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November 7, 1956

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Radiation Laboratory
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ABSTRACT

A detailed method of fabrication is given for the construction of a low-loss, rigid, 125-ohm coaxial line for the transmission of millimicrosecond (μsec) pulses. The characteristic impedance can be made uniform by use of this construction method, and can be predicted to about 1% by utilization of the charts relating dielectric density, dielectric constant, and diameter ratio to characteristic impedance.

A method is given for the correction of discontinuities associated with corners and dimensional transition sections. This method reduces reflections from corners or transition sections, when observed with an oscilloscope of 1- μsec rise time, to 1% or less.

The cost figures are given for six 150- μsec single transit-time lines.

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This note describes the "pulse-guide" (pg) transmission lines that were installed in the Bevatron; it is intended to inform others on how we fabricated our lines. The electrical characteristics of this line, as well as dimensional data,¹ have been published previously.² The pertinent data are represented in Figs. 1, 2, and 3.

All the pg installed so far consists of commercial hard-drawn 0.250-in. o. d. copper tubing as the center conductor, a foamed polystyrene dielectric,³ and copper foil outer conductor, held together with paper-backed tape,⁴ and dimensioned to produce a nominal characteristic impedance of 125 ohms. In two early versions the outer conductors were of nominally round and of square cross section. The square version was tried because it was easy to fabricate pieces of the dielectric on a band saw--with the aid of a suitable jig and with care in feeding the material--producing a sufficiently consistent outer dimension. However, the wrapping of the copper-foil outer conductor requires a great deal of care to assure a tight fit to the dielectric. Although we succeeded in wrapping a few sections of line, hand-wrapping rectangular sections did not seem to be a reasonable method for production of large amounts of line. A round cross section was the obvious choice, since there are pipe-wrapping machines of a simple nature that wrap a spiral of tape around a line of circular cross section, insuring a tight fit of the outer conductor.

The dielectric is fabricated from "logs," about 2 by 3 by 9 ft, which weigh about 80 lb. The nonuniform outer portions are removed by means of a hot wire so as to approximately square up the log (Fig. 4). The approximate effective dielectric constant may be conveniently obtained by determining the density of the roughed-out log (the log is approximately 20 times as dense as air). The normal range of the density of the logs is 1.3 to 1.7 lb/ft³, corresponding to dielectric constants of 1.0225 to 1.0275 (Fig. 1). Samples from different parts of the interior of a roughed-out log show but small variations.

¹ UCRL Engineering Note: C. N. Winningstad, "Pulse-Guide Diameter Gauge Chart," File No. 4311-03 E5, August 29, 1956.

² UCRL Counting Note: Kerns, Kirsten, and Winningstad, "Pulse Response of Coaxial Cables," File No. CC2-1, March 1, 1956.

³ Dow Chemical's "Styrofoam 22" in the log form.

⁴ Minnesota Mining and Mfg. Co.'s "Scotch Electric Tape No. 1," 2-in. crepe paper pressure-sensitive adhesive tape.

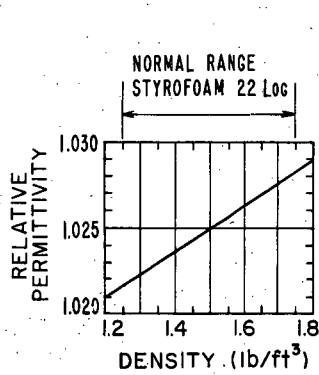


FIG. 1

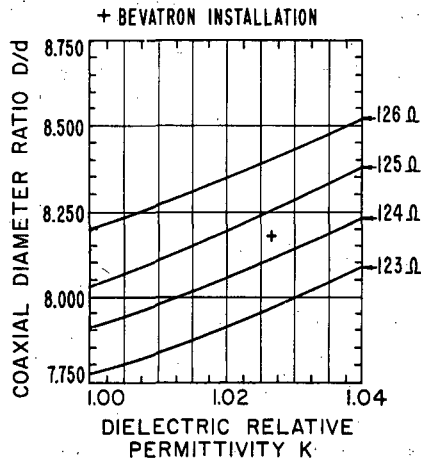


FIG. 2

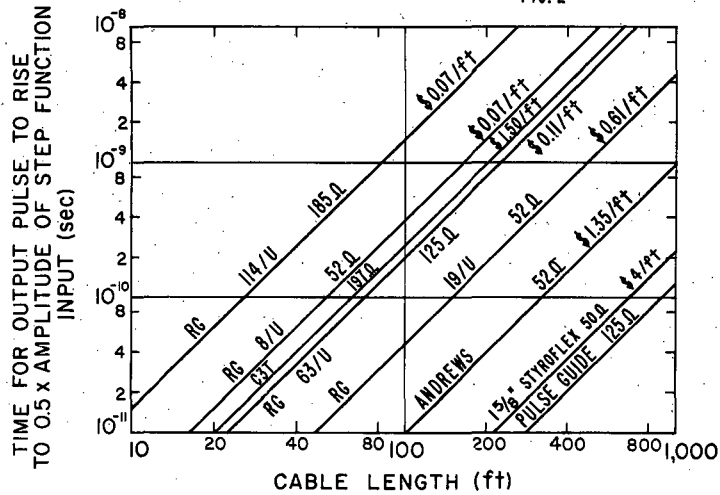


FIG. 3

MJ-12524

Fig. 1. Dielectric constant as a function of density of a styrofoam 22 log. Data from notes by F. Kirsten and Q. Kerns.

Fig. 2. Characteristic impedance family curves from $Z_0 = \frac{138.058}{\sqrt{k}} \log_{10} \frac{D}{d}$ (Ref. 1).

Fig. 3. Calculated step-function response of various coaxial cables based upon decibel attenuation varying as the square root of frequency (Ref. 2).

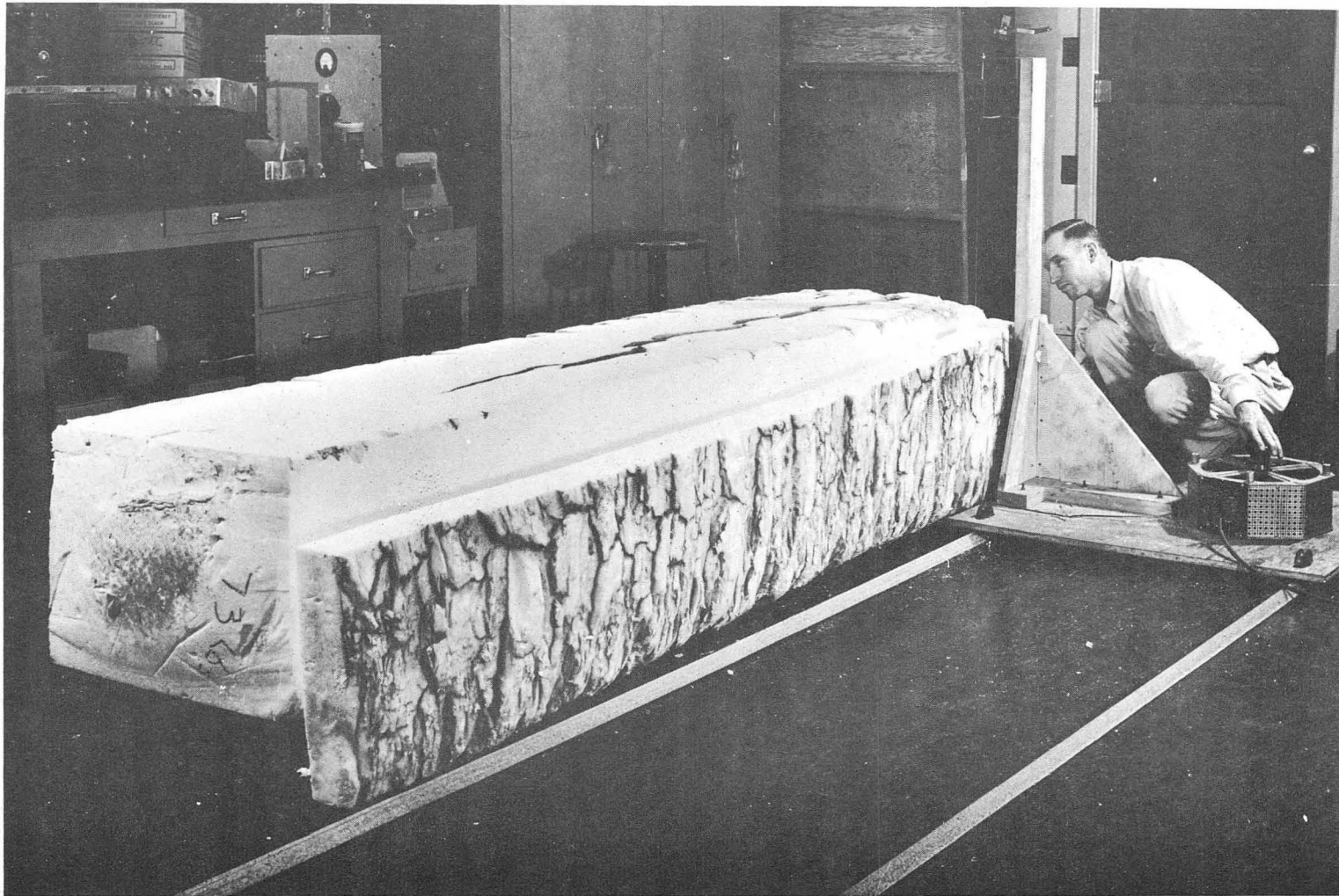


Fig. 4. Styrofoam log being roughed out with a hot-wire jig.

ZN-1633

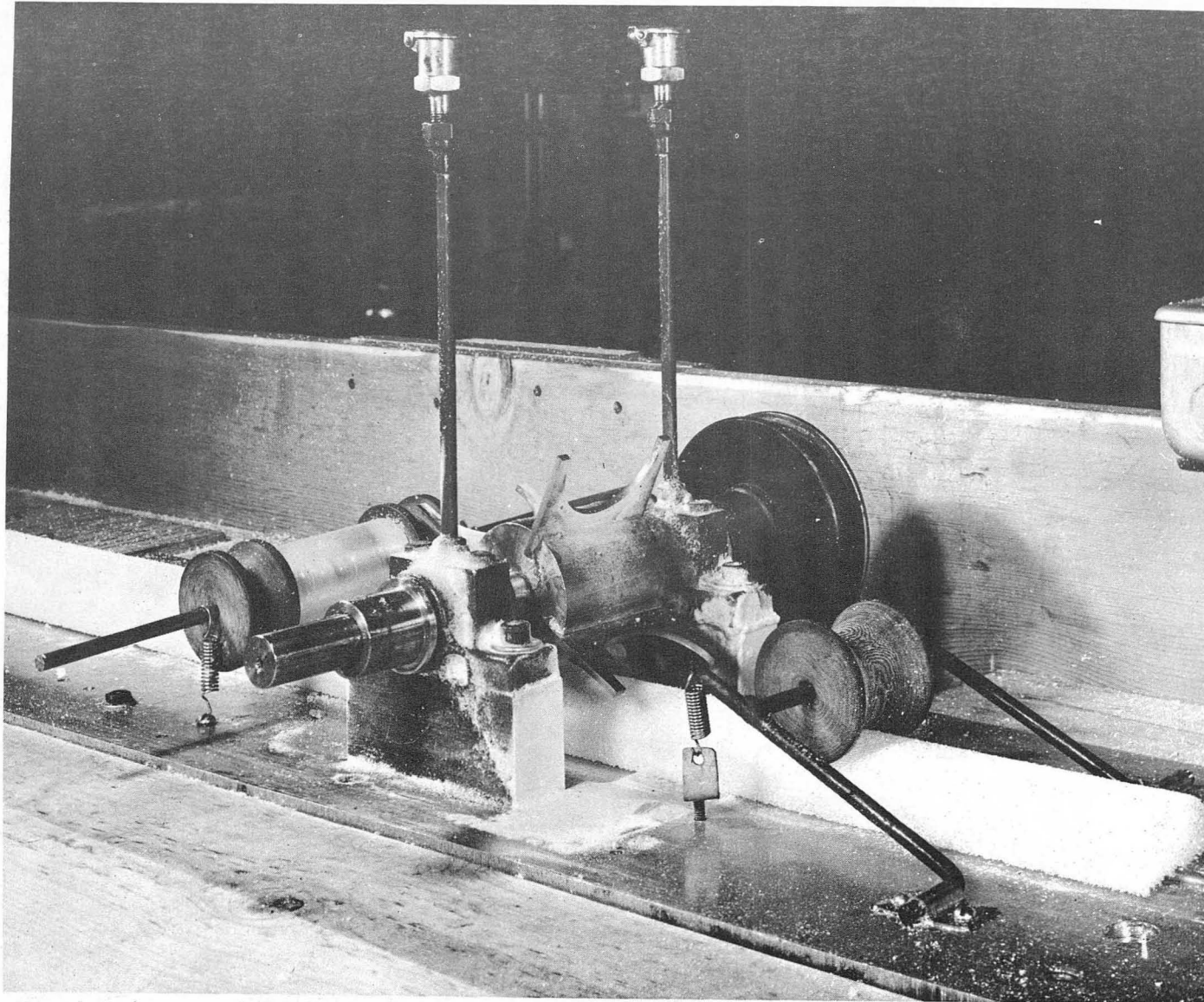
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The roughed-out logs are processed on woodworking saws to produce a rectangular cross section about $1\text{-}1/4$ by $2\text{-}3/8$ in. by 8 ft. These pieces are run through a shaper machine which cuts a semicircular groove of 0.250-in. diameter down the center of one of the $2\text{-}3/8$ -in. faces. Most of our logs have had a density of 1.60 lb/ft^3 , and thus a dielectric constant of about 1.0265. We chose 124.5 ohms as a reasonable compromise to match randomly chosen sections of RG 63/U. Our samples of $1/4$ -in. hard-drawn copper tube have all been 0.250 in., within ± 2 mils. Thus we use a shaper machine with a tool designed to contour the rectangular strips of dielectric into semicircular cross section of 2.045 in. diameter. (See Fig. 5.) The machine uses a $1/4$ -in. rod, half exposed above the table, as a guide for the dielectric. When a rectangular strip with the $2\text{-}3/8$ -in. face is placed with the $1/4$ -in. semicircular groove down over the $1/4$ -in. rod, the piece is guided straight into the center of the cutters. A cylindrical spring-loaded hold-down roller is used before the cutters, and a dished-out cylinder (spool shaped) hold-down roller is used after the cutters.

The $1/4$ -in. tubing is prepared by sorting out the tubing so that all the tubing for a given line is of the same diameter within ± 1 mil. The tubing is placed in a metal-working lathe collet, and the ends are squared off and tapped for a 10-32 screw thread. The tubing comes in 12-ft lengths. We join 12-ft lengths, and fractions thereof, with 10-32 stud bolts to make lengths up to 27 ft. (This is the longest straight-line run required in a transmission line totaling 130 ft in the Bevatron. Longer lengths would be difficult to handle, as it would then take two men to lift and carry the finished sections without risk of damage.) The sections of tubing must be connected carefully, as they must be very tight to assure continuous contact; they must not bulge at the joint, nor be so loose as to produce a gap after the lines have been moved a few times. The center conductor must not be scarred up by the gripping tool used to tighten the lines.

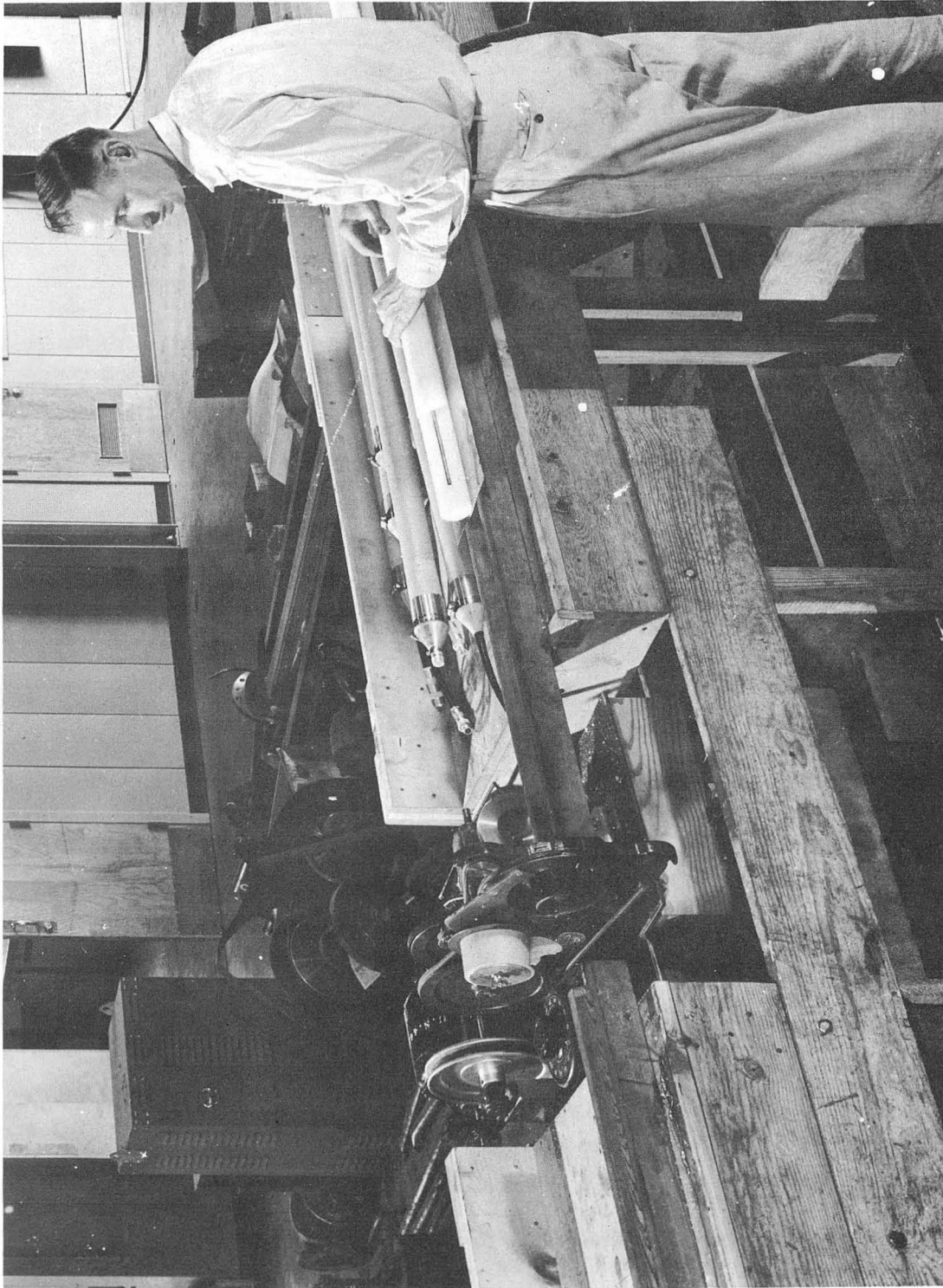
The assembling arrangement consists of a long table with the wrapping machine at the center (Fig. 6). A long trough, with a $2\text{-}1/4$ -in. semicircular cross section, is placed down the length of the table on each side of the wrapper. The copper foil (7 in. wide, 3 mils thick, and cut to length) is laid lengthwise in the input side of the trough. Strips of the semicircular dielectric are laid down in the trough on top of the copper foil. The copper center conductor is placed in the groove of the dielectric. A second group of strips of the dielectric is laid down on top of the first group of strips, so as to form a circular cross section with the copper tubing held firmly in the center. The second group of strips should be arranged so that the joints at the ends of the 8-ft lengths of the dielectric are not directly above the joints of the first group. The strips should have been cut to length in a carpenter's miter box, so as to assure square butt joints.

The copper foil is now folded around the dielectric, resulting in a circumferential overlap of about $1/2$ in. along the length of the pg line. The foil is temporarily held in place with pieces of 1-in. masking tape at 6-in. intervals. For advancing the line through the wrapper, screw eyes are placed into the threaded exposed ends of the center conductor, and a steel cable from the wrapping machine is connected to the forward end of the line, through the wrapping machine, along the table, under the table to the drive mechanism, to the opposite end, on top of the table, and finally to the rear



ZN-1630

Fig. 5. Dielectric being shaped to semicircular cross section (protective cover with vacuum cleaner chip removal system removed to show cutters).



ZN-1629

Fig. 6. Pulse guide prior to temporary taping.

end of the line. The machine has a die at the input which holds the copper foil tightly against the dielectric as it is being wrapped. As the line is advanced into the wrapper, one removes the temporary tape strips (Figs. 7 and 8). On the output side of the die, a roll of 2-in. -wide paper-backed pressure-sensitive tape⁴ is caused to circle the line (like a planet gear around a sun gear), depositing the tape in a spiral fashion with about a 3/8-in. overlap.

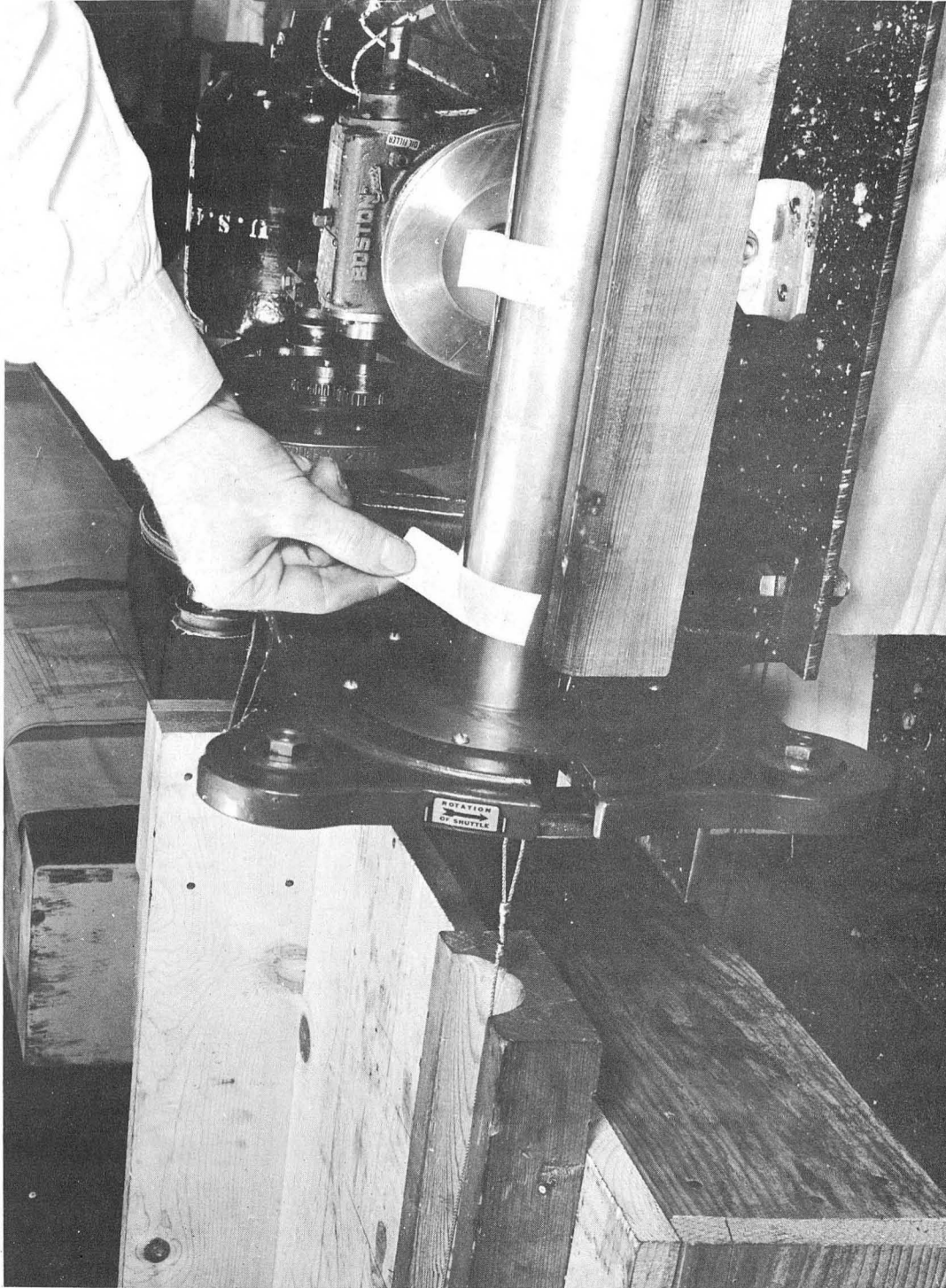
The resulting pg line is strong enough that a 27-ft line can be lifted without damage by one man at the center with his hands 3 ft apart. The cables are installed in a metal trough, which is desirable for both mechanical and electrical protection. The assembly of the various sections is accomplished by use of 10-32 studs to join the center conductors. The outer conductor of one section is pretinned on the outside with a low-melting-point solder, and the outer conductor of the joining section is fabricated with 1 in. of overhanging outer conductor. This overhang is slit longitudinally at about 3/4-in. intervals, bent outwards, and pretinned on the inside. Thus when the center conductors are screwed together end to end, the serrated outer conductor of one overlaps the other. A resistance heating unit is wrapped around the joint, and a timer regulates the heat. One can thus obtain a good joint without damage to the dielectric.

For waves propagating on the principal mode,⁵ a corner constructed by simply cutting two pieces of a transmission line at, say, 45°, and joining them results in a discontinuity which acts much like a capacity at the corner of an otherwise continuous line.⁶ By deliberately reducing the diameter of the line in a smooth fashion in the region of the corner, one can in effect make a compensating inductive discontinuity, resulting in a reflection from the corner which is less than 1% when observed in a 1-μsec rise-time system. (See Fig. 9.) The transition from the pg to short pieces of RG 63/U (for patching purposes) is compensated similarly. There is a conical section, of length about 1.5 times the diameter of the pg, connecting the pg to the RG 63/U. The taper of the center conductor is not linear; the center conductor is contoured so that the characteristic impedance at the input and output ends of the cone is 125 ohms, but is higher than 125 ohms in between.

The cost of the pg line is approximately 35 cents per foot for materials, and \$ 4.50 per foot installed. The installed cost is realistic, as this includes labor charges at the "overhead rate," and includes the extra time due to the usual problems associated with a "first time" project. Corner sections and transition sections cost about \$ 10 each. The installation consisted of six runs of about 133 feet each, each containing two right-angle corners, three

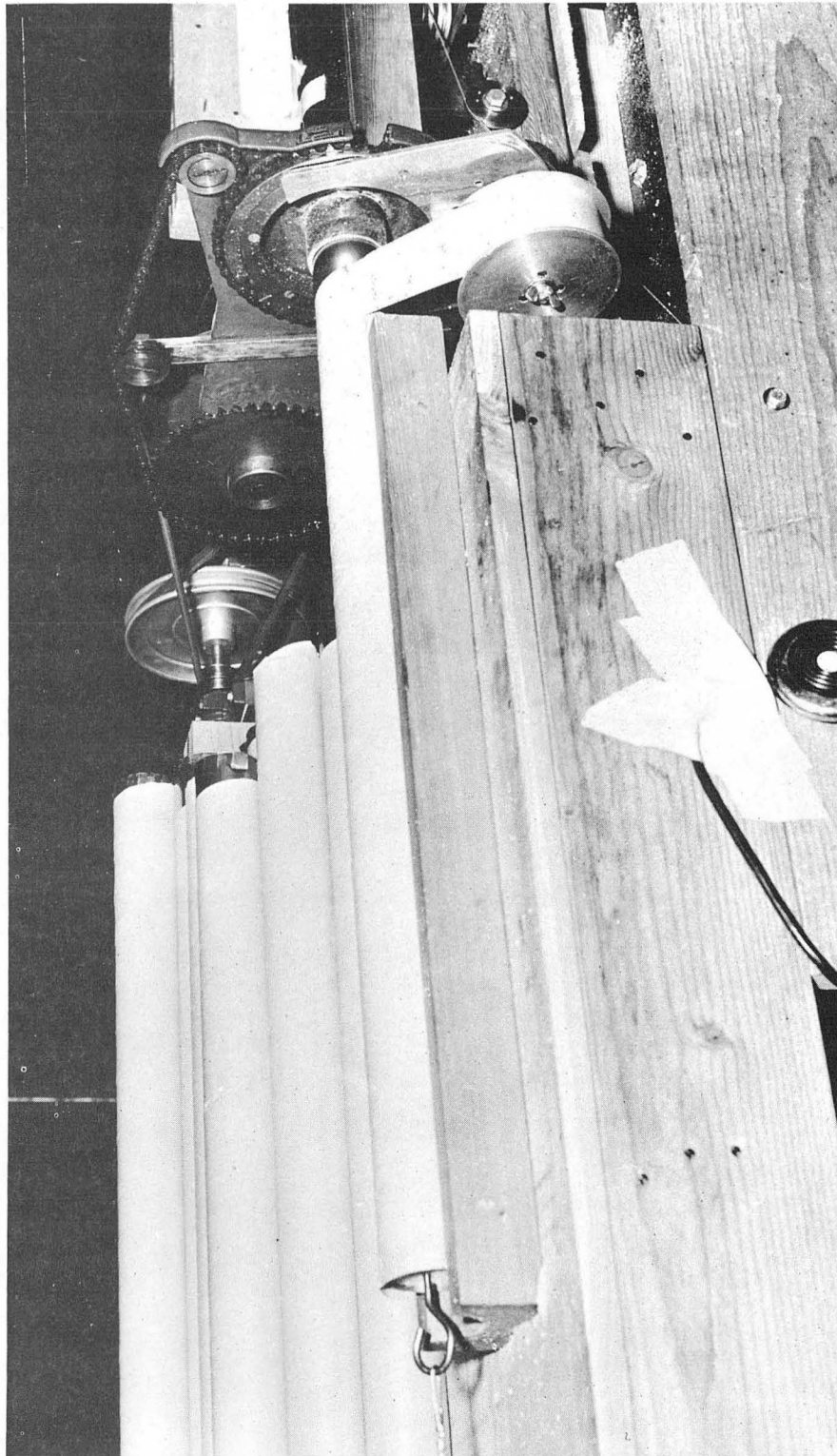
5 I. A. D. Lewis, Millimicrosecond Pulse Techniques (McGraw-Hill, New York, 1954), p. 18.

6 K. Tomiyasu analyzes a somewhat different case in detail (The Effect of a Bend and Other Discontinuities on a Two-Wire Transmission Line, Proc. I.R.E. 38, 679-82 (1950)), and requires series and shunt elements in his equivalent circuit. The use of only an equivalent shunt capacity seems justifiable in this case, because observation with a 1-μsec rise-time oscilloscope shows that reflections from an uncompensated pg corner are quite like simple capacitive reflections.



ZN-1631

Fig. 7. Pulse guide entering pipe-taping machine.



ZN-1632

Fig. 8. Pulse guide leaving pipe-taping machine.



ZN-1634

Fig. 9. Disassembled 90° corner and transition section.

small-angle bends, six straight sections, two transition sections, and just under 5 ft of RG 63/U at each end of the pg.

Future plans call for six more identical lines for the Bevatron: ten 14-ft sections, each with 1-ft RG 63/U pigtailed for portable use, and seven 100-ft lines for the 184-in. cyclotron. The cyclotron lines will be somewhat smaller, using 3/16-in. copper tubing as the center conductor. There is also an adjustable line under construction which will have a range of about 1 μ sec.

The work described was done under the supervision of Quentin Kerns. Much credit is due to the Electronic Installation group of Gerald V. Wilson in general, and to Herman Volz in particular, for their skill, patience, and perseverance in the fabrication and installation of the lines.

This work was done under the auspices of the U. S. Atomic Energy Commission.