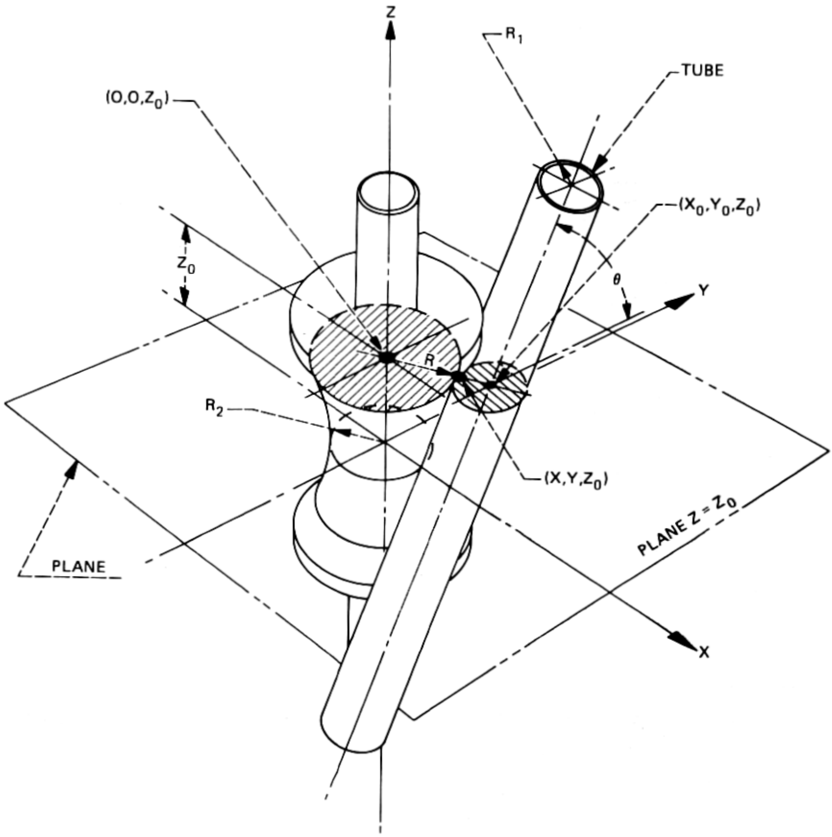

Fig. 5—Roller-tube interaction.

or

$$\frac{x}{y} = \frac{(x - x_0)b^2}{(y - y_0)a^2} \tag{5}$$

When solved for x, eq. (5) yields

$$x = \frac{x_0 y b^2}{y(b^2 - a^2) + y_0 a^2} \tag{6}$$

Substituting (6) into (3), we get

$$x_0 a^2 \left[\frac{y - y_0}{y(b^2 - a^2) + y_0 a^2}\right]^2 + \frac{(y - y_0)^2}{b^2} = 1 \tag{7}$$

which, in turn, can be expressed as

$$Ay^4 + By^3 + Cy^2 + Dy + E = 0 \tag{8}$$

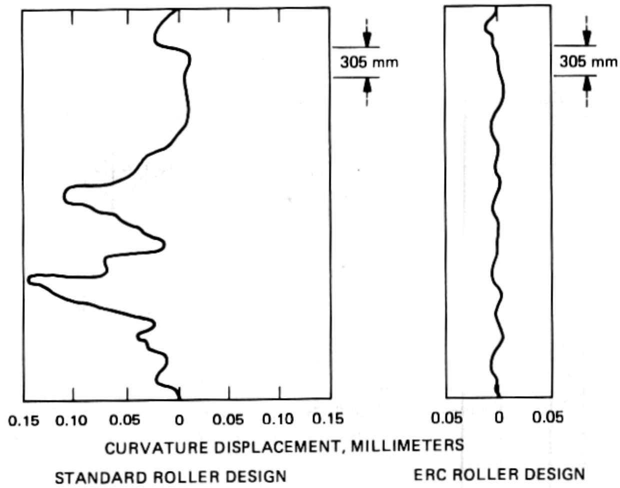

Fig. 6—Curvature results.

where A, B, C, D, and E are coefficients determined by the known parameters such as x_0, y_0, θ. The coordinate of the tangency point is y.

Equation (8) yields four roots when solved for y, two of which are complex.

One of the two real roots, only the one at point (x,y,z_0), Fig. 6, where the ellipse and the circle have a common tangent, is used. Solving eq. (3) for x, the result is:

$$x = x_0 - a\sqrt{1 - \left(\frac{y - y_0}{b}\right)^2} \tag{9}$$

In this manner, the tangent point coordinates x,y,z_0 are determined, and the radius of the roller at the given plane is computed by eq. (2). The longitudinal cross section of the roller is obtained by computing a series of R values for incremental distances from the origin of the coordinate system (0,0,0). A computer program is used to calculate the coordinates. The roller contour is then described by closely spaced points whose coordinates comprise arbitrarily chosen z_0 values and their corresponding R distances from the z axis.

The roller contour was computed for the straightener and N/C tapes were made at the ERC using the coordinates as input for the program routine.

The validity of the concept and the accuracy of the method were verified on small scale aluminum rollers and a full-size wooden roller. Six rollers of the ERC design were produced for experiments and use at the tube mill. The rollers were successful in producing tubes with greatly improved straigh tness by heavily suppressing the amplitude of the he-

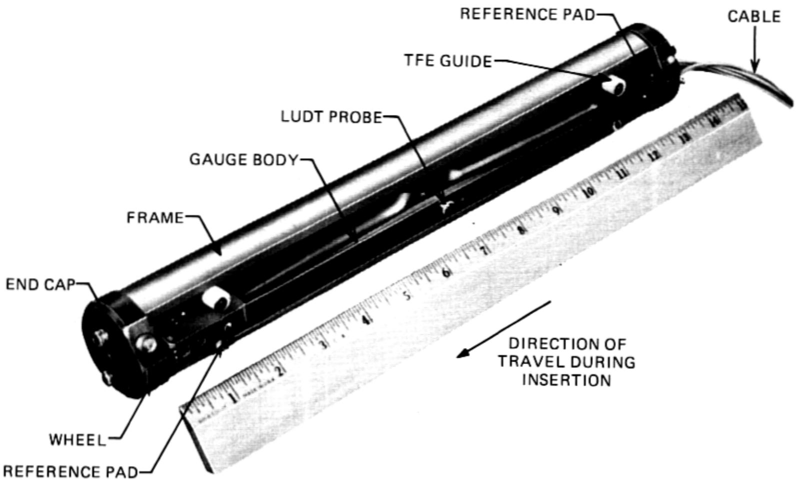

Fig. 7—Curvature gauge.

lical indentations normally introduced by the straightener process. Figure 6 compares early curvature measurements taken on waveguide tubing during trial runs using the standard roller designs in conjunction with a straightener which had not yet been optimized for waveguide tubing. The tubes typically had large helical impressions and poor straightness. The tubes processed on the specially designed rollers had no trace of helical deformations and showed an order of magnitude improvement in straightness. In addition, improvements in diameter control were also achieved over the same period. This was in part a response to the new roller design and also a result of improved methods of tube fabrication preceding the final rotary straightening operation.

The critical importance of tube geometry to transmission performance makes extremely accurate measurements as essential part of the waveguide medium evaluation program. A second aspect of the tube evaluation program involved the development of precision measurement facilities for use at the tube mill or at the waveguide fabrication plant. Gauges for measuring both the curvature and diameter of the tubing were developed.

The following discussion will center only on the curvature gauge.

The basic curvature gauge shown in Fig. 7 consists of a rigid frame maintaining two reference points and a displacement probe in fixed positions with respect to one another. In operation the curvature gauge is inserted into the waveguide tube contacting the inner tube on diametrically opposed lines by means of the two 3-point structures. All three points contact the surface but during measurement the middle point, which contains a linear variable differential transformer (LVDT), is

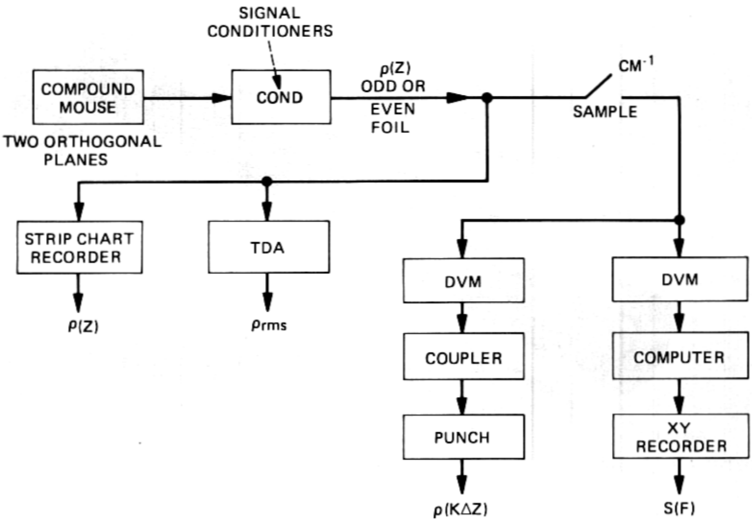

Fig. 8—Measurement system.

displaced with respect to the other two points. This displacement of the probe is proportional to the curvature of the tracked path.

The curvature gauge was incorporated into a system consisting of the gauge, drive mechanisms, and the control system. The system signal flow is shown in Fig. 8. The LVDT displacement probe generates a modulated ac signal which is demodulated, amplified, and directly recorded. The time-domain analyzer is used to compute root-mean-square curvature. The data acquisition system records curvature behavior for use in predicting transmission losses. The program and hardware for the system as noted were supplied by Bell Laboratories. The sequence of data gathering and analysis is as follows:

(*i*) Acquire and store curvature data to a maximum of 1024 points (one data word per centimeter of gauge displacement).
(*ii*) Compensate data record by means of a cosine taper.
(*iii*) Perform statistical detrending and filtering of the record.
(*iv*) Perform 1024-point fast Fourier transform on data record.
(*v*) Convert corrected transform to power spectral density (PSD).
(*vi*) Output curvature power spectral density to x–y recorder, plotting the PSD from 0 to 50 cycles per meter.

Figure 9 shows a comparison of the output curvature PSD before and after the roller-straightening operation.

The roller straightener effort and the development of very precise measuring equipment resulted in optimizing the overall tube processing at the tube mill. This combined effort resulted in a tube yield improve-

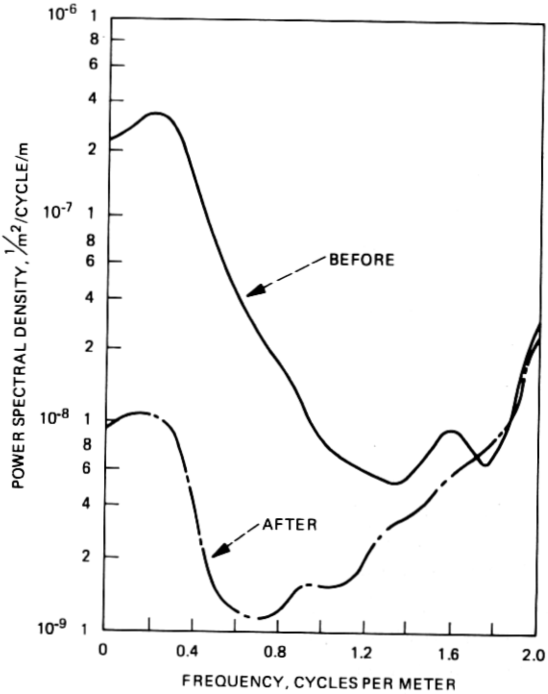

Fig. 9—PSD (before and after straightening).

ment from less than 50 percent to approximately 90 percent by the end of the field evaluation test.

2.3 Electrodeposition of copper for waveguide tubes

A second key development area involved the electrodeposition of copper on the interior surface of the millimeter waveguide tubes. The use of copper as a conducting surface is based primarily on achieving low ohmic losses, while achieving a high degree of reliability. The objectives of the effort were outlined as follows:

(*i*) Control average diameter variation within extremely tight tolerances.
(*ii*) Maintain the plated surface finish to less than 35 microinches rms.
(*iii*) Deposit a continuous, nonporous, high-conductivity copper layer.
(*iv*) Provide a deposition with excellent adhesion to the steel.
(*v*) Establish technical feasibility of plating long lengths.
(*vi*) Develop process suitable for future high volume production with low cost and high reliability.

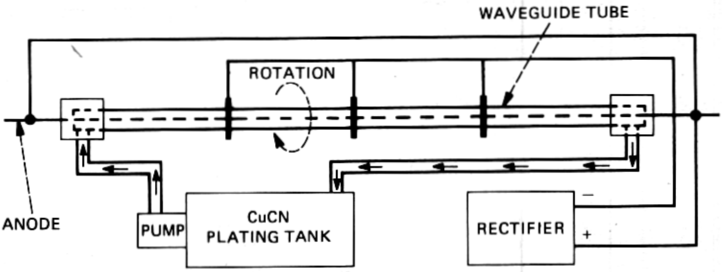

Fig. 10—Horizontal plating system.

Initial effort was directed toward obtaining plated tubes from outside suppliers. It was quickly determined that the technical capability for meeting the above requirements did not exist. As a result, the ERC proceeded at an accelerated pace to develop an in-house capability. The overall technology in this area was developed by D. J. Fineberg, R. Haynes, and W. E. Rapp.

Initial effort directed at vertical plating was followed by the development of a horizontal plating system. The horizontal system shown in Fig. 10 consists of a hollow stationary copper anode inserted into the steel tube. In operation, the electrolyte is circulated through the annulus between the tube (cathode) and the anode while the tube rotates. To prevent short-circuiting, the stationary copper anode and rotating cathode are separated by an insulating rod helically wound around the anode. The ends of the spacer are positioned in grooves in the stationary components of the head and tail stock assemblies, thus preventing rotation of the spaces. The tube is inserted into a sleeve fastened to the drive motor pulley.

Electrical connections between the rectifier and the exterior tube are made through copper blocks contoured to the outer diameter of the tube. Under operating conditions, 90 percent of the current is consumed for copper deposition. The 10 percent current loss is a result of a side reaction which evolves hydrogen gas at the cathode.

To ensure permanent adhesion of the deposited copper, the steel tube must be thoroughly cleaned and the surface chemically activated before plating. The cleaning solution must be compatible with the metal being processed. A cleaning process that does an excellent job of oil removal but severely attacks or even slightly etches the metal surface is undesirable. The millimeter waveguide bore requires a surface finish of less than 35 μin. rms. To maintain this preplating finish, the cleaning processes should not etch the steel substrate. Inspection of the tube after the cleaning operation is made more difficult by the fact that no visual observation of the surface is possible since the solutions are circulated through a closed system.

The first step is a soak cleaning in an alkaline solution at 160°F for 10 minutes to remove the oils and lubricants applied at the tube mill. This step is followed by draining and rinsing. Since the steel tubes are not heavily oxidized, a mild acid is sufficient to neutralize the residual alkaline chemicals from the preceding step and to remove any light oxide film from the steel substrate. After the pickling operation, the tube is drained and rinsed.

The final step is a sodium cyanide rinse for 3 minutes at room temperature. This accomplishes two things:

(*i*) It inhibits tarnishing of the activated steel substrate resulting from an inadvertently long dwell time between cleaning and plating.

(*ii*) It neutralizes the residual acid salts and, as a result, prevents their carryover into the plating solution.

The copper anode with its insulating spacer is inserted into the cleaned, wet tube and both are loaded into the plating machine. The end connections are fastened and the hot copper cyanide plating solution is pumped through the rotating tube at a flow rate of 25 gpm. When the tube reaches the operating temperature of the plating solution, the rectifier is turned on. Upon completion of the specified plating cycle, the rectifier automatically shuts off, the electrolyte is drained, and the tube rinsed in cold and hot water. After unloading the plated tube from the plating machine, the anode and spiral are removed. To dissolve residual plating salts, the waveguide tube is again cleaned with a sodium cyanide solution for 3 minutes at room temperature. The tube is then rinsed and dried.

The uniform current density distribution and therefore uniform plating is assured through the rotation of the tube and uniform mixing of the solution throughout the tube. The rotational speed, spiral dimensions, and the plating time (12 minutes for a 10-micron thickness) tend to minimize the periodicity. This occurs from the mechanical action of the insulator on the copper plate. The current density, fluid flow pattern, and temperature are coupled process parameters to insure a minimum effect of secondary current distribution on the copper thickness control.

The cathodic deposition efficiency is greater than 90 percent. The anode, which is a copper tube (25 microns in diameter), is dissolved at close to 100 percent efficiency and is used to plate an average of 75 steel tubes. The cathode-to-anode ratio begins at 5.58 and decreases to 14.29.

Waveguide tubes plated with this system showed uniform thickness with no significant diameter variations. Figure 11 shows the thickness results of the horizontal plating facilities at 0°, 90°, 180° and 270° positions around the diameter. The average thickness was controlled to

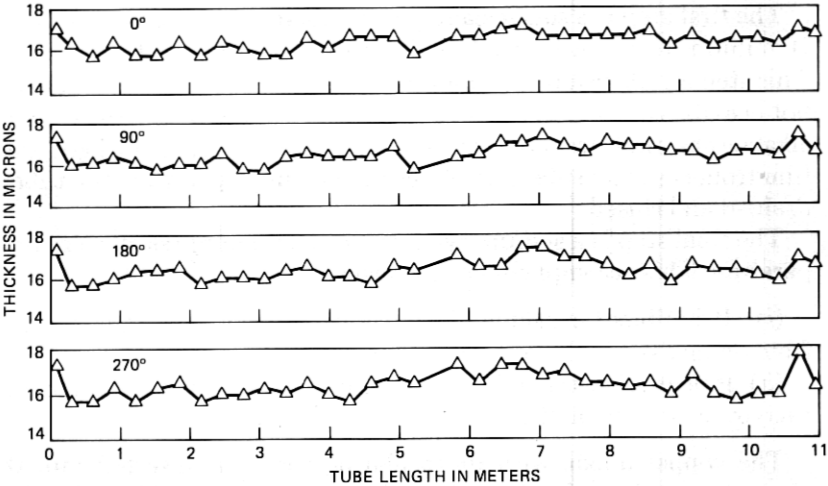

Fig. 11—Plating thickness results.

approximately 16 microns with a variation of ±2 microns. The developments in the copper plating and surface preparation prior to dielectric lining contributed significantly to the low ohmic loss characteristics of the dielectric-lined waveguide. Figure 12 shows the plating area during the pilot production period.

III. PILOT PLANT OPERATION

3.1 Operating strategy

The previous section of the paper discussed some aspects of the first objective, namely, the research and development of the manufacturing process technology. The second project objective—the fabrication of the waveguide for Bell Labs evaluations and the major field evaluation test—proved to be an equally challenging objective. During the period from 1970 through early 1972, effort was directed toward prototype facilities and providing approximately 2.3 kilometers of 51 millimeter waveguide for Bell Labs evaluations. During the period from late 1972 through 1973, effort was directed toward finalizing designs, establishing prototype production facilities, and adding operating personnel. This period essentially represented the "design, build, and prove-in" stages. By early 1974, Forsgate was producing approximately 2.3 kilometers of 60-mm waveguide per month.

As the waveguide installation designs and procedures were more clearly defined, it became apparent that additional space would be required for waveguide assembly, sheath preparation, and packaging for field installation. Discussions with Western Electric–Kearny resulted in the addition of approximately 25,000 ft^2 of space in the merchandise

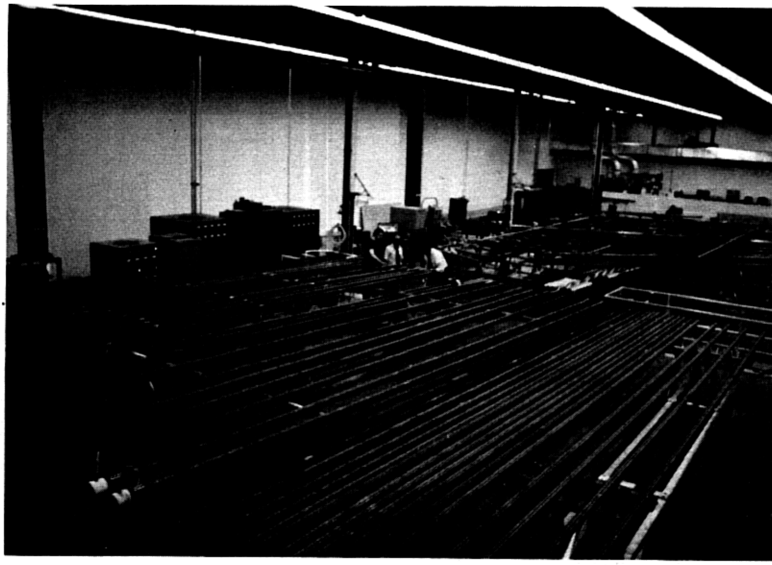

Fig. 12—Plating areas.

building at the Kearny Tract. A subsequent decision by Bell Labs to separate the sheath installation from the waveguide installation resulted in a reduction in space requirements to approximately 16,000 ft^2. This space was prepared in 1973 and early 1974 to include the following operations:

(*i*) Receive waveguide from Forsgate.
(*ii*) Test coupled waveguide sections (~6–9 meter lengths).
(*iii*) Purge with nitrogen and cap waveguide ends.
(*iv*) Install the waveguide roller supports.
(*v*) Construct shipping package.
(*vi*) Insert and package waveguide.
(*vii*) Ship to field installation.

With the space and processing considerations established, effort was directed toward staffing the operating (shop) organization. It was projected that 35 shop personnel would be required to staff the facilities for fabricating, testing, and packaging the waveguide medium. Arrangements were made with Western Electric–Kearny to provide both the shop supervision and direct work force. The consideration for shop operators involved establishing proper job classifications, personnel selection, and training. The overall training involved the rotation of shop operators on process facilities to provide the flexibility of moving personnel to various facilities for maximizing the efficiency of the shop operation.

The operating personnel, while reporting to the Forsgate management, were retained on the Kearny personnel roll. The shop experience was provided from Kearny in order to minimize the start-up of pilot plant production facilities. In addition, this arrangement provided ERC with the unique position of having both engineering and operating responsibility.

3.2 Scheduling

The scheduling of waveguide fabrication was closely coordinated with the projected Bell Labs installation plans for the field evaluation test.[4] The original schedule was to provide 13.5 km in 1974 and 16.5 km in 1975 for a total of 30.0 km. The revised schedule provided 12 km in 1974 and 2 km in 1975 for a total of 14.0 km. The schedule was such that initial fabrication began during the first quarter of 1974 and reached a peak of 2.3 km per month during the third quarter of 1974. This output represented an average daily processing rate of 20 waveguide tubes.

3.3 Process and reliability control

The waveguide installation for the field evaluation test initially was planned to be part of a commercial route in New Jersey. As such, the fabricated waveguide required a quality level consistent with long-term reliability. Considerable effort by both Bell Labs and Western Electric was directed toward meeting this goal. The Forsgate Laboratory quality control included the following plans:

(*i*) Develop a quality control program for the waveguide processing and testing areas for:

In-coming material inspection
Facility inspection
In-process checking at all operations
Overall quality survey prior to shipment

(*ii*) Establish inspection procedures and personnel training.
(*iii*) Document key waveguide processing data for design and specification purposes.

A complete history of dielectric-lined waveguides was kept through the field evaluation test production. The information included:

(*i*) Steel melt, tube run, tube geometry.
(*ii*) Process data, date, parameters, material.
(*iii*) Inspection and reliability data.

The detailed information was compiled for data analysis, fault analysis, and determining the process capability at each step of the assembly operations. The 1974–1975 field evaluation test waveguide fabrication had an overall process yield of 77 percent during the peak operating period. During the final months of operation, the overall yield exceeded 90 percent. This overall improvement in process yield was mainly due to two factors:

(*i*) The valuable manufacturing experience gained throughout the field evaluation test.

(*ii*) The improvements on the individual process parameters and the implementation of quality control procedures.

The two technologies discussed earlier, namely the tube and plating developments, were indicative of such improvements as noted below:

	Field evaluation test production yield		
Process step	*Initial 1/3 prod.*	*Next 1/3 prod.*	*Final 1/3 prod.*
Tube Processing	96.9%	99.1%	99.7%
Copper Plating	86.6%	97.2%	98.9%

The waveguide tube mill improved inspection allowed for few tube rejects at the fabrication plant, and as a result provided the capability for a very high overall process yield. One of the key factors in the increased copper plating yield was the reduction in thickness to 12 microns nominal.

The improvements made during the field evaluation test fabrication definitely demonstrated the capability of expanding the process technology to a factory producing 750 km to 1500 km per year.

IV. OVERALL SUMMARY

The Western Electric Company utilizing the ERC technical capability established the Forsgate Laboratory. This laboratory very successfully met the objectives for the research and development of manufacturing process technology for waveguide fabrication. The waveguide medium as developed exhibited extremely low-loss transmission characteristics. This represented a key development in proving that a reliable and cost-competitive waveguide system could become a reality.

The technology and facility developments at the Forsgate Laboratory demonstrated the manufacturing process feasibility for high-volume factory production.

ACKNOWLEDGMENT

The highly successful manufacturing process research and development was mainly attributed to the dedicated, aggressive, and hard-working Forsgate staff. This staff combined in a team effort to overcome tremendous technical challenges in a very short period of time.

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