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WT4 Millimeter Waveguide System:

Waveguide Installation

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This paper describes the insertion method for installing WT4 waveguide. The rationale for the selection of the insertion method over competing installation techniques is provided, and the field installation tools and techniques developed to splice and push waveguide are described. Insertion sites are selected by the criteria given in this paper. The analysis of expected push forces is presented, and an example push force problem is solved.

I. INTRODUCTION

The buried portion of the WT4 waveguide system is a coaxial twin pipeline composed of three main elements: waveguide, compliant supports attached to the waveguide, and sheath.[1] When waveguide is installed by the insertion method, described more fully in the sections which follow, the sheath is constructed to completion (including restoration of the right-of-way and acceptance testing of the sheath line) in entire repeater or multirepeater spans before waveguide is installed from access points located at convenient places on the route.

The installation of the sheath is an operation resembling so closely the construction of a conventional pipeline that the familiar equipment and techniques of the pipeline industry have been adopted.[2] In contrast, the flange splicing and push inserting of waveguide required new developments of tools and methods. The particular tools and methods evaluated during the field evaluation test are described in detail in the following sections. Design of a new waveguide insertion system based on the results of the field evaluation test experience is also discussed.

II. BACKGROUND

2.1 Modular installation

Although direct burial of unsheathed waveguide was the first installation method developed, the very costly trenching and padding specifications which were required to protect the waveguide from backfill pressures quickly led to the introduction of a protective sheath. The resulting coaxial pipeline was initially installed by the so-called modular method in which both waveguide and sheath were weld-spliced over the open trench and buried simultaneously.

For modular installations the units delivered to the field were coaxial modules* in which the waveguide and sheath were carefully matched in length. Because of this precaution, an installation sequence which was begun with the waveguide and sheath weld positions slightly staggered (with the waveguide protruding from the sheath in the direction of construction) set the pattern for staggered weld positions thereafter. With the waveguide flange thus exposed, each coaxial module was simply attached by welding first the waveguide flanges (the waveguide in each new module was accessed by sliding the waveguide a few inches out of its sheath) and subsequently sliding the sheath in the reverse direction to set up a butt weld in the sheath.

Yet, even while this modular method was under active development, the potential economies which could be achieved in manufacturing and construction if the installations of sheath and waveguide could be separated were evident. Modular installation required the manufacture of waveguide-sheath modules, which implied handling sheath in the assembly plant. Furthermore, a sheath trimming operation was needed to match the length of the sheath to its enclosed waveguide. Probably most important, the installation of waveguide-sheath modules required field equipment and construction methods which departed considerably from established pipelining technology. Since a large part of the installed cost of any buried transmission medium is associated with grading, excavation, and restoral work, it is desirable to avoid complicated techniques or unusual equipment which may cause delays during these stages of construction. The insertion installation method so satisfactorily solved these problems that the modular method was abandoned.

2.2 Insertion feasibility

The insertion method of waveguide installation became feasible with the development of a low-friction roller support[1] and the demonstration

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* Herein, a module means a factory-produced length of waveguide flanged at both ends. In the pipeline industry an equivalent meaning is communicated by a "joint" of pipe. Waveguide lines made up by connecting modules together can be installed by the "modular" method discussed here or by the insertion method described in other sections.

by analytical and experimental work that long push distances could be achieved with push forces well under the roller support loading limit (axial load 10,000 lbs). In fact, since the roller support has a coefficient of friction of only 0.058, insertion distances of 7½ miles could be achieved with a push force of 10,000 lbs if the waveguide sheath were perfectly level and straight.

Of course, the sheath is not perfectly straight, and in forcing the waveguide to follow its shape the sheath places increased loads on some roller supports. Furthermore, when waveguide is pushed through a route bend the axial compression (or tension) in the waveguide in the bend causes the waveguide to displace laterally in proportion to the severity of the bend and the axial force so that the roller supports are placed under additional loads. Loads from both of these sources increase the frictional resistance in the bearings and a greater push force is required to move the waveguide through the sheath.

Practically, the forces required to insert waveguide can be predicted from a route-independent "effective" coefficient of friction, which combines the inherent roller support coefficient with the additional clamping resistance caused by imperfect sheath profiles, and the route-dependent additional restraints caused by route bends and elevation changes. Appendixes A and B are devoted to an analytical investigation of these coefficients and restraints—Appendix A to the argument that the "effective" coefficient will not be greater than 0.075 and Appendix B to a method for calculating route bend restraints. To demonstrate their use, an example push force problem is worked out in Appendix C.

Because push forces predicted by the analytical work matched the insertion forces measured during the field evaluation test, it can be quite confidently predicted that 3-mile insertion distances will be routinely achieved with push forces much less than 10,000 lbs.

III. GENERAL PLAN FOR WAVEGUIDE INSTALLATION

The first step in the waveguide installation process is to develop an insertion plan which identifies push sites. In unusual terrain or for routes with many bends it may be necessary to verify that the distance between push sites is not excessive by calculating the insertion forces. A schedule is then prepared for each push site which specifies the sequence of installation of dielectric and helix modules.

At the push site an excavation is made which exposes approximately 100 feet of sheath. The sheath is cut at one end of the excavation, lifted, and supported so that the free end is horizontal and above ground level. An extension is welded to the sheath so it will project beyond the end of the excavation. The components of the insertion equipment are then aligned with and attached to the extension on the sheath.

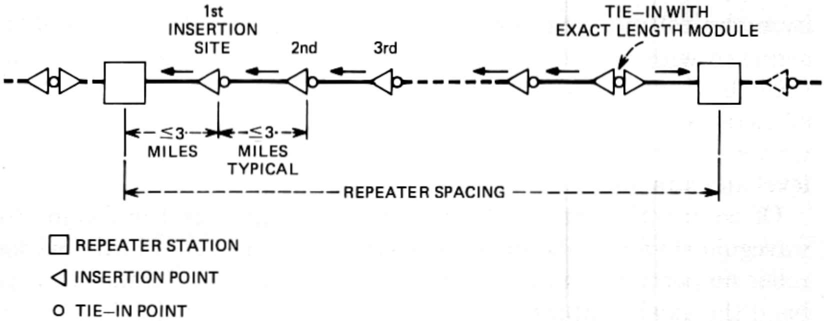


Fig. 1—Insertion segments within a waveguide repeater span.

As shown in Fig. 1 the initial insertion is made toward a repeater station from the first push site beyond the repeater station. Waveguide splices and pushes are made until the leading waveguide flange reaches the repeater station and is secured. At the push site the waveguide and sheath ends are temporarily sealed and lowered to the trench bottom. The insertion equipment is moved to the next adjacent site and is set up to repeat the process except that this time the push is made to the first push site instead of the repeater station. When the leading waveguide flange reaches the waveguide at the first site, the waveguide lines are spliced in the trench with special equipment, the gap in the sheath is closed, and the excavation is filled. This move-ahead-and-push-back procedure is repeated at each successive insertion site. The only variation required is to insert in both directions from the last site. At the last site a special-length waveguide module is fitted and spliced into the final gap in the waveguide line, and the sheath is closed, completing a repeater-to-repeater span.

If desired, insertions can be made in both directions from any site large enough to allow reversal of the insertion equipment. For example, an alternative installation technique might consist of inserting waveguide in both directions from every second site, thereby limiting activities at the remaining sites to the welding together of the abutting waveguide lines.

IV. THE SELECTION OF INSERTION SITES

The following requirements must be considered when push sites are selected:

(*i*) The temporary use of an easement 50 feet in width and 200 feet in length is required at each one-way insertion site. A much shorter span is acceptable for a site (a tie-in site) which will be used only for joining waveguide lines pushed together from adjacent push sites. At two-way insertion sites, the required easement length is twice that needed for a one-way site.

(*ii*) Access to each push site for heavily laden supply trailers will be necessary.

(*iii*) The distance and the route configuration between push sites must not combine to require a pushing force in excess of 10,000 lb. The force can be calculated as shown in Appendix C.

(*iv*) Well-drained locations are desired, and bends in the sheath should be avoided so that alignments of the waveguide and sheath for the final tie-in splices are simplified.

Since each set-up for waveguide insertion is the second disturbance of right-of-way which was completely restored after the installation of sheath, it is important that insertion sites be carefully selected to avoid areas with substantial improvements and be located as closely as possible to public access. Ideally, affected property owners will be informed from the outset of negotiations for an easement of the two-stage nature of sheath and waveguide installation. However, the large distance allowed between sites should make their selection and acquisition simple.

V. INSTALLATION OF FIELD EVALUATION TEST WAVEGUIDE

5.1 General

During the field evaluation test, 8.75 miles of waveguide were installed using the insertion technique. The waveguide was installed in a series of eight pushes performed according to the general plan for waveguide installation discussed in Section III. The longest segment was 1.5 miles long and required a push force of about 2000 lb.

Each of the three possible kinds of field site was needed. To recount, they are sites used for a push in one direction only and a subsequent tie-in, sites used for pushes in both directions and a tie-in, and sites used only for a tie-in. The decision about the use to be made of a site was usually easily made from an assessment of the available space.

5.2 Insertion operations

Figure 2 shows the arrangement of the equipment used to install the field evaluation test waveguide. The flow of waveguide is from the shipping containers on the right to the sheath on the left. Each waveguide module leaves the sheath-like tube in the shipping container by way of a feeding tray, is delivered to the aligning and splicing fixture in the waveguide splicing vehicle (WSV) through an entry tube where it is joined to the waveguide line, travels from the splicer to the pusher in a second support tube, rolls the length of the pusher (where it picks up the pushing force), and enters the permanent, buried sheath by way of a temporary

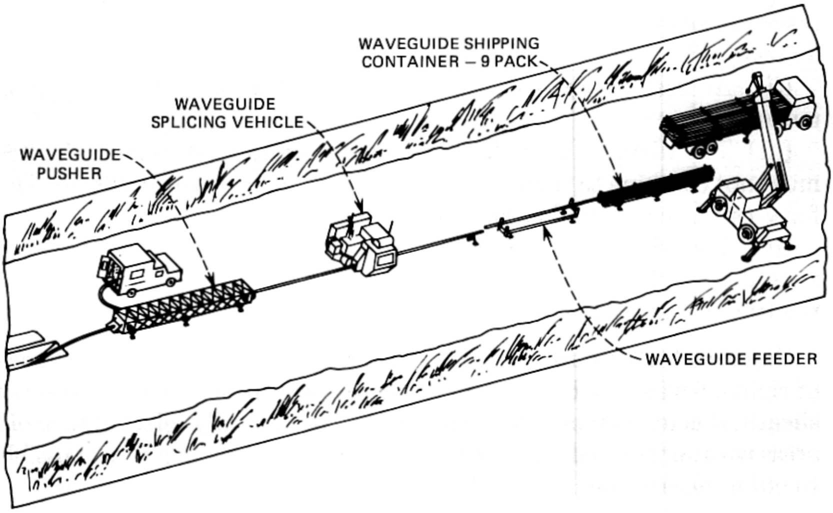


Fig. 2—Arrangement of field evaluation test equipment.

extension from the sheath to the frame of the pusher. The guiding principle in the design of all components which transported waveguide was that the waveguide would be supported at all times by the roller supports on the modules.

The distances separating the equipment shown in Fig. 2 were governed by the nominal length of 9 m (29 feet) for a waveguide module. The following relationships between waveguide and equipment resulted;

(*i*) When a flange pair was in proper position for welding in the WSV, the next flange pair to the left was very near the point of entry to the pusher, but entry had not yet occurred.

(*ii*) The next flange pair in the same direction was gripped in the pusher machine somewhere near the exit end of the pusher.

(*iii*) The right end of the waveguide module which was being welded to the waveguide line in the WSV projected to the right to a point just beyond the end of the support tube providing entry into the WSV.

(*iv*) The waveguide feeder machine was approximately the same length as a waveguide module, and a small separation distance was needed between the feeder and the WSV support tube to avoid interferences with the mobile feeder tray.

(*v*) Another small separation distance was provided between the waveguide feeder and the shipping container frame, also to avoid interferences. Beyond that the shipping container projected another 30 feet.

The entire set-up was approximately 180 feet in length.

Waveguide modules were transported to the site on flat-bed trailers which could carry 12 shipping containers. Each container had nine tubes in which waveguide modules were secured with expanded duct plugs. To use, the containers were first moved from the trailer to the shipping container frame, which was aligned with the feeder. In that position all tube ends and duct plugs were accessible to the feeder operator and were within the ranging zone of the waveguide feeder machine. The feeder operator aligned the feeder tray with the desired tube, removed the duct plug, and pulled the waveguide module into the tray where its length was measured. The tray was then shifted into alignment with the support tube entering the WSV, and the waveguide module was coupled to the protruding end of the module in the WSV with a spring-loaded flange clipping device. At this time the feeder operator's contribution to the feed-splice-push cycle was complete so the operator set a switch in the "ready-to-push" mode and thereby completed a part of the control circuit to the pushing machine.

In the waveguide splicing vehicle the splicer operator removed the clip connecting the waveguide module to the waveguide line. An aligning and preloading fixture was attached to the flanges which were pushed together face-to-face, with a large force, and the flanges were welded. On completion of the weld, the fixture was rolled to the side to permit an unobstructed visual inspection of the splice. When the inspection was completed the operator depressed a "ready-to-push" switch which notified the pusher operator of his readiness and completed another stage in the pusher control circuit.

When both the feeder and splicer operators had completed their tasks and were prepared for waveguide motion under pusher power (signified by their activations of "ready-to-push" switches), the pusher operator could push waveguide. He did so by activating the third in a series of three switches which provided power to the pusher controls (and released the pusher brake) and increasing the swash plate angle in the hydraulic pump to accelerate the pusher. If necessary, either the splicer operator or the feeder operator could stop the push instantly with emergency stop switches located in their areas. The splicer operator had an additional way to stop the waveguide; he was in the best position to determine when the waveguide line had been pushed far enough (one module length), and he stopped the pusher by simply releasing the "ready-to-push" switch when the next pair of flanges was in the proper position for welding.

A cycle of operation consisting of the described feeding, splicing, and pushing tasks hypothetically could be performed in about 5 minutes. The time averaged over all the cycles of the field evaluation test was 9.5 minutes, but this average included time used exchanging empty shipping containers and making test welds for quality checks.

5.3 Ending operations at an insertion site

Since the feeder operator measured each module of waveguide as it crossed the feeder, a record of the total assembled length was available at all times for comparison with the estimated distance to the tie-in point at the opposite end of the insertion section. When this measured length was within five modules of the estimated length, the operation was interrupted. A tie-in crew, dispatched to the opposite end, measured the actual remaining push distance by inserting quick-coupling duct rods into the sheath until the rod string contacted the front end of the waveguide. This remaining push distance minus the measured distance between the centerline of the splicing fixture in the WSV and the point at which the waveguide sheath had been cut at the insertion site determined the number of modules which remained to be spliced and pushed. When a fractional part of a module resulted, the actual number of modules added was equal to the rounded-down whole number.

To make the final positioning pushes, after the waveguide had cleared the pusher, special module-like extensions with mechanically coupled flanges were used to supply a pushing force to the waveguide line. These extensions were fed through the pusher one by one as needed until the gap between waveguide lines at the tie-in site at the opposite end was closed. An observer at the tie-in site directed the operation.

The tie-in crew utilized a special fixture and welder which could be lowered into the trench to make the splice which joined the waveguide lines in the tie-in pit (see Section 5.6). The gap in the sheath was closed by fillet-welding both ends of a special piece of sheath (an oversized tube which was slipped over the waveguide sheath prior to splicing the waveguide) which bridged the gap and slightly overlapped the waveguide sheath ends.

The tie-in anchored the waveguide line and freed the insertion crew to detach the mechanically coupled push links from the line at the opposite end. The sheath extension was removed, and the waveguide sheath was trimmed back to expose the waveguide end. Waveguide and sheath were sealed with temporary caps (and, for the field evaluation test, nitrogen gas was supplied to the waveguide to produce a protective internal pressure of a few psi). The insertion crew then disassembled and moved all equipment to the next push site.

5.4 Waveguide splicing vehicle

The WSV used to splice waveguide during the field evaluation test (Fig. 3) was originally built for waveguide installation by the modular technique. The modular technique, of course, required complete mobility of the aligning fixture and welding machine, and that accounts for the tractor-mounted sidecab which houses the splicing equipment. The

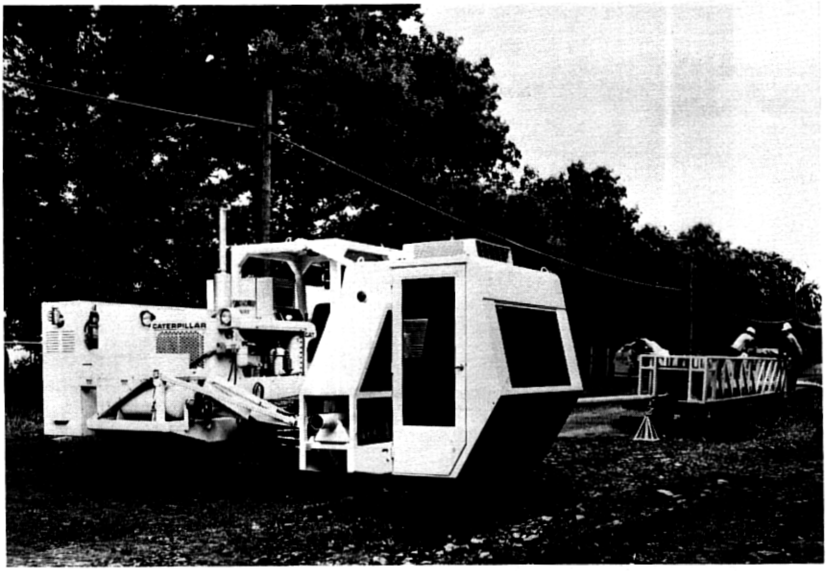


Fig. 3—The waveguide splicing vehicle.

tractor additionally served as a mounting platform for the compressed air, chilled water, hydraulic power, and electric power generators and housed the compressed gas cylinders which supplied the mixture of helium and argon which shielded the weld arc.

5.4.1 Splicing fixture

The flange aligning mechanisms and the welding torch were mounted in the splicing fixture, shown in Fig. 4, which was located in the WSV sidecab. The primary functions of the fixture were locating, aligning, preloading, and welding waveguide flange pairs, and it accomplished them with two waveguide flange clamps located in a C-shaped frame, a preloading mechanism for applying compressive face loads on the pair of flanges to be welded, a welding torch mounted on a ring gear, a torch cable retraction mechanism, and various associated controls, sensors, and indicators. All fixture equipment was mounted within a cabinet on a carriage which permitted movement of the fixture parallel to the axis of the waveguide line. This mobility of the fixture within the WSV permitted the flange clamps and welding torch to "seek out" the flange pair to be welded, which could be in various positions within the sidecab, and, subsequently, to "leave" the freshly welded flange pair to permit a visual inspection.

5.4.2. Torch, torch drive, and cable retraction mechanism

The torch is the welding electrode vise and the terminal for the electrical cable. It was secured in a bracket which permitted precise electrode

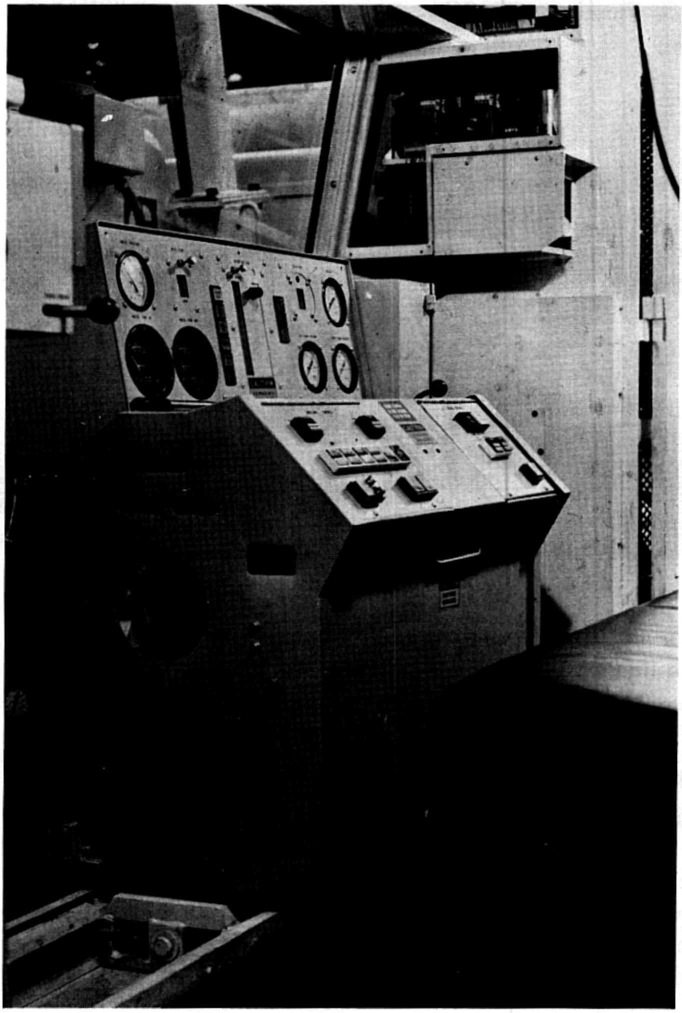


Fig. 4—The WSV aligning and splicing fixture.

adjustments in relation to the flange joint, and this bracket was in turn attached to a ring gear driven by an electric motor which produced one complete revolution of the torch (and therefore a completed weld) in approximately 95 seconds.

The torch was alternately driven in forward and reverse directions so that a torch-driver cycle was completed after two flange pairs had been welded. Sufficient electrical cable was provided to allow a complete revolution of the torch, and this cable was paid out and retracted during a cycle with a pair of sheaves, one of which was mounted on a traveling block in vertically oriented ways under the other. The weight of the traveling block produced a constant tension on the cable and thereby retained it in guides on the ring gear which held the cable away from the flange and moving fixture parts.

5.4.3 Flange clamps

Actual contact with waveguide flanges was made with flange clamps. Each flange clamp was composed of two halves which traveled in vertical ways to produce a clamp/unclamp action. As shown in Fig. 5, which illustrates the aligning mechanisms, the entire left clamp was in turn mounted on horizontal ways which permitted gripped flanges to be brought together. Figure 5 gives particular emphasis to the method by which the fixture was initially calibrated with shims to produce coincident left and right clamp centerpoints to control offset misalignments of waveguide flanges. To produce automatic centering of gripped waveguide flanges when outside diameters of the flanges varied, in conformance with specifications, as much as 0.0005 inch, each flange clamp had four equally spaced pins with precisely identical contact surfaces arranged on a diameter slightly smaller than the minimum flange diameter permitted. Centering of a flange within a clamp was therefore achieved by the uniform embedment (assuming homogeneous flange materials) of the four contact pins into the outer rim of the flange. Theoretically, optimum fixture calibrations made with the furnished shims should have limited maximum offset misalignments of flange pairs to 0.0007 inch. In practice, the average of misalignments in flange pairs made during the field evaluation test was 0.0011 inch.[1]

Each clamp half was faced with a copper lining which acted as a heat sink to limit the temperature rise of the flanges (and thereby limited the danger to the dielectric lining) during welding. The copper linings, in turn, had cavities through which chilled water was continuously circulated.

5.4.4 Preload mechanism

Tilt misalignment of waveguide at the flanged coupling was controlled with large-surfaced faces on the flanges accurately machined normal to the waveguide axis during manufacture. In the field these faces were pressed together with 10,000-lb forces applied at the outer edges of the flanges prior to welding. This preload force and the flange face relief design[1] results in a residual compressive force between the flange faces after welding, which is particularly effective in controlling gaps or tilts in the couplings when the waveguide is placed under tension or is curved or is subjected to both curves and a tensile force. In the fixture, the movement which brought flange faces together and the force which preloaded the faces were produced with the mobile left flange clamp

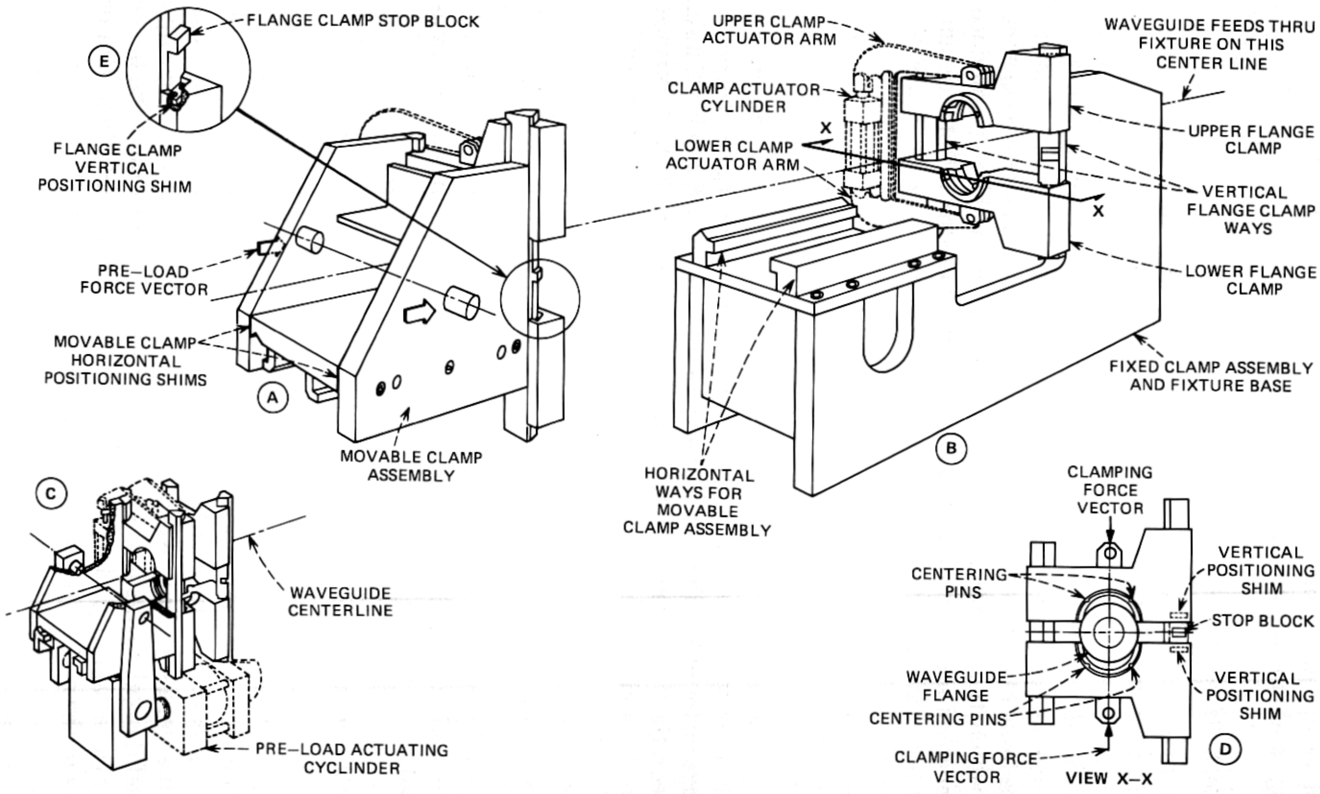


Fig. 5—The WSV aligning and preloading mechanisms.

which was mounted on horizontal ways and linked to a hydraulic cylinder located beneath the clamps in the fixture.

5.4.5 Welder and ozone evacuation

The welding process utilized was the tungsten electrode, inert-gas-shielded-arc process. Because dimensional tolerances of the waveguide flanges were exceptionally small, the material of the flanges could be reliably fused without using filler metal. The Hobart model CT300-DC CYBER-TIG welder was used with a 600 series programmer maintaining control of arc formation, weld current, shield gas application, and cooling water flow.

The fusion of flange pairs by electric arc welding is accompanied by the production of some smoke and ozone. These products were drawn out of the weld chamber through a duct to a blower which exhausted to the exterior of the splicer cab.

The welding machine made over 1600 welds during the field evaluation test and suffered only one malfunction. Although that malfunction damaged a flange pair beyond further use, a suitable flange weld cut-out tool was successfully pressed into service so that the only lasting effects of the malfunction were two lost waveguide modules and an hour of production time. Weld inspection was strictly visual and was adequate to assure that only tight welds free of leaks were installed during the Field Evaluation Test.

5.5 Waveguide pusher

The waveguide pusher, shown in the background in Fig. 3 and in close-up in Fig. 6, applied the insertion force to the waveguide line. It essentially consisted of a pair of endless roller chains which were synchronously turned, when commanded from the pusher operator's control panel, by two reversible hydraulic motors. The hydraulic motors were in turn powered by an electrically driven pump located in the truck shown parked next to the pusher in Figure 2. The source of electrical power was the motor-generator located on the WSV tractor.

The pusher transmitted the pushing force through the roller chains to the waveguide by means of a yoke which was manually placed over each waveguide flange pair just before those flanges entered the pusher. Each yoke had teeth which meshed with the roller chain as it entered the pusher. Meshing was aided by the pair of small synchronizer chains shown clearly in Fig. 6. The forces required to insert, brake, or hold waveguide on inclined routes were in turn transmitted back to the waveguide sheath through a connection between the sheath extension and the pusher frame.

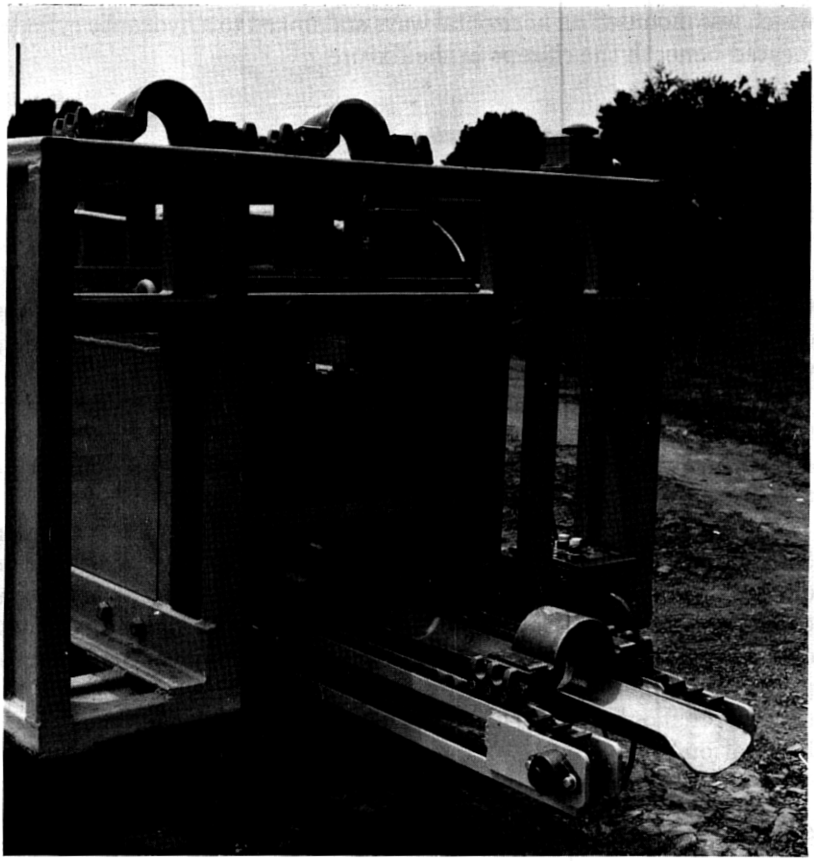


Fig. 6—The pusher.

Since the pusher was 32 feet long and the longest waveguide module was only 29.5 feet long, at least one yoke was fully engaged in the chains at all times, and, during a small part of every push cycle, two yokes on adjacent flange pairs were in the machine at the same time. Two yokes, when both were engaged in the chains, were separated by a unit multiple of the pitch of the chain. Since waveguide modules were manufactured in random lengths unrelated to the roller chain pitch, the yokes had to be designed with clearance around the flange pair equal to the chain pitch, which in this case was in excess of one inch. The load was always carried by the leading yoke and when this yoke was released from the pusher its load was transferred quite suddenly to the trailing yoke. The clearance around the second yoke resulted in an impact which limited the amount of force that could be safely applied to the waveguide, and thereby restricted the maximum insertion distance during the field evaluation test to about 8300 feet.

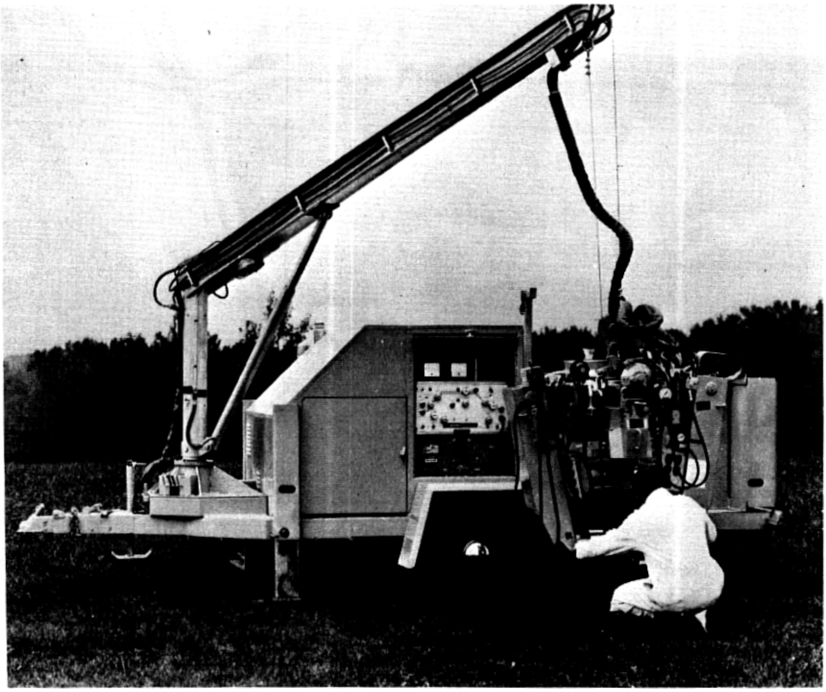


Fig. 7—The in-trench splicer.

5.6 In-trench splicer

The In-Trench Splicer (Fig. 7) does exactly the same waveguide flange splicing job that the WSV does, except that it was designed with an aligning, preloading, and splicing fixture which can be lowered by hoist to the trench bottom to make tie-ins. The welds made with this machine during the field evaluation test were indistinguishable from those made with the WSV.

Figure 8 is a close-up view of the flange clamps of the In-Trench Splicer shown just before they were lowered over the flange pair to be spliced. The small gap seen between the flange faces will be closed by the hydraulic cylinder which supplies the preloading force to squeeze the flange faces.

VI. EVOLUTION OF INSERTION EQUIPMENT SINCE THE FIELD EVALUATION TEST

The field evaluation test waveguide was installed during the fall and winter months using Long Lines craftsmen and operating engineers assigned at random from the local union hall. The insertion technique was demonstrated to be a forgiving and, therefore, practical method to install waveguide. The demonstration equipment was reliable under

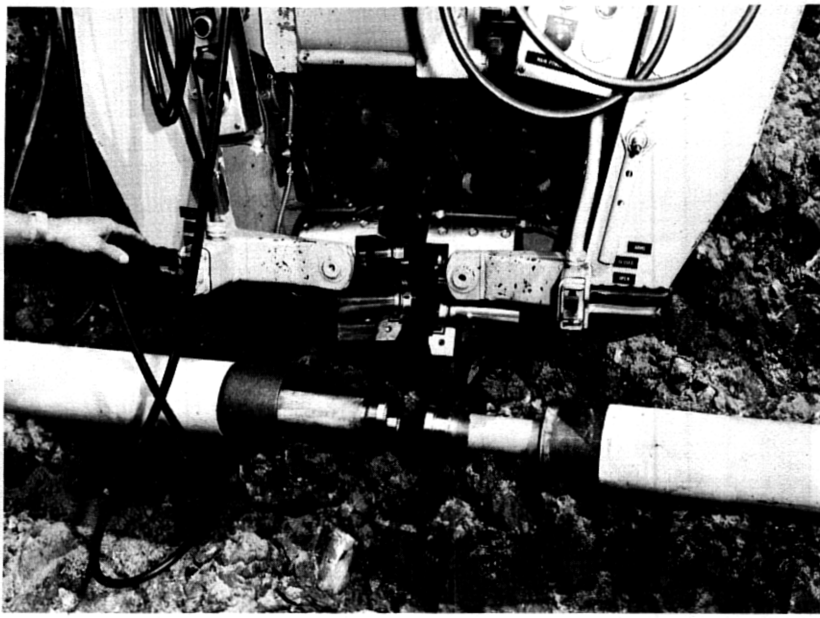


Fig. 8—Close-up of the flange clamps on the in-trench splicer.

sometimes unfavorable weather conditions, but as usual, one of the most useful outcomes of the field test was a list of suggestions, many of them offered by the operators, for improving the waveguide insertion system. Those suggestions which promised major improvements were:

(*i*) Eliminate the need to remove the shipping containers from the trailers, and thereby eliminate the crane.
(*ii*) Make the operation an all-weather operation.
(*iii*) Provide inherent protection against vandalism.
(*iv*) Provide a greater pushing distance capability by eliminating the load transfer problem associated with the waveguide pusher.
(*v*) Reduce the time required to set up the insertion equipment by having fewer components which require independent alignment.
(*vi*) Reduce the time required to make tie-ins and eliminate the need for the in-trench splicer.

Each of these suggestions was incorporated in the design of a new Waveguide Insertion System (WIS). All WIS equipment is contained within two 45-foot-long highway vans designed to be linked in precise alignment in the field. Enclosing the equipment satisfactorily eliminated the weather- and vandal-related problems. To eliminate the crane the feeder concept was expanded to permit bringing the tray into alignment with all shipping tubes when those tubes are in packages still on a flat-bed trailer. A corollary improvement is reflected in the design of 54-module waveguide shipping packages which increase a trailer-load capacity to 1 mile from the 0.6 mile limit in a load of nine-packs.

New concepts were required to remove the limits on push distance and productivity. Some of these new concepts can be seen in Fig. 9, which illustrates the principal activities in a cycle of operations. As with the demonstration equipment, waveguide modules (which may be either 29 or 34 feet long) are shipped in sheath-like tubes bound into packages, except that the packages are not removed from the delivering trailer. All of the tubes can be reached from within the van containing the feeder equipment without special equipment when the supply trailer is properly docked. One operator rolls waveguide modules into troughs on a mobile tray, as in sequence number 2 in the illustration, and measures the module length. Trays are handled with a carriage and vertical lift mechanism so that a supply of full trays is maintained in a floor-level indexing device. Properly managed, this reserve capacity allows production to continue without external waveguide supplies for 30 minutes. Empty trays are cycled for refilling.

The WSV splicing fixture (Fig. 4) is retained in the WIS and is operated in the familiar way, as depicted in sequences 5 and 6 in Fig. 9. The pushing machine, however, is very different. Waveguide is inserted a distance equal to the length of one module after every weld; however, the push force is transferred to the waveguide by gripping the last welded flange pair in a traveling clamp which is permanently attached to an endless chain. A hydraulic motor supplies power as commanded to the chain; since the motor is reversible, extraction forces can be supplied to the waveguide if necessary. Push loads are continuously monitored and displayed to the operator.

At the end of the push stroke, the traveling clamp delivers the flange pair to a stationary clamp where a transfer of any residual force is made. When released, the traveling clamp can be returned to the splicing fixture for the next push cycle. This decoupling of the two clamps which are required to positively control waveguide overcomes the distance limiting problem of the field evaluation test pusher.

For the safety of the operators, all controls were carefully designed to prevent the unintentional simultaneous release of both clamps. This prevents a possible runaway line for certain right-of-way configurations.

The WIS is designed to be operated in 4-minute cycles with no interruption in splicing provided that exhausted supply trailers are exchanged within 30 minutes. The overall objective is 100 miles of production per year, which can be accomplished with single-shift operations, a five-minute allowance for each splice-and-push cycle, and 200 working days per year.

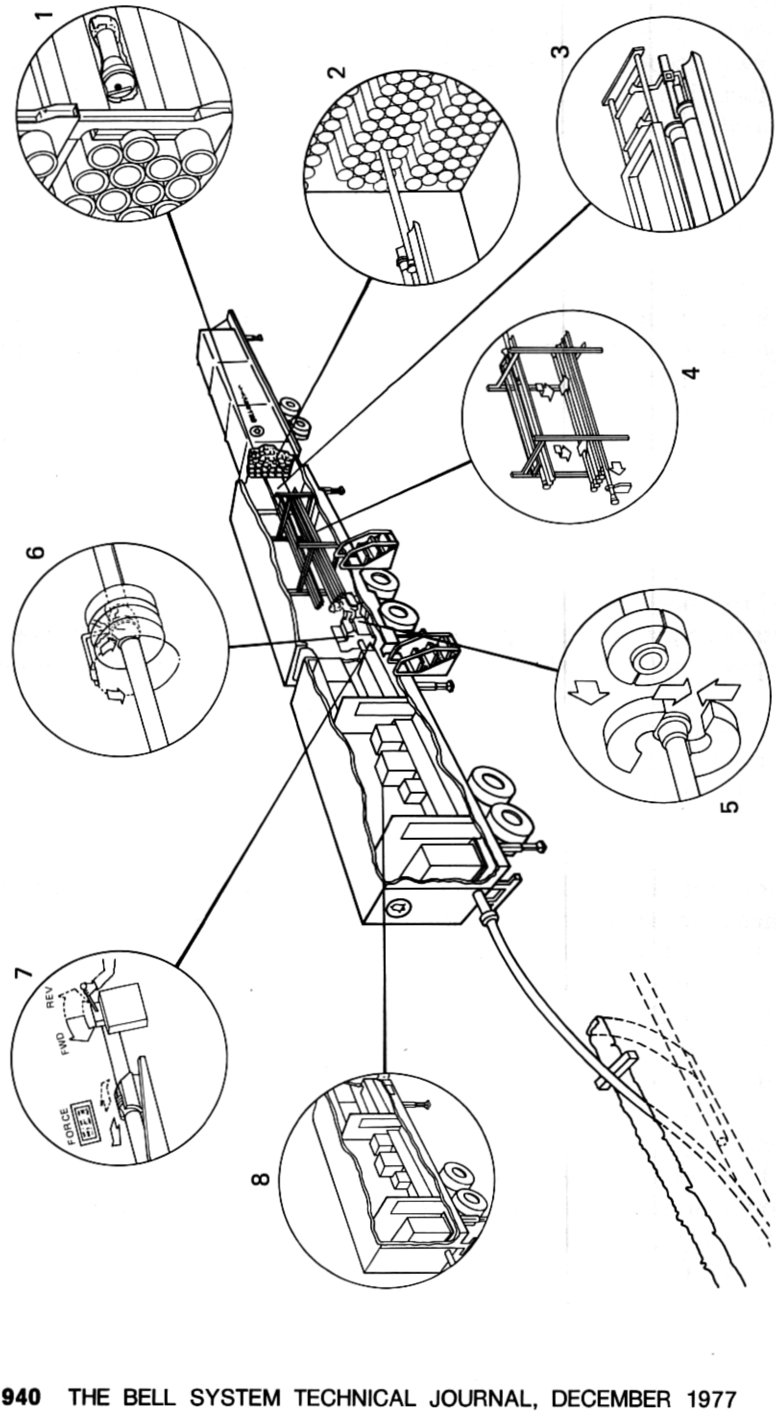


Fig. 9—The operating cycle of the waveguide insertion system.

The in-trench splicer is capable of making fusion splices in waveguide with a quality equal to those produced in the insertion fixture but at a much higher cost per splice. A mechanical coupler which can be used to make tie-in splices in the waveguide has been developed since the field evaluation test. This coupler is self-aligning and provides a gas-tight seal after installation with simple hand tools.

VII. SUMMARY

The insertion method for the installation of WT4 waveguide is the successor to various other methods which included direct burial of waveguide and simultaneous installation of sheath and waveguide. The insertion method is possible because of sheath encasement, discrete waveguide supports with rollers, and the absence of expansion joints in the waveguide. The technique has been tested to a distance of 8300 feet, and theory and test indicate that 3-mile insertion distances will be routinely achieved with push forces less than 10,000 lbs.

Equipment has been developed and used to demonstrate reliable installation of waveguide by the insertion method.

APPENDIX A

The effective coefficient of friction

Installed sheath will not be perfectly straight, and waveguide pushed into imperfect sheath will be forced to deform to follow its shape. Increased loads on some roller supports, and therefore increased resistance to insertion, will result. This increased loading can be accounted for analytically be defining the effective coefficient of friction as that coefficient which produces a reliable prediction of the pushing force needed to insert waveguide in sheath constructed to WT4 system specifications when only the unit weight of waveguide and the length of sheath are known. The effects of route bends and elevation changes are not included in this definition.

The effective coefficient was calculated for those shapes which result when sheath is supported at various regular intervals. Since the inside diameter of the sheath is slightly larger than that of a circle circumscribed about the roller supports, the problem of finding the deflected shape of the waveguide from the sheath's known profile is a nonlinear one. It was solved by a method using an iterative Green's Function solution. Figure 10 shows the results of the calculations. The ordinate of the graph is expressed in terms of the midspan sheath deflection. The contour $M = 1.0$ identifies the deflections below which there is no resistance in excess of that encountered in a truly straight sheath. The curves $M = 1.25$ and $M = 1.5$ identify the deflections for which the insertion force is the stated multiple of the straight sheath value. The lower

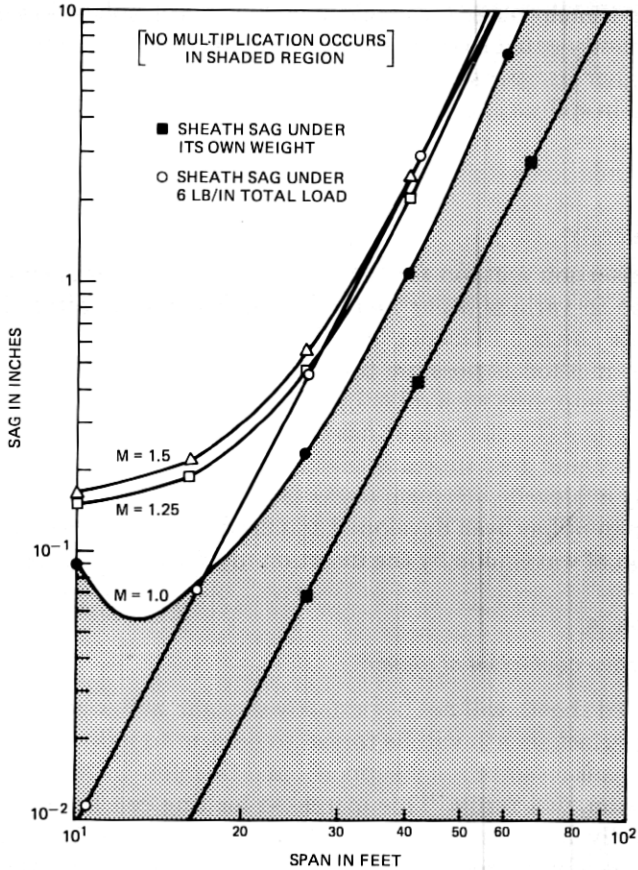


Fig. 10—Friction multiplication factor for the diametral clearance model.

of the two straight lines of the graph represent the maximum midspan sag which a periodically supported sheath could assume under its own weight. The upper straight line gives the maximum midspan sag which the sheath could assume under a 6 pound per inch sheath-weight-plus-backfill load. Six pounds per inch is a backfill load representative of field evaluation test experience. Notice that, for the periodically supported sheath considered, the required insertion force is not greater than 50 percent more than the straight sheath value for unsupported spans of any length.

With the current sheath installation specifications[2] limiting the maximum unsupported sheath span to 30 feet, a periodically supported sheath with 30-foot spans represents a worst-case condition. Under this assumption the friction multiplication contours of Fig. 10 predict a maximum multiplication of about 1.3. Since the straight conduit coefficient of friction is 0.058, a curvature multiplication factor of 1.3 implies an effective coefficient of friction which will, at all times, remain below 0.075. Insertion force measurements during the field evaluation test correspond to an effective coefficient of friction of 0.064 (average), a number which is closer to the truly straight sheath coefficient than to the theoretical upper limit.

An insertion distance of up to 6 miles could be realized in sheath with no route bends assuming a 10,000 pounds pushing force and a 0.075 effective coefficient of friction.

APPENDIX B

Route bends—effect on insertion forces

When waveguide is pushed through a route bend, the loading on the roller supports is increased due to deflection of the waveguide relative to the sheath. The deflections occur at transition zones between the straight and curved sections and along the entire length of the curve due to the axial loading on the waveguide. The increased loading on the roller supports, of course, increases the frictional resistance in the bearings and a greater axial load is required to move the waveguide through bends.

The waveguide deflection at transition zones between straight and curved sections is highly dependent upon the transition curvature and the radius of curvature of the bend. For sheath installations with a minimum radius of curvature of 250 feet it can be shown that the added roller support friction caused by deflections in the transition zones of the waveguide is negligible. The lateral displacement along the entire length of the curve due to the axial loading is the only significant contributor to increased roller support loading. Because of this the waveguide may be treated as a pushable-flexible cable in curves.

The waveguide is modeled as a beam whose neutral axis in the undeformed state forms a circular arc of radius r. The beam is subjected to bending forces acting in the plane of curvature. The roller support reaction is everywhere normal to the axis of the beam and proportional to the radial deflection y of the beam. Vertical plane curvature is not considered, but the effects of elevation changes are included in the analysis.

An infinitesimal element of the beam (Fig. 11) is acted upon by shearing force Q, normal force N, bending moment M, spring reaction $ky\,ds$, and friction force $\mu k|y|$, where μ is the coefficient of friction. These forces all arise from the beam's deformation in the plane of curvature. In addition the beam is acted upon by friction force $\mu w\,ds$ and the projection of gravity onto the beam's axis, $w\alpha\,ds$, where α is the inclination of the axis with respect to the horizontal and w is the beam's weight per unit length.

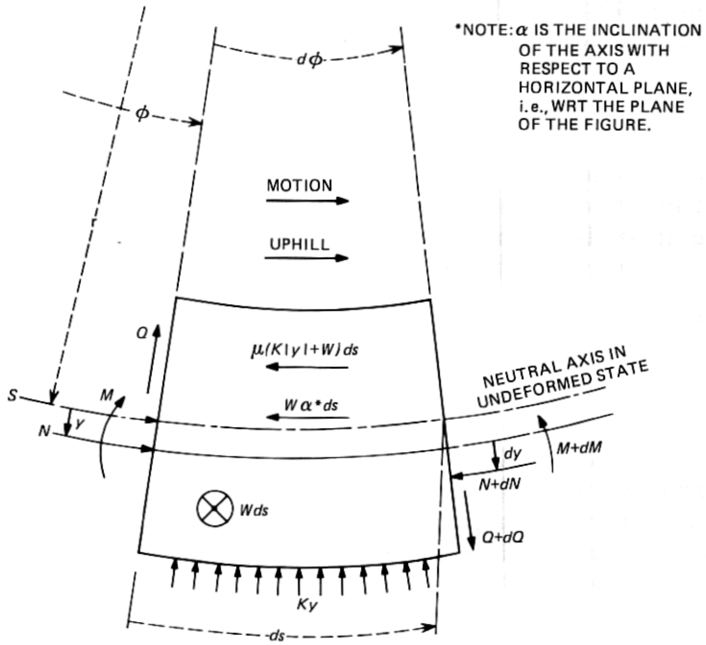


Fig. 11—Equilibrium of an element of waveguide.

The beam is inserted into the sheath from left to right in Fig. 11, and the route slopes uphill in the direction of insertion.

The radial, tangential, and moment equilibrium equations are:

$$\text{(radial) } dQ + N\,d\phi - kyr\,d\phi = 0 \tag{1}$$

$$\text{(tangential) } Q\,d\phi - dN - \mu(k|y| + w)r\,d\phi = w\alpha r\,d\phi \tag{2}$$

$$\text{(moment) } Qr\,d\phi + N\,dy = dM \tag{3}$$

The moment M may be expressed in derivatives of deflection by the relation

$$M = -\frac{EI}{r^2}\left(\frac{d^2y}{d\phi^2} + y\right) \tag{4}$$

to give a set of equilibrium equations expressed in terms of shears, axial forces, and displacements:

$$\frac{dQ}{d\phi} + N - kyr = 0 \tag{5}$$

$$Q - \frac{dN}{d\phi} - \mu(k|y| + w)r = w\alpha r \tag{6}$$

$$Q + \frac{N}{r}\frac{dy}{d\phi} + \frac{EI}{r^3}\left[\frac{d^3y}{d\phi^3} + \frac{dy}{d\phi}\right] = 0 \qquad (7)$$

When the intermediate variables are eliminated from these equations the following fundamental differential equation governing waveguide insertion into a curved sheath is obtained:

$$\frac{d^5y}{d\phi^5} + \left[2 + \frac{Nr^2}{EI}\right]\frac{d^3y}{d\phi^3} + \left[1 + \frac{kr^4}{EI} - \frac{Nr^2}{EI}\right]\frac{dy}{d\phi} + \mu\frac{kr^4}{EI}|y| = -\frac{wr^4}{EI}(\mu + \alpha) \qquad (8)$$

With the axial loads and bend radii permissible in waveguide, some terms in eq. (8) may be neglected. The following conditions apply:

$$w = 4.34 \text{ lb/ft}$$

$$N < 10^4 \text{ pounds}$$

$$EI = 27.21 \times 10^6 \text{ lb-in}^2$$

$$r \geq 3000 \text{ in}$$

$$k = 20 \text{ lb/in}^2$$

$$\mu \leq 0.1$$

For any axial compression N greater than about 60 pounds, the term Nr^2/EI dominates in the coefficient of $d^3y/d\phi^3$. For all permissible waveguide radii the terms *1* and Nr^2/EI are negligible in the coefficient of $dy/d\phi$. Therefore eq. (8) may be approximated by

$$\frac{d^5y}{d\phi^5} + \frac{Nr^2}{EI}\frac{d^3y}{d\phi^3} + \frac{kr^4}{EI}\frac{dy}{d\phi} + \mu\frac{kr^4}{EI}|y| = -\frac{wr^4}{EI}(\mu + \alpha) \qquad (9)$$

If the waveguide deformation y is of one sign only, or if the waveguide in a curve is subdivided for analysis into parts each having a single direction of deflection, then eq. (9) reduces to the linear equation

$$\frac{d^5y}{d\phi^5} + \frac{Nr^2}{EI}\frac{d^3y}{d\phi^3} + \frac{kr^4}{EI}\frac{dy}{d\phi} \pm \mu\frac{kr^4}{EI}y = -\frac{wr^4}{EI}(\mu + \alpha) \qquad (10)$$

where the plus sign is chosen for waveguide deflection toward the outside of a curve and the negative sign is chosen for deflection toward the inside of the curve.

The waveguide insertion force may be found by returning to eqs. (5), (6), and (7) and deriving an analytic expression for the axial compression N in terms of derivatives of the displacement. Since the solution of the governing differential equation is known as a sum of exponentials there is conceptually no difficulty in this approach. However, a more direct approach is possible if we recognize from the beginning that shear and moment effects are negligible in the central section of long route bends. A long route bend is one whose arc length exceeds 80 feet. For the minimum 250-foot radius a long bend is any bend exceeding 18 deg.

Neglecting the shear and bending moment in waveguide is tantamount to equating it to a flexible cable. This equivalence is tempered by the requirement that the waveguide be able to support compressive stress. Careful manipulation of eqs. (5) and (6) preserves this distinction between waveguide and cable while still illustrating their essential similarities.

If the shear Q and its derivative $dQ/d\phi$ are negligible, and if waveguide deflection is assumed positive (outward), then eqs. (5) and (6) may be solved simultaneously to give the first-order differential equation

$$\frac{dN}{d\phi} + \mu N = -wr(\mu + \alpha) \tag{11}$$

with solution

$$N = N_o e^{-\mu\phi} + wr\left(1 + \frac{\alpha}{\mu}\right)(e^{-\mu\phi} - 1) \tag{12}$$

where N_o is the compressive stress at position $\phi = 0$, as illustrated in Fig. 12.

If the shear Q and its derivative $dQ/d\phi$ are negligible, and if waveguide deflection is assumed negative (inward), then $|y| = -y$, and eqs. (5) and (6) may be solved simultaneously to give the first-order differential equation

$$\frac{dN}{d\phi} - \mu N = -wr(\mu + \alpha) \tag{13}$$

with solution

$$N = N_o e^{\mu\phi} + wr\left(1 + \frac{\alpha}{\mu}\right)(1 - e^{\mu\phi}) \tag{14}$$

where again N_0 is the axial compression at position $\phi = 0$. In the case where the deflection y is negative, eq. (5) says that the axial compression N is also negative, i.e., in fact tensile. If then N is replaced by $-T$ in eq. (14), the conventional relation governing tension in a flexible cable is obtained:

$$T = T_o e^{\mu\phi} + wr\left(1 + \frac{\alpha}{\mu}\right)(e^{\mu\phi} - 1), \tag{15}$$

where T_o is the axial tension at position $\phi = 0$.

Equations (12) and (15) apply under the assumption that deflection in a route bend is either everywhere outward or everywhere inward. Since

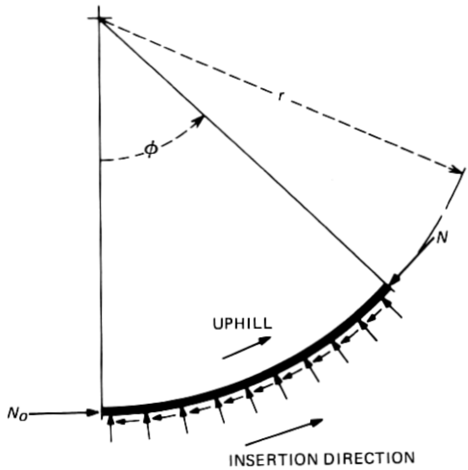


Fig. 12—Plan view of forces on a segment of waveguide in a curve.

waveguide is installed by pushing from the trailing end, it is usually safe to assume a compressive state; however, the axial load is not always compressive. Sometimes the front end of waveguide is pushed into sheath which slopes so steeply downhill that the gravitational pull exceeds the frictional resistance, and therefore at least a part of the waveguide line is in tension. If all of the waveguide line is in tension, then a restraining force is required at the trailing end and eq. (15) is applied without difficulties.

It may be possible to have both compressive and tensile forces in a bend, for example when the leading end of the waveguide is going down a steep hill and the trailing end is in less steeply sloping sheath so that the frictional resistance is greater than gravitational pull. When this happens it is necessary to locate the point where the force is zero and to apply the correct equation [either (12) or (15)] to the segments of the curve either side of the null point.

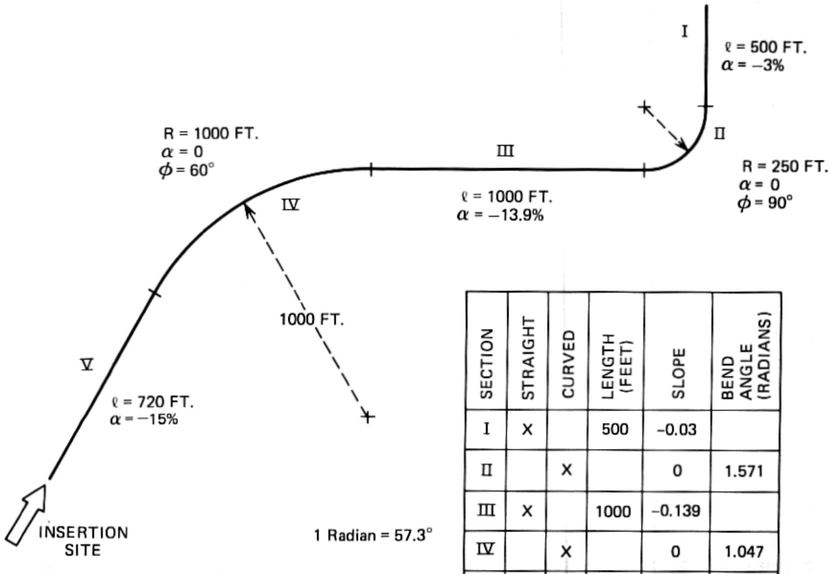
The null point is equivalent to a free end and can be found by setting N_o equal to zero in eq. (12). If the position in a curve where a null point exists is defined by θ, then

$$\theta = -\frac{1}{\mu} \ln_e \left[\frac{N}{wr\left(1 + \frac{\alpha}{\mu}\right)} + 1 \right] \tag{16}$$

APPENDIX C

Calculating insertion forces for a hypothetical route

To determine the force required to insert waveguide in any route, the route is partitioned into straight and curved sections, as illustrated on



SECTION	STRAIGHT	CURVED	LENGTH (FEET)	SLOPE	BEND ANGLE (RADIANS)
I	X		500	-0.03	
II		X		0	1.571
III	X		1000	-0.139	
IV		X		0	1.047
V	X		720	-0.15	

Fig. 13—Hypothetical route for push force calculation.

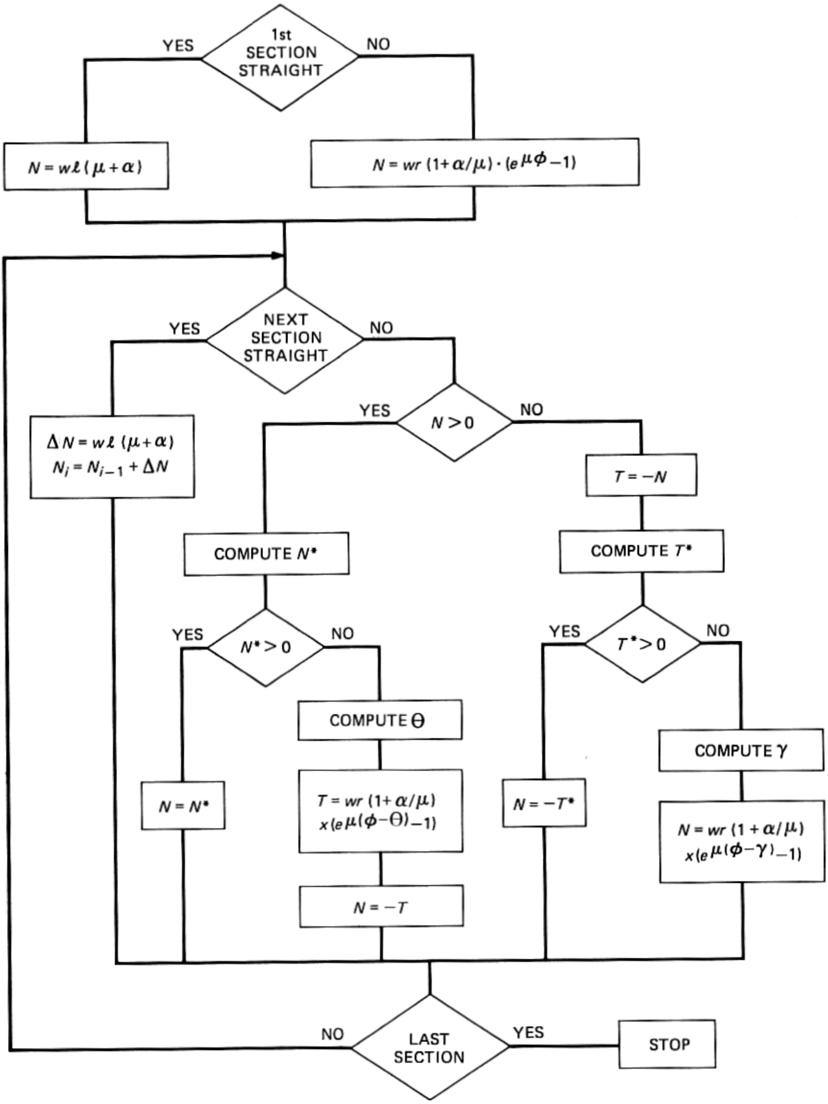
the example route shown in Fig. 13. It two adjacent curved sections of different radii had existed, they would have been treated as two distinct sections. Then, for each straight section the length and grade are tabulated, and for each route bend the radius of curvature, r, the included angle, ϕ (measured in radians), and the grade are tabulated. All grades, α, are calculated by

$$\alpha = \frac{\text{Far end elevation} - \text{Near end elevation}}{\text{Section length}}$$

The contribution of each of the partitioned sections to the total resistance to insertion is calculated. In route bends, eq. (12) of Appendix B [or eq. (15) of Appendix B if the tensile condition is discovered] is applied, and the simple relationship

$$N = wl(\mu + \alpha)$$

is used to find the contribution to axial force of each straight section. From eqs. (12) and (15) of Appendix B it can be seen that the thrust N_o and tensile T_o are determined at the *trailing end* of the waveguide. For this reason it is convenient to start at the leading end of the waveguide and work back to the insertion point, calculating the insertion forces segment by segment. The process is described in the flow chart of Fig. 14, and the axial force which results is the push force at the moment the



$$N^* = Ne^{\mu\phi} + wr\,(1+\alpha/\mu)\,(e^{\mu\phi}-1)$$

$$T^* = Te^{-\mu\phi} + wr\,(1+\alpha/\mu)\,(e^{-\mu\phi}-1)$$

$$\Theta = -1/\mu\ \ln\left\{1+\frac{N}{wr\,(1+\alpha/\mu)}\right\}$$

$$\gamma = 1/\mu\ \ln\left\{1+\frac{T}{wr\,(1+\alpha/\mu)}\right\}$$

Fig. 14—Insertion force flow diagram.

final piece of waveguide leaves the insertion machine. Depending on the topography of the particular route, the force during insertion may be either higher or lower than the final push force. Computation of the force history during insertion is more complicated although the procedure is essentially the same.

The hypothetical route of Fig. 13 is now used to illustrate insertion force calculations. The route is divided into five sections.

Section I. This section is straight and unloaded at the front end. The total force at the transition point to Section II is simply the change of force ΔN. The grade in this section is −3 percent.

$$N = wl(\mu + \alpha)$$

$$= 4.34 \text{ lb/ft} \times 500 \text{ ft} \times (0.07 - 0.03)$$

$$= 86.8 \text{ lb}$$

Section II. The next section is curved. The axial compression N at the junction with Section I is greater than zero, and since the slope in this section is zero there is no possibility of sign reversal. The axial force at the junction with Section III is given by

$$N = N_o e^{\mu\phi} + wr\left(1 + \frac{\alpha}{\mu}\right)(e^{\mu\phi} - 1)$$

$$= 86.8 \times \exp(0.07 \times 1.1708) + 4.34 \times 250 \times [\exp(0.07 \times 1.5708) - 1]$$

$$= 223 \text{ lb}$$

Section III. This section slopes steeply downhill. The slope is sufficient to overcome the restraining action of friction. A compression-tension transition is possible, but since the section is straight this possibility is of no particular concern.

$$\Delta N = wl(\mu + \alpha)$$

$$= 4.34 \times 1000 \times (0.07 - 0.139)$$

$$= -229.5$$

$$\text{N} = 223 - 299.5 = -76.5 \text{ lb}$$

The axial force at the junction with curved Section IV is tensile.

Section IV. The axial force at the forward end of this section is tensile, and since the slope in this section is zero, a sign reversal within the section is possible. To test, compute an assumed tension T* at the trailing end.

$$T^* = Te^{-\mu\phi} + wr\left(1 + \frac{\alpha}{\mu}\right)(1 - e^{-\mu\phi})$$

$$= 76.5 \exp(-0.07 \times 1.05) + 4.34 \times 1000 \times (1) \times [1 - \exp(-0.07 \times 1.05)] = -237$$

Since the computed trailing end force is a negative tension, that is, a compression, there is actually a sign reversal somewhere in the bend. The angle at which zero force occurs is found by applying the formula

$$\mu\theta = \ln_e \left\{ 1 + \frac{T}{wr\left(1 + \frac{\alpha}{\mu}\right)} \right\}$$

$$\mu\theta = \ln_e \left\{ 1 + \frac{76.5}{4.34 \times 1000} \right\}$$

$$\theta = 0.2495$$

The point at which the axial force goes to zero is equivalent to an unloaded front end. Since the complete route bend encompasses 1.05 radians, (1.05 − 0.2495) radians remain in which an axial compression can build up from zero.

$$N = wr\left(1 + \frac{\alpha}{\mu}\right) \times \{\exp\left[\mu(\phi - \theta)\right] - 1\}$$

$$= 4.34 \times 1000 \times \{\exp\left[0.07 \times (1.05 - 0.2495)\right] - 1\}$$

$$= 250 \text{ lb}$$

Section V. The force increment in this long straight section is computed by the same formula used previously.

$$\Delta N = wl\ (\mu + \alpha)$$

$$= 4.34 \times 720 \times (0.07 - 0.15)$$

$$= -250 \text{ lb}$$

The total force at the insertion site is given by adding this increment to the force at the junction of Sections IV and V:

$$N = 250 - 250$$

$$= 0$$

This route was designed to illustrate one way in which the final insertion force can be zero (or even negative). During insertion in a route which slopes generally downward the insertion force may be expected to assume both positive and negative values during the course of installation.

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