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

WT4 Millimeter Waveguide System:

Reliability and Maintenance of the WT4 Transmission Medium

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(Manuscript received April 7, 1977)

The reliability of the waveguide medium depends upon its resistance to damage from external forces, the restoral time in case it's damaged, its resistance to gradual deterioration, and the ability to move the location of the medium after it is installed. Trouble estimates, their causes, and restoration methods for the WT4 medium are discussed. This includes electrical and pneumatic fault location. Also discussed from both a systems design and operations viewpoint are maintenance systems designed to prevent deterioration of the WT4 medium (corrosion protection system and the nitrogen system) and the concepts for methods to change the location (route rearrangements) of the medium after it is installed.

I. INTRODUCTION

The maintenance plans for the WT4 transmission medium are unique when compared to other operational waveguide maintenance systems and conventional coaxial cable maintenance systems. Very high reliability and very low-cost on-going maintenance are achieved without high first-cost access points (manholes) and monitoring devices between the widely spaced repeater stations. Elimination of the access points and monitoring devices was made possible by developing techniques and methods to:

(*i*) Locate electrical faults in the waveguide with accuracy of a few meters when testing from repeater stations up to 20 miles from the fault.

(*ii*) Localize leaks in the waveguide sheath when testing from repeater station up to 20 miles from the leak.

(*iii*) Minimize water ingress into the waveguide in the event of a waveguide rupture.
(*iv*) Restore damaged waveguide to service very quickly.

The developments are part of a totally integrated maintenance plan which takes maximum advantage of the very rugged steel sheath to provide the reliability required for the high-capacity WT4 system. This paper discusses the WT4 transmission medium reliability and the steps that were taken to control medium outage.

II. RELIABILITY OF THE WT4 TRANSMISSION SYSTEM

2.1 General

For long-haul transmission systems, reliability is defined as the percent of time that a 4000-mile line is available for service. The reliability objective for the WT4 medium is 99.99 percent or service outage of less than 1 hour per year.

Outage on the WT4 transmission medium is determined by the number of service-affecting troubles, the restoration time for such troubles, and outage caused by the medium being unavailable for service due to operations such as route rearrangements.

2.2 Service-affecting troubles

Service-affecting troubles interrupt service on the waveguide medium by the introduction of transmission impairments. A 3 dB margin is allocated in the system loss budget so that minor transmission impairments in the medium do not become service-affecting. Therefore, incidents that cause less than 3-dB transmission impairments are considered to be routine troubles.

The causes of transmission impairments can be divided into three categories:

(*i*) Component failure
(*ii*) Corrosion
(*iii*) Mechanical damage

Component failures are controlled by the design of the medium, corrosion is controlled by design and by the maintenance systems, and mechanical damage is controlled by protection.

2.3 Component failure

The WT4 medium has several manufacturing and construction processes that are considered to be vital to the reliability of the medium. These are the bonding of the waveguide dielectric lining to the waveguide tube, the joining of the waveguide modules, and the termination of the waveguide in building walls. Boyd et al.[1] discuss the dielectric bonding process. Gretter et al.[2] discuss the coupling design, and Liss et al.[3] discuss the termination of the waveguide in buildings.

During the design of the medium there was a conscious effort to eliminate components that could compromise reliability. As a result, the WT4 medium has no manholes, expansion joints (except inside buildings) or auxiliary cable for signaling.[4]

With the transmission impairment margin of 3 dB and the methods of locating and repairing routine troubles discussed later in this paper, it is expected that component failure will cause negligible outage.

2.4 Corrosion failures

The WT4 medium is buried and it can gradually deteriorate from corrosion. Continued corrosion could eventually lead to failures and service outages.

Early in the development of the WT4 medium it was recognized that the waveguide could not be effectively protected against corrosion if it were placed in a nonmetallic nonpressurizable sheath material such as PVC. The decision to use a steel sheath was heavily influenced by the need to protect the waveguide from corrosion. To minimize the corrosion of the steel sheath, a high-quality coating is used in conjunction with rectifier and sacrificial anode installations. The selection of coatings, and design and maintenance of cathodic protection systems is well covered in the literature.[5]

No economically justifiable corrosion control system can eliminate corrosion entirely and corrosion failures can be expected to occur. It is important that such failures do not cause service-affecting troubles. One function of the nitrogen pressurization system which is discussed later in this paper is to insure that corrosion sheath failures do not lead to service-affecting troubles. WT4 medium corrosion will cause negligible outage.

2.5 Failures caused by mechanical damage

Mechanical damage that causes transmission impairment is the main source of service-affecting troubles on coaxial cable systems. It is also expected to be the main source of service-affecting troubles for the WT4 medium which is installed on similar rights-of-ways.

The WT4 medium can be damaged in much the same way as coaxial cable, i.e., crushed, severed, etc. However, its susceptibility to such damage is drastically reduced due to the combined mechanical strength of the steel waveguide and its protective steel sheath.

The reliability information gathered on coaxial cable can be used to predict the reliability of waveguide if the greater mechanical strength of the WT4 medium is considered.

Since 1969 the Long Lines Department of AT&T has been preparing detailed reports on all service-affecting coaxial cable troubles. Table I gives the trouble rate average for the years 1973 to 1975 for the major categories of trouble.

Analysis of the trouble reports shows that the Bell-associated troubles generally damage only a few coaxials in the cable and contribute very little to system outage. The WT4 medium will not be damaged by actions that cause only minor damage to coaxial cable because of the protective steel sheath. Bell-associated troubles will cause negligible WT4 medium outage.

Lightning entering the ground and jumping to the metallic sheath on coaxial cable produces an impact that can crush coaxial tubes. In only very rare occurrences are lightning damages severe enough to affect service on all coaxials in a 20-tube coaxial cable.

To determine how the WT4 medium would be affected by lightning, the sheath was subjected to lightning thermal and crushing tests. Tests with high-current energy depositions that were sufficient to crush all tubes in a 20-tube coaxial cable produced only small dents in the waveguide sheath. Lightning should therefore cause negligible WT4 medium outage.

2.6 Foreign Workers

"Foreign" workers (non-telephone-company related) cause the most severe damage to coaxial cables and are by far the biggest contributor to coaxial cable system outage. The damage occurs when construction equipment used by the workers accidently strikes the cable. Seventy percent of the foreign worker troubles in the years from 1973 to 1975 damaged all of the coaxials in the cable. Troubles caused by foreign workmen should be the only significant contributor to WT4 medium outage.

Table II shows the relative frequency with which various types of construction equipment damage coaxial cable. Backhoes and earth penetration devices such as drills, probes, and augers cause almost 70 percent of the troubles. A good measure of the reliability of the medium is its ability to withstand strikes from such equipment. Several field tests were conducted to determine the WT4 medium resistance to damage. The results are summarized below:

(*i*) Small backhoes (smaller than 3/4 yard) are not capable of causing service-affecting troubles with accidental hits on the medium. (Small backhoes most frequently damage coaxial cable.)

(*ii*) Large backhoes (3/4 yard and larger) can severely damage a buried

Table I — Coaxial cable troubles

Trouble category	Service-affecting troubles: Average number per year	Rate per 1000 miles per year
Bell associated (including engineering construction)	26	1.28
Lightning	25	1.25
"Foreign" Workers	19	.95

Table II — Construction machinery: relative frequency for damaging cable

Backhoe	40%
Drills	
Probes	29%
Earth augers	
Trencher	9%
Bulldozer	9%
Front-end loader	4%
Other	
Drag line	
Clam digger	
Plow	9%
Hand tools	

waveguide medium but only if the operator is determined to dig out an obvious foreign object. Most experienced operators would not damage the WT4 medium severely enough to cause outage.

(*iii*) Trenchers of moderately large size (30 inch width buckets, 8 foot diameter wheel) will not seriously damage the WT4 medium.

Although no specific tests have been conducted to determine the resistance of the WT4 medium to probes, drills, and augers, these tools are not likely to severely damage the medium because of the concentric design of the sheath and waveguide. The resistance of the WT4 medium to dig-ups by foreign workers is expected to be a factor of 10 to 100 better than coaxial cables. A factor of 25 is required to make the WT4 medium meet the reliability objective of 99.99 percent assuming a restoration time of 6 hours.

III. WT4 NITROGEN SYSTEM

3.1 General

The nitrogen system is the heart of the maintenance plan for the WT4 transmission medium. In addition to providing a low-loss medium for millimeter wave transmission, it is used in trouble prevention, corrosion protection, sheath fault location, and electrical fault location. It is designed for automated operation. The use of liquid nitrogen as the gas source provides for high reliability with low on-going operational costs.

The nitrogen system was developed to meet the following requirements:

(*i*) Provide a low-loss transmission medium for the interior of the waveguide. Nitrogen is selected as the gas to pressurize the waveguide because it has no resonant frequencies in the bandwidth from 35 to 110 GHz as do oxygen and water vapor. The nitrogen used must contain no more than 25 ppm of O_2 and H_2O. With this specification the maximum loss due to the water vapor is 0.008 dB per mile at 110 GHz. The maximum loss due to oxygen is 0.005 dB per mile at 60 GHz.

(*ii*) Prevent corrosion of the waveguide exterior, roller supports, couplings, and sheath exterior. It is more cost-effective to provide corrosion protection for the annulus between the sheath and waveguide with nitrogen than with coating systems. Nitrogen is used instead of dry air because it is more economical, since a nitrogen system must be provided for the waveguide.

(*iii*) Prevent the entrance of contaminants into the waveguide and sheath when small leaks develop. If a small leak develops in the waveguide or sheath, the nitrogen flows out preventing the entrance of water or other contaminants. The operating pressures chosen for the waveguide and sheath are 25 psia and 23 psia respectively.

(*iv*) Minimize the entrance of contaminants into the waveguide in the unlikely event of waveguide and sheath rupture. Flooding of the waveguide with water could cause very long restoration times. To minimize the distance that water can contaminate the waveguide, the nitrogen system must be capable of providing a minimum of 25 scfm (standard cubic feet per minute) nitrogen flow at the rupture.

(*v*) Provide large volumes of nitrogen for purging waveguide during installation. A minimum of six volumes purge is required for the waveguide after installation and before electrical testing. Six volumes of nitrogen in a typical 25-mile repeater section is equivalent to approximately 25,000 scf of N_2.

(*vi*) Provide a nitrogen flow system that propels electrical measurement devices (pistons) through the waveguide bore. Electrical acceptance testing and fault location may use a piston that is propelled by a flow of nitrogen. Moving the piston at the desired speed of 1 m/second requires controlled flows in the range of 5 to 10 scfm.

(*vii*) Provide a stable absolute pressure source for the sheath to aid in leak localization. The sheath leak location method depends upon localizing a sheath leak to $\pm\frac{1}{2}$ mile using test sets at the repeater station. This operation requires stable sheath pressures.

(*viii*) Provide automatic sectionalization of leaks to a repeater span.

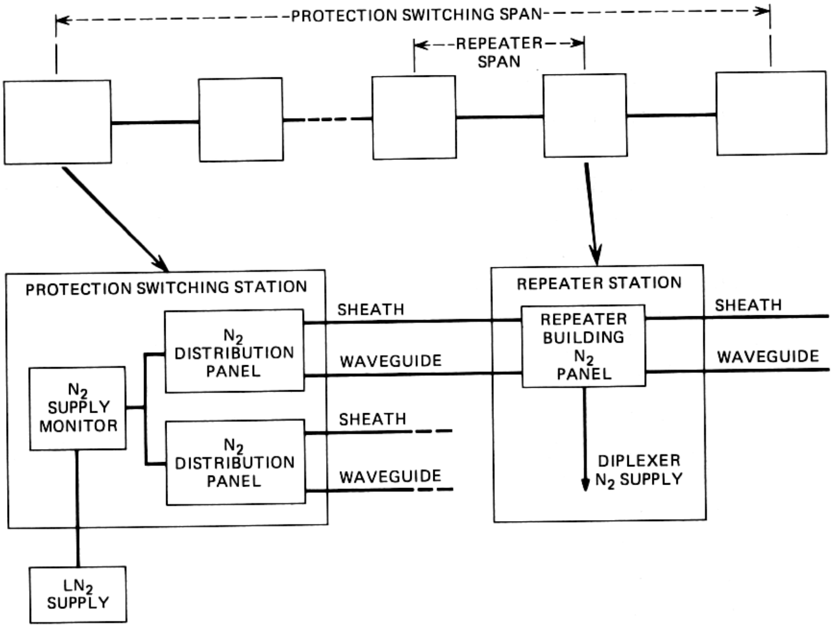

Fig. 1—WT4 nitrogen system maintenance area.

The nitrogen system must contain monitoring equipment that isolates leaks that develop in the waveguide or sheath to a particular repeater span.

(*ix*) Provide nitrogen for the diplexers located at the repeater stations. The diplexers and repeaters require a low-pressure dry nitrogen supply with a maximum usage of 100 cu ft per day. This nitrogen is most economically provided by the nitrogen system.

3.2 WT4 nitrogen system—description

The WT4 nitrogen system covers one protective switching span, a maximum distance of 250 to 300 miles (Fig. 1). At each protection switching station there is a nitrogen supply, monitor, and distribution system. Each repeater station has a monitor and control panel.

The nitrogen supply comes from a LN_2 storage system. The LN_2 storage system is commercially available and consists of a storage tank, evaporator, regulator circuit and economizer circuit. The tank is located outside of the station. The liquid nitrogen is delivered in tank trucks and is pumped into the LN_2 storage tank, which has a 900-gallon capacity.

The LN_2 is converted into a gas as needed in a heat exchanger or evaporator that is mounted on the outside of the tank. Heat transfer through the walls of the superinsulated tank generates about 200 scfd of nitrogen. The economizer system uses this gas first to provide system needs. If the total system need is less than 200 scfd, the excess gas is vented to the atmosphere.

The gas from the supply system is piped into the station to the nitrogen supply monitor. The nitrogen, which is at a pressure of 50 to 100 psi, is checked for water vapor content and oxygen content. The supply monitor also measures the amount of nitrogen remaining in the supply tank and generates a warning alarm when it is 50 percent full and an action alarm when it drops to 20 percent full. A gross flow meter on the supply monitor is used by station craftspersons to determine usage rate of nitrogen. Nitrogen for the diplexers in this station is provided with a pressure-regulated source from the supply monitor.

Nitrogen from the supply monitor is piped to the nitrogen distribution panels. There is one nitrogen distribution panel for each WT4 waveguide run entering the building. The nitrogen distribution panel regulates the pressure and monitors the flow of nitrogen being supplied to the waveguide and sheath.

During normal operation all waveguide flow passes through a flow monitor which has insufficient flow capacity for purging or ruptures. The flow monitor is shunted by a normally closed, high-capacity valve which is opened either remotely or locally to enable large flows (up to 50 scfm to a leak in the first waveguide span outside a main station). A vent valve provides the means to depressurize the waveguide.

The sheath flow circuit is quite similar. It contains all features of the waveguide circuit with the addition of a two-level absolute pressure regulator. In normal operation, sheath pressure is maintained at 23 psi absolute, about 2 psi below waveguide pressure. Like the waveguide the sheath too contains a flow monitor and high-flow shunt. In addition the sheath pressure may be boosted to 35 psia by remote or local control. This higher sheath pressure is required in emergencies to assure adequate flow volume for line breaks.

The nitrogen from the distribution panel enters the sheath in the sheath end section and the waveguide through the nitrogen inlet section. It leaves the sheath and waveguide through like devices in each repeater station where it passes through the repeater station nitrogen panel. The repeater station panel monitors the flow rate in the waveguide and sheath and provides alarms at two flow levels. The repeater station nitrogen circuits also contain flow monitors of insufficient capacity for purging or ruptures. The monitors are shunted by normally closed, high-capacity valves which are opened either remotely or locally. An additional normally closed, high-capacity valve is used to interconnect the waveguide and sheath nitrogen circuits.

3.3 Operation

In the development of the WT4 system, a basic design philosophy was to integrate the maintenance of the repeater stations, electronics, and nitrogen system by using a common monitoring and control system.

The SCOTS (Surveillance and Control of Transmission Systems) system had been developed for transmission system maintenance and is used for WT4 maintenance. SCOTS has a computerized central control. Remote terminals are located in protection switching and repeater stations. The telemetry system for SCOTS is discussed by Bonomi et al.[4]

The alarms and status indications that the nitrogen panels generate will be transmitted to the SCOTS central control. The information will be continuously analyzed in the central computer and commands to operate the appropriate valves will be generated as needed for real-time control of the nitrogen system.

3.4 LEAK location methods

Although the WT4 waveguide and sheath have been designed to be mechanically rugged and corrosion resistant, methods must be available for locating the occasional leaks which may occur in order to prevent the gradual deterioration of the medium. A procedure for locating these leaks has been developed based on the following assumptions:

(*i*) Small sheath leaks are tolerable for an extended period and need not be located as rapidly as large leaks. Leaks under 200 scfd need not be located at all.

(*ii*) Large leaks which develop suddenly are most probably produced by large, easily visible causes, e.g., construction equipment or gross geological disturbances.

Leak location is envisioned as a three-stage process. The first stage identifies the repeater section in which the fault has occurred. The second stage produces a rough estimate of the leak's position accurate to within ±½ mile. The third stage pinpoints the leak to within a few feet. The first stage of the leak location is accomplished by the nitrogen system flow alarms which were discussed previously.

For both large and small leaks, pinpointing leaks is a straightforward process. Massive leaks will generally be associated with highly visible indications of damage, caused by construction activity or natural disturbances. Equipment sufficiently massive to damage waveguide is not quickly deployed or concealed and can be visually located.

Small leaks can be pinpointed using a helium tracer gas method. At the projected location of the leak, the sheath is uncovered, it is then tapped and helium is injected into the tap hole. The helium flows to the leak where it escapes the sheath and rises to the surface in a funnel

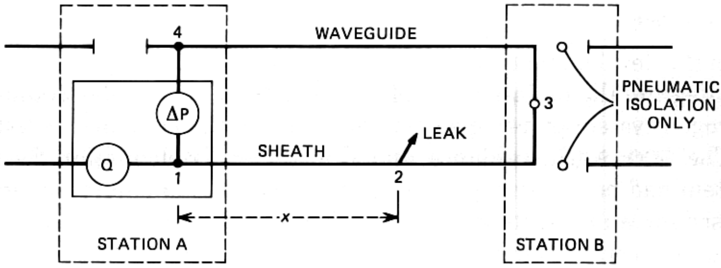

Fig. 2—Locating a leak.

pattern. Two-inch deep probe holes are made every 4 feet along the route, working away from the projected leak location. A simple thermal-conductivity gas monitor is used to sample gas from the probe holes immediately after they are made. When helium is detected the leak is located, usually within a couple of feet from the point where helium is detected. The third or pinpointing stage of leak location uses the helium tracer gas method or visual inspection.

3.5 Localizing small leaks

Since the helium method of leak pinpointing is impractical for the large repeater spans, which may be as long as 37 miles, a method of localizing leaks to within ±½ mile was developed.

The leak localization system uses a test set which has a sensitive electronic manometer, an accurate flow transducer, and data recording equipment. The test set is installed at a repeated station only when a leak has been indicated by the flow monitors present in the station.

During normal operations sheath sections are interconnected at repeater stations by means of flow monitored channels. Waveguide sections are similarly joined. There is no normally open flow path between the sheath and the waveguide systems. The first step in the leak localization process is to pneumatically isolate the waveguide and sheath from the adjacent repeater spans. The waveguide and sheath are then joined together (Station B in Fig. 2) and the pressure is reduced by venting until it is equal to the sheath pressure in the adjacent repeater span. At the other end of the span (Station A in Fig. 2) the leak localization test set is installed. The flow meter in the test set monitors the flow from the adjacent sheath into the leaky sheath span. The electronic manometer is installed between the sheath and waveguide to measure the extremely small pressure between them.

There is a waiting period required for the sheath and waveguide to come to a common equilibrium. After equilibrium is achieved, there is no flow in the waveguide, and all flow to the leak passes through the

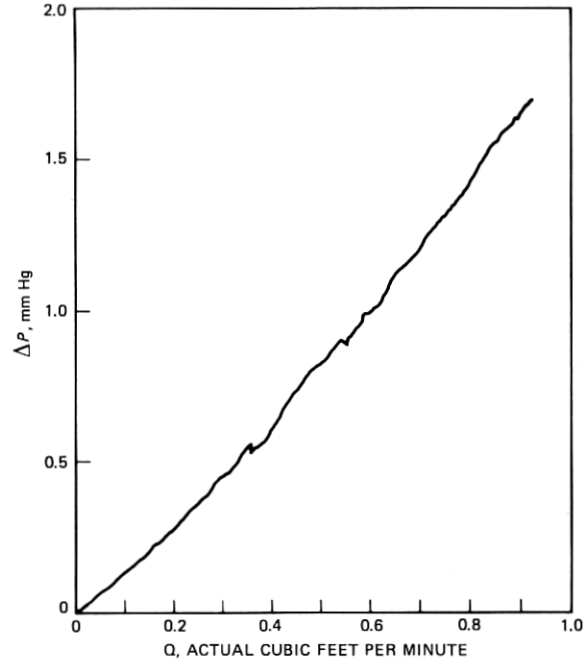

Fig. 3—Flow characteristics of WT4 sheath.

precision flow monitor in Station A. The estimated position of the leak, $\hat{x}$, is determined by application of a simple formula to the flow and differential pressure readings obtained with the test set:

$$\hat{x} = \Delta P/f(Q)$$

$$\Delta P = \text{Pressure drop measured by test set} \qquad (1)$$

$$Q = \text{flow measured by test set}$$

The differential pressure, ΔP, measured by the test set is the pressure drop caused by the flow to the leak because (*i*) the difference in absolute pressure between any two points in the waveguide-sheath circuit is quite small, (*ii*) the nitrogen temperature at any location is the same in both waveguide and sheath, and (*iii*) the use of a differential pressure manometer eliminates hydrostatic components.

The use of eq. (1) depends upon knowning $f(Q)$, the pressure gradient in the sheath as a function of volumetric flow. This function was determined experimentally during the field evaluation test and is plotted in Fig. 3.

The accuracy in projecting the location of a leak depends upon the stability of the sheath pressure and the accuracy of the test set. Esti-

Table III — Accuracy requirements for leak localization

Objective:	
Localize 200 scfd leak to within ±½ mile	
Requirements:	
Input Pressure Stability	±0.002 psi
Flow Measurement	±3 scfd
Differential Pressure	±0.0001 psi

Table IV — Leak localization test results

	Leak size	
	300 scfd	130 scfd
Known distance to leak	40,307 ft	20,147 ft
Projected distance to leak	40,641	21,240
Error	340 ft	1,093 ft

mating the position of a leak requires a precise knowledge of the leakage flow. What is measured by the leak localization test set is not the leakage flow, but the flow into the sheath under test. Because the nitrogen is compressible any small variation in applied pressure results in a corresponding change in flow into the sheath. The pressure variations are controlled in two ways: (*i*) by providing high-precision absolute pressure regulation in the distribution panel, and (*ii*) by having more than one repeater span between regulated pressure feed points. The latter method uses the sheath adjacent to the section under test as a "settling" tank.

The accuracy required for the test set was determined by analysis of the sheath annular flow data shown in Fig. 3. Table III gives the accuracy requirements for the leak localization procedure.

A leak localization test set was developed that exceeded the accuracy requirements listed in Table III. The test set, which was constructed of commercially available instruments, was used to locate two leaks that were introduced in the sheath at known locations. Table IV gives the results of these tests.

Both projections were well within the ±½ mile objective for leak localization accuracy.

IV. RESTORATION

4.1 Overview

The outage of the WT4 medium is directly proportional to the restoration time for failures. To meet the outage objective, a restoration time not exceeding 6 hours must be achieved. Four of the 6 hours are allocated for travel and trouble location and 2 hours are allocated for repair. The restoration of the WT4 medium proceeds as follows:

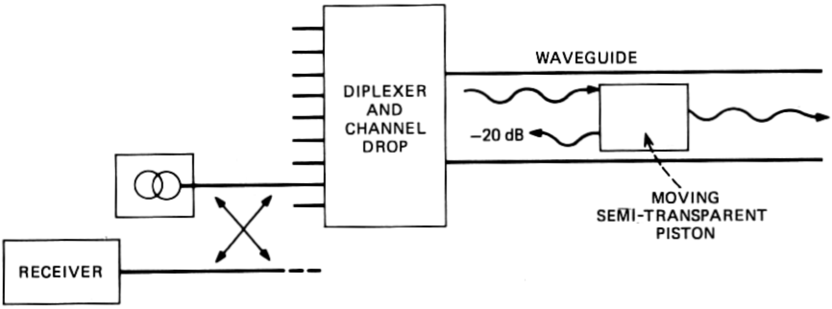

Fig. 4—Electrical fault location technique.

(*i*) A service outage occurs and the monitoring system detects the failure and determines the failed repeater span.

(*ii*) Simultaneous failure of many channels indicates a medium failure. When this happens (*a*) A crew with a portable electronic fault location test set is dispatched to the repeater station nearest the failure. (*b*) An immediate patrol of the route between repeater stations where the trouble occurred is initiated. The object of the patrol is to look for construction activity that might have damaged the waveguide. (*c*) Restoration equipment consisting of a small backhoe, a WT4 restoration trailer, and a cable restoration trailer is transported by the restoration crew from the maintenance center to a convenient location near the failed repeater section.

(*iii*) Upon location of the damaged waveguide by inspection or electrical or pneumatic fault location techniques, the restoration equipment is dispatched to the trouble site.

(*iv*) The damaged section is repaired with a temporary patch and service is restored.

After service is restored a permanent repair is engineered. A construction crew rather than a maintenance crew makes the permanent repair.

4.2 Waveguide electrical fault location

Waveguide faults such as delamination of the dielectric liner or rupture of a welded joint while the sheath is intact cannot be located with the gas pressure methods. A characteristic of these internal waveguide faults is that electromagnetic energy will be scattered from the TE_{01} mode into other modes causing a net forward propagation loss but little backscatter into the low-loss TE_{01} mode. Conventional reflectometers as used in cables for discontinuity detection are therefore not applicable here.

For internal waveguide fault location, therefore, a semitransparent dielectric piston (Fig. 4) is used in conjunction with a millimeter wave

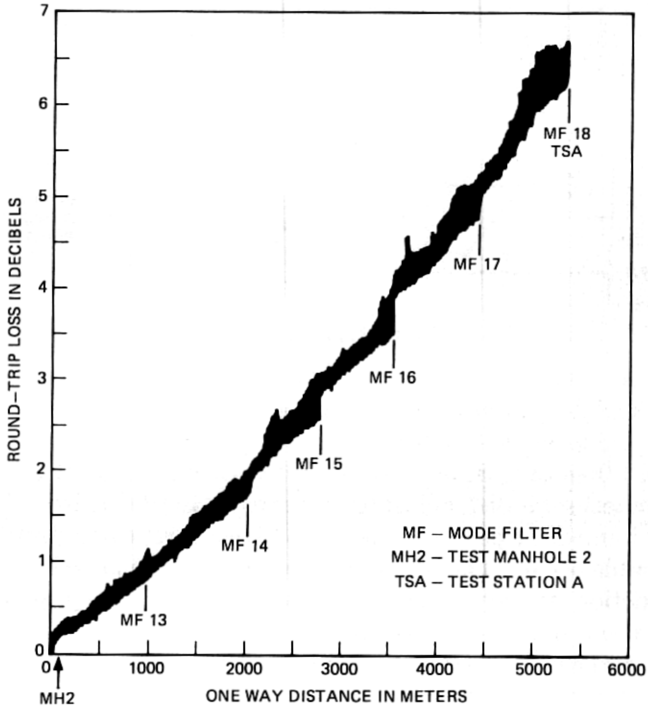

Fig. 5—Moving piston measurements, 95.8 GHz.

reflectometer operating for convenience in the vicinity of 80 GHz where the line loss has a minimum. A polystyrene foam piston normally is stored in the guide at one of the repeater stations where it causes only 0.1 dB forward loss and where the −20 dB discrete reflection has no significant effect on overall system performance. During routine maintenance testing or when a fault is suspected, the piston is propelled (by nitrogen flow) through the waveguide at a speed of about 1 to 2 meters per second until it hits an obstruction in the waveguide or arrives at the next repeater station. Throughout its journey through the guide, the piston is tracked by the reflectometer both in range and signal amplitude.[6] A typical loss versus distance trace of a 5.3-km-long piston run from the Netcong-Long Valley field evaluation installation is shown in Fig. 5. The waveguide line is characterized for its amplitude-versus-distance characteristics at the time of installation as part of the line acceptance test. The as-installed loss record is then compared with the newly taken record which then will reveal specific locations at which a fault in the line has increased the loss measurably as a result of one of the waveguide defects referred to initially.

Waveguide discontinuities with a very low reflection can also be de-

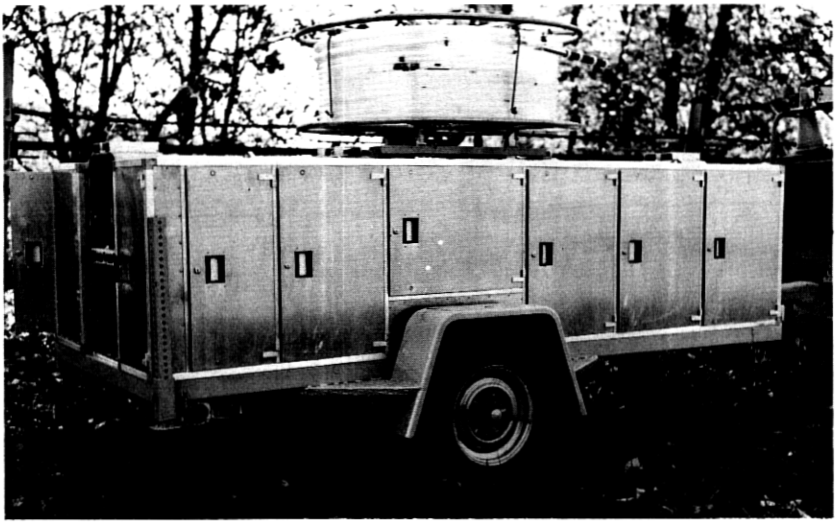

Fig. 6—Trailer for restoration equipment.

tected with a spatial resolution of 3 m using an adaptation of a reflectometer which uses coherent detection and was developed for the field evaluation test.[7] This set can measure reflected signals which have a combined reflection and line loss as high as 90 dB.

4.3 Repair methods for waveguide restoration

Repair of a damaged waveguide within the 2-hour objective requires special equipment and training. To minimize the training problem, the restoration operation is patterned after cable restoration techniques which are well understood. The equipment developed for restoration is simple, rugged, and is easily transportable by trailer or helicopter. All of the restoration equipment is carried on a specially designed trailer (Fig. 6). The tool and hardware cabinets on the trailer can be removed for transportation by helicopter to the trouble site.

Figure 7 illustrates the step-by-step restoration procedure, which is as follows:

Step 1. A small backhoe is used to uncover the damaged waveguide and expose undamaged sheath on each end.

Step 2. The restoration crew removes a length of the sheath on each side of the damaged section. The tools used for this operation consist of commercially available pipe cutters and abrasive disk saws.

Step 3. Waveguide sheath restrainers are installed to lock the waveguide to the sheath at each end. This is necessary because the waveguide will be in compression or tension and could move several feet if not restrained.

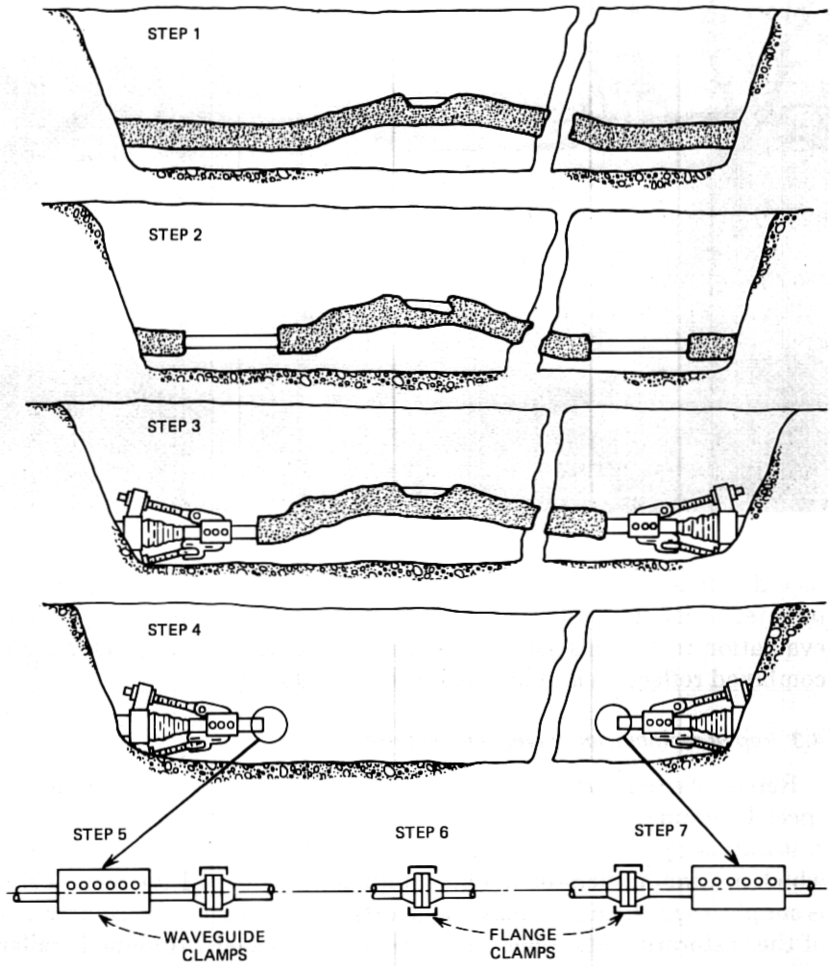

Fig. 7—Restoration concept.

Step 4. The waveguide is cut off at each end and pushed aside to make room for the patch waveguide sections.

Step 5. A patch waveguide section is joined to the end waveguide with a waveguide tube coupler

Step 6. Flange clamps are used to quick-connect waveguide patch sections until the patch spans the damaged area.

Step 7. The last patch section of waveguide is cut off and is joined to the waveguide end with a tube coupler. This completes the restoration and service can be resumed.

Field demonstrations of the repair methods and equipment have confirmed that the 2-hour objective is realistic.

V. Route rearrangements

It is sometimes necessary, despite the best planning efforts, to move or rearrange a right-of-way medium to allow for construction of roads, drainage ditches, etc. Route rearrangements can be divided into two categories: (*i*) rearrangements which do not require a break in the medium (generally a lowering operation) and (*ii*) rearrangements requiring the installation of new medium (generally a reroute).

Waveguide route rearrangements of the first category are similar to lowering operations for coaxial cables. Slack can be generated or removed for lowering operations by cutting the sheath but not the waveguide. The waveguide will stretch or compress to conform to the new profile.

Waveguide route rearrangements of the second category are very different from coaxial cable reroutes. With coaxial cables, service can be transferred from a working pair of coaxial tubes to a protection pair. The working pair is then cut and spliced into the new cable and service is then "rolled" back. Waveguide has only one transmission path so the rolling process is not possible.

To minimize service outage and to provide reroute capability, the concept of a "hot switch" was developed for the WT4 medium. The new waveguide and sheath are brought in parallel and above the in-service waveguide is prepared by removing a section of sheath and cutting coupling welds on each end. A series of synchronized "hot switch" machines then push the new section down displacing the old waveguide section to transfer service to the new waveguide. Fig. 8 shows the conceptual hot switch equipment.

The mechanical switch causes a transmission hit but will not drop service on the digital network provided the total outage is less than 140 milliseconds. Sixty milliseconds is needed for reframing the terminal equipment and 80 milliseconds is allocated to the hot switch.

The dynamics of the switch were analyzed and a machine was built to demonstrate feasibility and test critical subsystems. The results of the tests show that the hot switch is a practical concept to use for reroutes of the WT4 medium. The final machinery has not been designed.

VI. SUMMARY

In order to insure long life and low maintenance costs, the WT4 medium is designed with a steel sheath. The steel sheath provides excellent mechanical protection for the waveguide and it should eliminate all service-affecting troubles (lightning, Bell associated) except those caused by foreign workers. Considering the 3-dB repair margin, the service-affecting trouble rate due to foreign workers should be one to two orders of magnitude less than that for coaxial cable systems. With this low

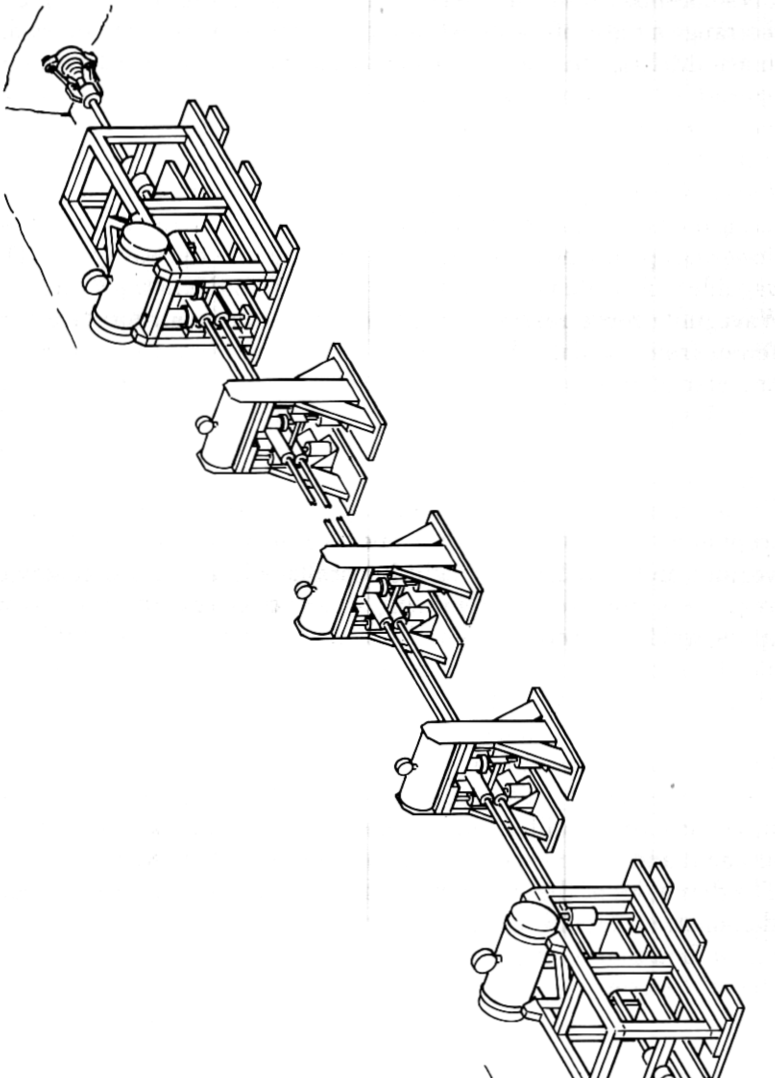

Fig. 8—Hot switch equipment.

trouble rate the overall reliability objective of 99.99% for a 4000-mile system is realizable.

The WT4 nitrogen system is designed to minimize the impact of service-affecting troubles by preventing contamination of long lengths of waveguide. It is also used for localization of leaks by pneumatic techniques and aids localization by electrical techniques by propelling transparent pistons through the line.

The pneumatic and electrical trouble-location methods insure the quick location of most troubles. Restoration is then accomplished using specialized equipment and methods.

VII. ACKNOWLEDGMENTS

Many individuals at Bell Laboratories and American Telephone and Telegraph Company, Long Lines Department, contributed to the development of the maintenance systems. Particular acknowledgment is due to C. J. Willis for development of the restoration methods and D. A. Alsberg for development of the electrical fault location concepts.

REFERENCES

1. R. J. Boyd et al., "Waveguide Design and Fabrication," B.S.T.J., this issue.
2. R. W. Gretter et al., "Waveguide Support and Protection System," B.S.T.J., this issue.
3. W. J. Liss, et al., "The Repeater Building," B.S.T.J., this issue.
4. M. J. Bonomi et al., "Protection Switching, Auxiliary Communications, and Maintenance," B.S.T.J., this issue.
5. A. W. Peabody, *Control of Pipeline Corrosion,* National Association of Corrosion Engineers, 1969.
6. D. A. Alsberg, U.S. Patent 4021731, May 3, 1977.
7. J. L. Doane, "Measurement of the Transfer Function of Long Lengths of 60-mm Waveguide with 1 MHz Resolution and High Dynamic Range," Digest of the Conference on Precision Electromagnetic Measurements, Boulder, Colorado, June 28 to July 1, 1976, pp. 153–155.