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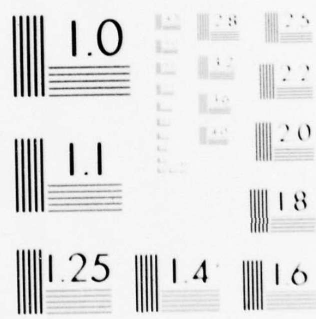

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FIBER OPTICS FOR TACTICAL COMMUNICATIONS

BY C.W. KLEEKAMP AND B.D. METCALF

APRIL 1979

Prepared for

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This technical report describes the FY 77 MITRE/ESD Fiber Optics Technology Applications Program. The objective of this program was to define and demonstrate high-payoff applications of fiber optic technology to Air Force ground-based tactical C^3 systems. During this program a fiber optic link for replacing 26-pair metallic cabling, currently used for 407L shelter interconnection and radio remoting, was

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designed and developed. This link was successfully demonstrated to Air Force users at the Bold Eagle 78 exercise in October 1977.

ACKNOWLEDGEMENTS

The success of this project was the result of a devoted team effort. The authors acknowledge the significant project contributions of Stephen J. Forde and George E. Schertell. The expertise of Jan A. Malouin is credited for the electrical circuit designs used in the transmitter and receiver units. We also greatly appreciate the project momentum developed by our Department Head, Kenneth C. Taylor, and ESD Project Officer Major Neal Adams. For preliminary field testing, we express our thanks to the Commander and staff at the 102nd Tactical Control Squadron of the Rhode Island Air National Guard. Finally, we are indebted to Col. C.W. Flippo for providing the opportunity to demonstrate the fiber optic system at exercise Bold Eagle 78.

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SECTION I

INTRODUCTION

The Fiber Optic Technology Program is intended to introduce a new technology which now has demonstrable advantages in performance and cost. This document describes the MITRE program during FY 77, which was sponsored by the Electronic Systems Division of the U.S. Air Force Systems Command. This document is organized as follows. Section II explains the program objectives of defining and demonstrating high-payoff applications. Section III gives a brief fiber optics technology background for readers unfamiliar with the area. Section IV discusses the results of an analysis for defining near-term, high-payoff applications of fiber optics to ground-based tactical command and control communication systems. Section V describes in detail a fiber optic demonstration system used as a replacement for multiconductor metallic cabling currently employed for radio remoting and shelter interconnection in tactical deployments. Section VI discusses preliminary testing at an Air National Guard facility, and the final system demonstration at the Bold Eagle 78 exercise on Eglin Reservation. Section VII presents conclusions and recommendations.

SECTION II

PROGRAM OBJECTIVE

The transmission properties of the fiber optic medium offer unique solutions to many problems inherent in wire or RF transmission. These properties include: electrical isolation and immunity to lightning, EMP, EMI and crosstalk, as well as enhanced security, weight, power and cost savings. These advantages of fiber optics over conventional media make a number of potential applications attractive.

The objective of the Fiber Optics Technology Applications Program was to define and demonstrate high-payoff applications of fiber optic technology to Air Force ground-based tactical command and control communication systems. To meet this objective, it was first necessary to study ground-based communication system requirements and identify applications which could best exploit the advantages of the technology. Among applications considered were the replacement of existing cable as well as new command post (inter- and intrashelter cabling) applications. The most promising, for near-term application, were point-to-point links. The future development of fiber optic taps (couplers) precluded work on multiterminal systems in the time frame of this project.

Within the scope of this program, one application in particular, the remoting of the AN/TRC-97 troposcatter radio terminal, was chosen for a field demonstration. During the remainder of the fiscal year the fiber optic link was designed, fabricated and tested. Several ideas relating to the construction of optical source packages and connectors were implemented and evaluated. The effort culminated in a successful demonstration of the fiber optic TRC-97 link at the joint-service Bold Eagle exercise held on Eglin Reservation in Florida, October, 1977. This demonstration has stimulated many fresh ideas for future applications and exploitation of the fiber optics alternative.

SECTION III

TECHNOLOGY BACKGROUND

The first serious consideration of glass fibers for medium- and long-distance information transfer came from Standard Telecommunications Laboratories in England. At that time, 1968, typical fiber losses were more than 1000 dB/km, but it was suggested that much lower losses could be achieved with purer materials. There followed several efforts in England, Germany, Japan and the United States to purify glass and work out fiber transmission problems. The breakthrough occurred in 1970, when Corning Glass Works announced achievement of fiber losses under 20 dB/km in single-mode fibers.

FIBER OPTIC CABLES

Since 1970 there has been rapid progress in the development of low-loss fibers (figure 1). Optical fibers are now commercially available in cable form at losses of 6 dB/km with 400 MHz-km bandwidth. Recent laboratory research has reported fibers with losses less than 0.5 dB/km and 3000 MHz-km bandwidth.

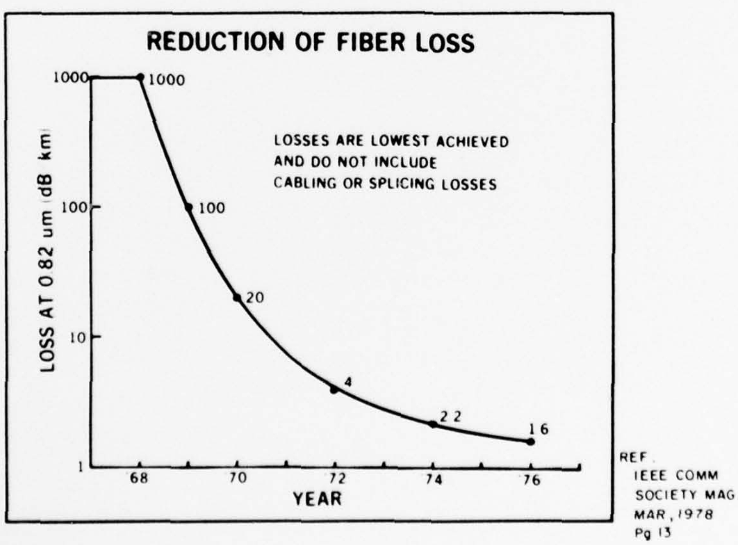


Figure 1. Fiber Loss Achieved in Recent Years

In early fibers, the main cause of attenuation was absorption of the signal due to metallic impurities and water in the form of the oxygen-hydrogen radical. When the metallic impurities are reduced below one part per billion, Rayleigh scattering becomes the dominant source of loss at lower wavelengths, and infrared absorption in the glass itself establishes limits at the longer wavelengths.

The attenuation of a typical commercial fiber (ITT type T-103) is shown in figure 2. Currently available light sources and photodetectors operate in the region of the first attenuation minimum from about 0.8 to 0.9 microns. Here the loss is about 5 dB/km. There is even less attenuation beyond the OH radical absorption peak: for example, 3 dB/km at 1.1 micron.

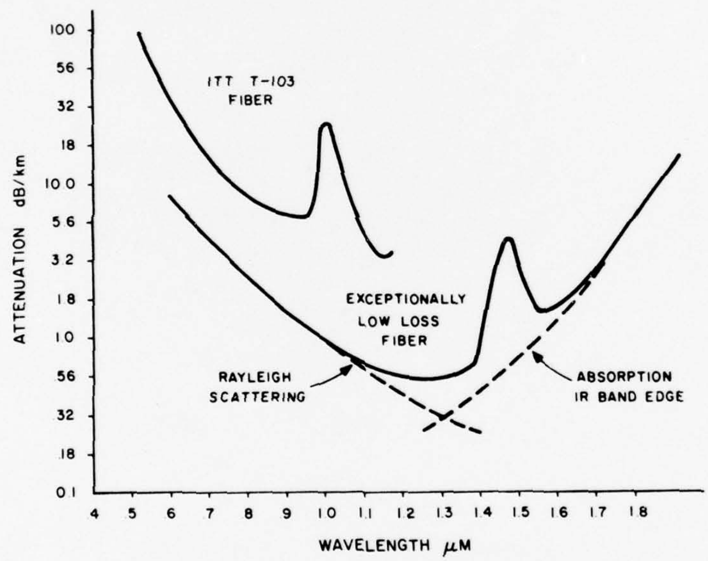


Figure 2. Fiber Loss Vs. Wavelength

The exceptionally low-loss experimental fiber shown in figure 2 has an attenuation of only 0.5 dB/km at 1.2 microns. Many efforts are underway to extend the operating points of current sources and detectors so as to take advantage of the attenuation minima at the longer wavelengths. The low attenuation of currently available optical fibers (6 dB/km) permits very long cable runs between repeaters, on the order of 8 km (= 5 miles). The resulting reduction in the required number of repeaters has attractive economic advantages for long-haul applications as well as reliability enhancements.

The bandwidth of an optical fiber can be viewed most simply as a function of the variation in transit times of the many propagating light rays. The less the variation, the greater the bandwidth. In the "step-index" type of fiber, whose core is of constant refractive index, light rays propagate by total internal reflection at the interface with the cladding material (figure 3). At the interface, the index of refraction changes abruptly to a lesser value. The result is a comparatively wide variation in the propagation times of the light rays due to their differing path lengths, and a consequent "smearing" or distortion of any signal carried by the rays. With practical core diameters in the order of 50 to 60 microns the differences in propagation times, called modal dispersion, limit the bandwidth of such fibers to approximately 20 to 40 MHz in a kilometer length.

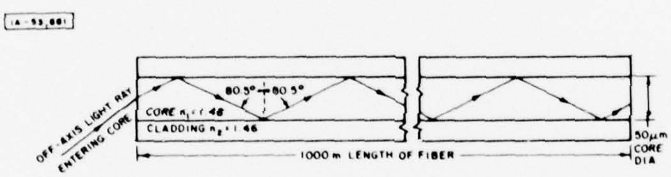


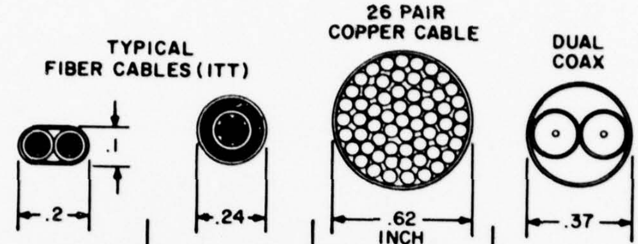
Figure 3. Light Ray Propagation in An Optical Fiber

The "graded-index" type of fiber was designed to correct for this effect. Its refractive index decreases continuously with radial distance from the fiber axis. Light propagation is sustained by refraction; a continual bending of the ray toward the axis. Light travels faster at the outer extremities of the core, reducing differences in arrival time, and lessening dispersion. This type of fiber has bandwidths of 200 to 600 MHz in a kilometer length.

Considerable progress has been made in ruggedizing fiber optic cable. As demonstrated by MITRE in a roadway test, current cable designs allow tens of thousands of vehicles to roll over ruggedized cables without fracturing the fibers.

Figure 4 compares typical commercially available fiber optic cables (a two- and six-fiber version by ITT) and two types of metallic cable (26-pair and dual coax) presently used for ground-based tactical communications.

ADVANTAGES OF FIBER OPTIC CABLES



	TYPICAL FIBER CABLES (ITT)		26 PAIR COPPER CABLE	DUAL COAX
SMALL SIZE:	.2	.24	.62 INCH	.37
LIGHTWEIGHT	8#/1000 ft	22#/1000 ft	208#/1000 ft	60#/1000 ft
BANDWIDTH (5 MI) (CAPACITY)	45 Mb/s 672 VOICE CH.	140 Mb/s 2016 VOICE CH.	.05 MHz 12 VOICE CH.	19 Mb/s 768 VOICE CH.
REPEATER SPACING (ATTENUATION)	5 MILES 10 dB/MILE	5 MILES 10 dB/MILE	N/A	¼ MILE 112 dB/MILE
PRESENT COST PER FOOT	$ 1.83	$ 4.50	~~$ .35~~ $ .98	$ .33 ?

- NO GROUND LOOP, LIGHTNING OR EMP PROBLEMS
- EXTENDED DEPLOYMENT RANGE
- POTENTIALLY COST EFFECTIVE

Figure 4. Advantages of Fiber Optic Cables

The cost of the fiber medium is continually decreasing, while the performance parameters are improving. Examining the cost projections of one manufacturer, Corning (figure 5), one can see that the near-future emphasis is on lowering cost through better manufacturing techniques and economies of scale. As a rough rule of thumb, the cost of a finished cable can be estimated as twice the cost of the total number of fibers contained.

SPLICES AND CONNECTORS

Maximum transfer of light between the ends of two fibers in a splice or connector demands highly accurate alignment. Assuming that there is an excellent end finish on the mating fibers, there are three types of alignment offset which contribute to the "insertion loss" of the splice or connector (figure 6): lateral displacement of the fiber

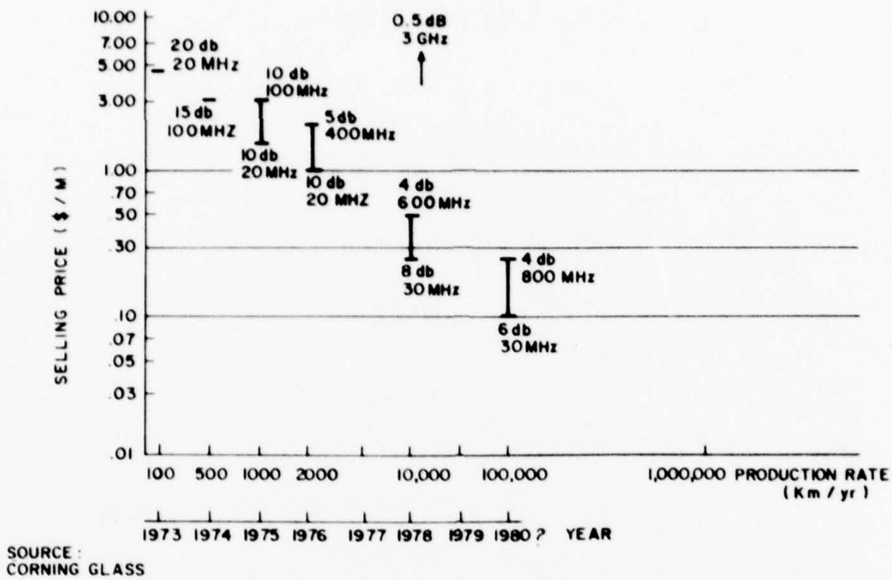


Figure 5. Corning – Single Fiber Price Projections

axes (which is the most critical offset), fiber end separation, and angular misalignment. The latter two depend on the numerical aperture of the fiber; higher apertures produce higher losses. In addition, there are end reflections which typically introduce a 0.4-dB loss. These reflections may be eliminated by using an optical matching substance whose refractive index closely matches that of the fiber core.

Fiber splices can be used to repair damaged and broken cables. Commonly used splicing techniques include the "V" groove and its variations (figure 7). A sharply formed V, or corner, holds and aligns the prepared fibers, which are butted under slight pressure. A drop of index matching adhesive secures the joint. Losses around 0.2 dB are typical.

Another technique is the "three-rod" splice (figure 8). The fibers are inserted into the interstice of three parallel rods that touch tangentially. A low-viscosity adhesive is applied, and by capillary action uniformly bonds all elements.

In the fusion or "hot splice" technique, the fibers are butted and welded together with a flame or electric arc. Losses of 0.25 dB are easily achieved with the fusion method.

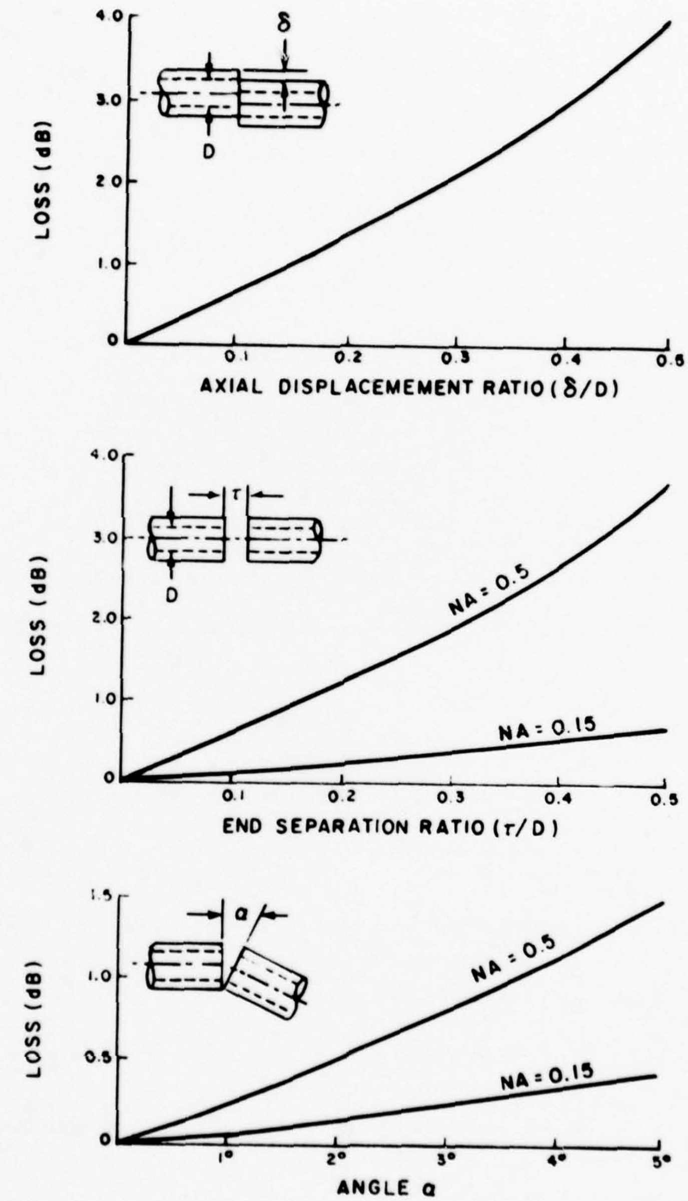


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Figure 6. Loss Mechanisms in Fiber Splices and Connectors

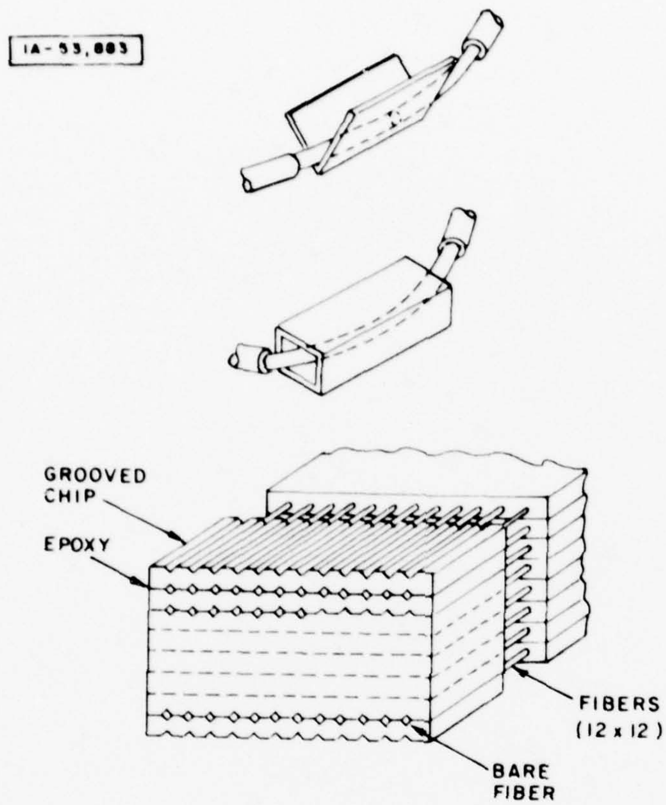

Figure 7. Groove Splice and Variations

Whereas the splice is a permanent joint, a connector is a demountable joint, which is required for the deployment of ground-based tactical systems. At the outset of this program, no suitable low-cost, low-loss single fiber connector was available. MITRE therefore developed a connector*, which has been successfully used in its research and applications to date. More recently the connector picture has improved, with new, promising devices available from several manufacturers. The connector problem has generated a wide range of design solutions, some of which are illustrated in figure 9.

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*Described in detail in section 5.

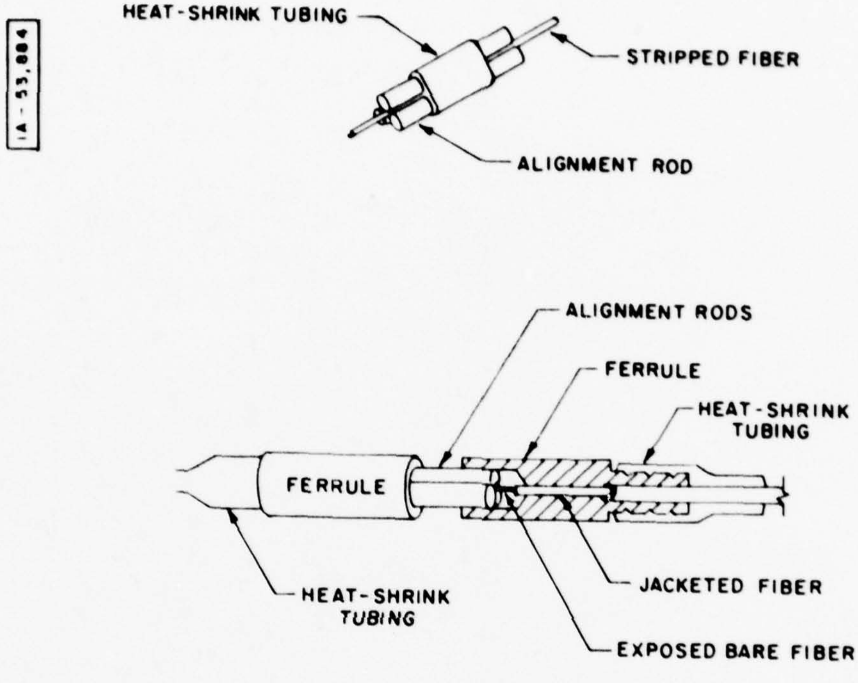

Figure 8. Three Rod Splice

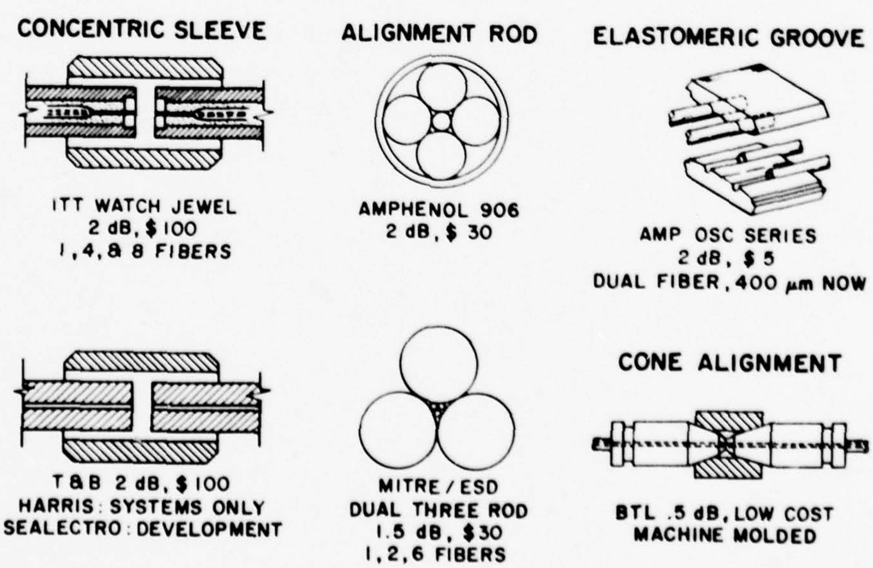

Figure 9. Single Fiber Connector Technology – Jan 78

Concentric sleeve designs are typified by the watch jewel connector from ITT Cannon, and other metallic concentric insert connectors such as those of the Harris Corporation. This is generally the most expensive type, costing approximately $100 per fiber at present.

The alignment rod connectors locate the fibers in interstitial gaps formed by a configuration of alignment rods. A commercial product available from Amphenol uses four alignment rods with a fiber in the center. The MITRE connector uses a dual three-rod approach.

All-plastic connectors have been developed by AMP Inc. and Bell Telephone Laboratories. In the AMP connector, an elastomeric block self-centers the fibers within V grooves. As now designed, the connector accommodates 400-micron-diameter fibers. This connector sells for about $4 per mated pair. AMP is working on a variation which will accommodate the 125-micron fibers more typically used in long-haul communication systems. If this can be done, it will make available a highly promising connector costing two orders of magnitude less than other precision mechanical designs using metallic components.

The Bell Laboratories connector uses a cone alignment principle. Cone-shaped plugs are injection-molded around the fibers. The plugs are aligned with a biconic sleeve. This connector is not now available to the industrial or military user.

It is our opinion that the present variety of connectors, either in manufacture or on the drawing board, will overcome the lack of a suitable single-fiber connector, which was a major impediment to widespread use of fiber optic technology.

LIGHT SOURCES

Light sources used for fiber optic communications are the light emitting diode (LED) or the injection laser diode (ILD). These are semiconductor devices whose light output is controlled by current driven through the diodes.

The requirements for optical sources used in single-fiber technology are very demanding. To maximize link length (that is, to extend repeater spacing) a source should be as intense as the state of the art allows. To launch optical power efficiently into the fiber, the emitting area of the source should be smaller than the fiber core area. Moreover, the emitted beam pattern of the source must be very directional to fit within the acceptance cone of the fiber. To minimize material dispersion within the fiber (different wavelengths travelling at different velocities) the light output must be spectrally pure; that is, it requires a narrow spectral linewidth. Fast rise and fall times are required for high-capacity digital systems, while analog modulated systems require an optical power output linearly related to the drive current over a wide dynamic range.

Injection laser diodes are well suited for use in digital (or pulsed) fiber optic systems. They are made from gallium arsenide doped with aluminum. The laser pellets are very small – typically cubes 10 mils on a side – and are mounted on transistor heat sinks. The devices employ a stripe geometry, which confines the laser cavity region to an active output area measuring about 1 x 10 microns. Emission through the narrow slit output aperture produces a rather broad diffracted beam in the plane perpendicular to the P-N junction (20° to 40° half-angle). The beam in the plane parallel to the junction is much more narrowly confined (2° to 5° half-angle).

The beam of the ILD is far more directional than that of an LED, and typical numerical aperture losses into flat-ended fibers measure about 6 dB. Current continuous-wave laser diodes have a much higher power output (5 to 10 mW) than LEDs, and are very fast (rise time of less than 1 nsec). Finally, their spectral linewidth is so small that material dispersion in fibers is usually negligible.

One of the early problems with the injection laser was its short lifetime. Considerable effort has been devoted to extending the lifetime, and the material problems are now reasonably well understood. Starting from a two-hour lifetime in 1970 (figure 10), ILDs now have extrapolated lifetimes of more than one million hours.

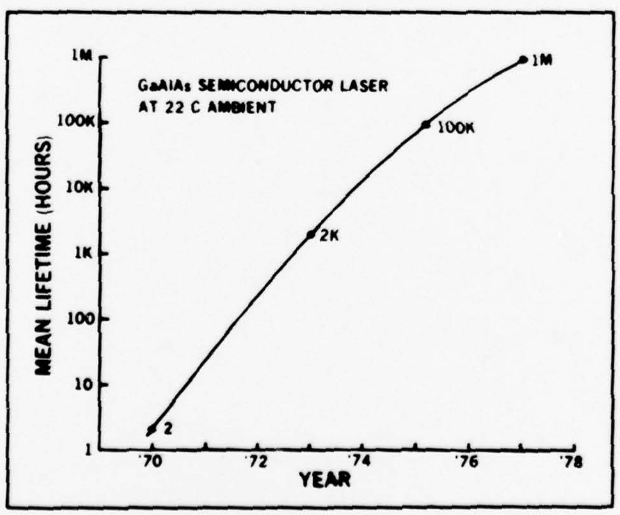

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Figure 10. Improvement in Laser Lifetime

One problem with the injection laser source not found with the LED is its temperature sensitivity. For example (figure 11) if the operating temperature should fall from 30° to 20° C with the forward drive current constant, the optical power would rise drastically and perhaps damage the facet of the laser pellet.

THERMAL CHARACTERISTICS

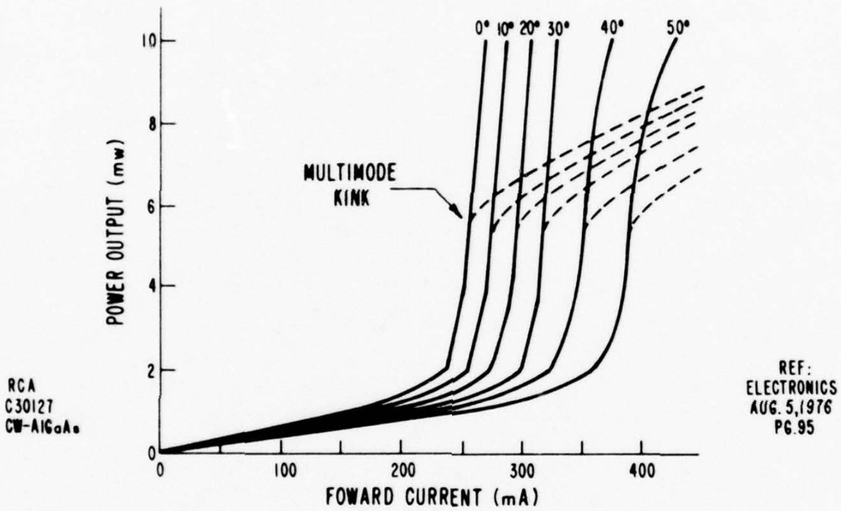

Figure 11. ILD Output Power Vs. Drive Current

Remedies to the temperature dependence of the laser can be incorporated in the transmitter circuitry. Optical feedback schemes use a photodetector located behind the laser pellet to monitor the average optical power output. A feedback control circuit regulates the drive current. This overcomes the low-temperature difficulty. In addition, a thermoelectric cooler can be used to control the operating temperature of the pellet. Commercial injection laser transmitter units with these temperature compensation circuits are available.

A second problem, at least for linear modulation, is the multimode kink (figure 11) in the characteristic curve of the ILD. This is not very important for pulsed operation, but it prevents the device from being used for linear modulation due to harmonic and intermodulation distortion resulting from the kink. Recent developments in injection laser technology, however, have produced single-mode lasers which are free of multimode kinks up to several milliwatts of optical output power.

PHOTODETECTORS

The receivers most common in fiber optic systems use photodiodes to convert incident light energy to electrical current. The positive-intrinsic-negative (PIN) photodiode (figure 12) has a large intrinsic (very lightly doped) region located between p- and n-doped semiconducting regions. Photons absorbed in this region create electron-hole pairs that are then separated by an electrical field produced by an applied reverse bias voltage on the diode. This generates a current in the load circuit.

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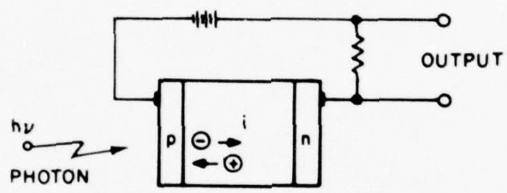


Figure 12. PIN Photodiode

The efficiency of the optical photon-to-electron-hole conversion process is specified by the quantum efficiency of the photodiode, which measures the average numbers of electrons generated by an incident photon; a quantum efficiency near one indicates a highly efficient diode. Quantum efficiencies of 0.8, at a wavelength of 0.9 microns, are typical of PIN diodes.

Another photodiode performance parameter characterizing the optical power/electrical current conversion process is responsivity. This parameter gives the ratio of output electrical current to incident optical power, measured in amperes/watt. Typical responsivities for PIN diodes are around 0.5 to 0.6 amp/watt.

The avalanche photodiode (APD) is designed for applications requiring greater sensitivity. Because of a strong electric field created by a large reverse bias voltage, the APD exhibits internal gain. Primary electrons, generated by the incident light, are accelerated by the strong field and undergo ionizing collisions with surrounding atoms, thus liberating more electrons.

Compared with the PIN diodes, the APDs require a considerably higher bias voltage. Biases on the order of 300 to 400 volts are not uncommon. The resulting current gain, however, produces APD responsivities about an order of magnitude greater than PIN diodes. Moreover, the gain of an APD, and hence its responsivity, is quite temperature-dependent (figure 13). For general-purpose use in a fiber optic receiver, the APD requires thermal compensation for gain control. APD prices are typically around $150 to $250, compared to $10 to $50 for PIN diodes.

For further details on fiber optic technology, the reader is referred to the authors' four-part designer guide series (Reference 1).

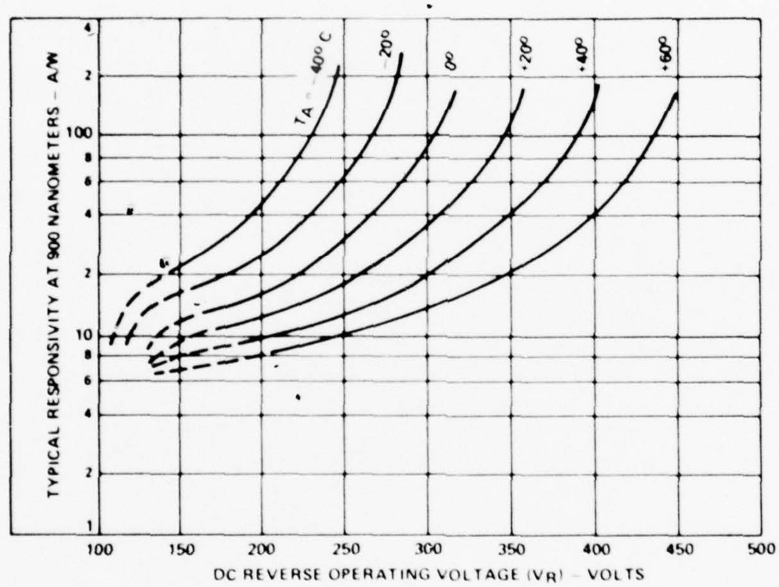


Figure 13. APD Responsivity Vs. Voltage (At Wavelength of 900 nm)

SECTION IV

APPLICATIONS ANALYSIS

ANALYSIS OBJECTIVE AND SCOPE

Air Force tactical C^3 systems were evaluated with the objective of determining specific applications in which the advantages of fiber optics would be significant. Only ground-based systems were examined. The analysis was further constrained by the requirement for demonstration in the near term – within FY77. Due to the lack of a commercially available fiber optic coupler (tap), this near-term requirement eliminated multiple-access (multiterminal) system architecture applications. The analysis (referred to in another document) therefore concentrated on point-to-point links, which appear to be most promising for initial exploitation.

APPLICATIONS WITHIN THE TACTICAL AIR CONTROL SYSTEM

The Control and Reporting Center (CRC) is the senior element of the Tactical Air Force's surveillance and control system. The central hub of the communications complex for a typical CRC deployment (figure 14) is the AN/TSC-62 technical control center. Metallic 26-pair cables connected to this shelter (figure 15) carry communications to several types of radio vans. The cable comes in lengths of 250 or 1000 feet, with a hermaphroditic connector on each end, and weighs 208 pounds per 1000 feet. While the cable has an attenuation of only 2.7 dB/mile (=1.7 dB/km) at voice frequencies, there can be considerable signal attenuation due to degraded connector contact impedance. This typically limits the series connection of 250-foot lengths to three or four sections in tandem. In special situations, usually no more than two 1000-foot sections are connected in tandem.

Radio Remoting

For reasons of component availability and time constraints, the system chosen to implement in FY77 was the TRC-97 troposcatter radio remoting link.

The TSC-62 technical control communications central and the TRC-97 radio terminal are conventionally interconnected as shown in figure 16. Typically, three separate parallel links are established, two carrying voice and the third for teletype information. The voice channels are 4-wire circuits and each 26-pair cable usually carries 12 channels. Using a multiplexed fiber optic link, all voice and teletype information can be transferred on a two-fiber cable.

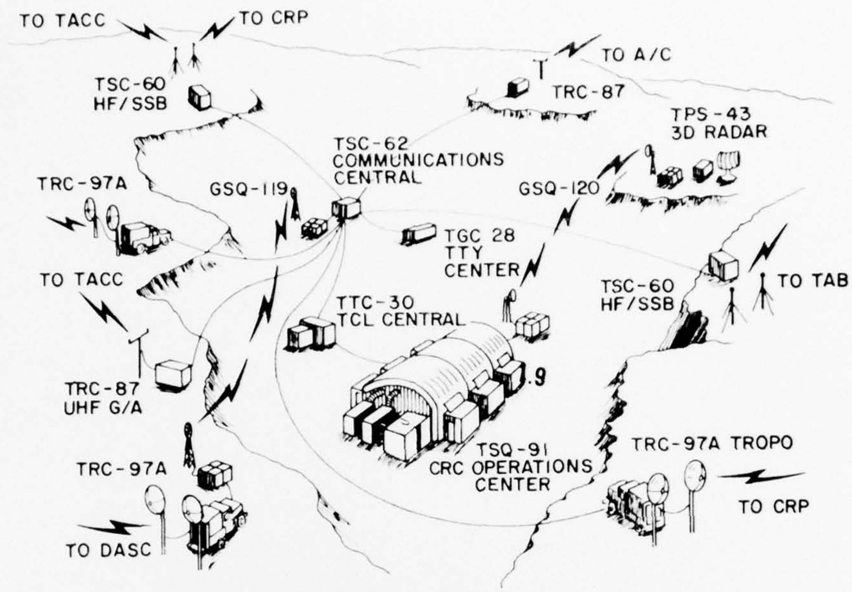


Figure 14. CRC Typical Deployment

Figure 15. AN/TSC-62 Communications Central with Communications Cable

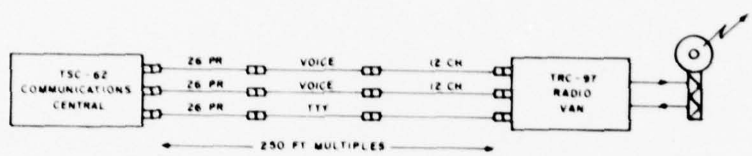


Figure 16. Existing TSC-62/TRC-97 Interconnection

There are several other incentives for using fiber optics in this application. The weight reduction is quite significant. As depicted in figure 4, a typical two-fiber cable weighs 8 pounds per 1000 feet compared to 208 pounds for the 26-pair cable. The joint weight and volume reduction would relieve transport requirements and ease deployment for rapid setup. Bold Eagle 78, a typical field exercise, required some 250,000 feet of 26-pair cable. This puts a considerable strain on airlift operations – thirteen C-130 aircraft loads are needed to transport 250,000 feet of cable. For ground transportation, this quantity of cable requires twelve 2 1/2 ton trucks, each accommodating a load of approximately 20,000 feet of cable.

Low loss fiber optic cable permits deployment of long repeaterless links, so that the radio terminal can be remoted to considerably greater distances than the few thousand feet possible with 26-pair cable. Extended remoting permits flexibility of deployment (for example, hilltop siting of the radio), and by widely separating the emitting radio antennas from the central CRC complex, reduces personnel exposure to anti-radiation missiles (ARMs). Furthermore, since optical fibers are electrically insulating, communications problems resulting from ground loops, lightning, and electromagnetic pulse (EMP) currents are all eliminated.

Radar Remoting

Another application identified, but not implemented in FY77, is the remoting of the AN/TPS-43E radar. This radar is conventionally interconnected to the AN/TSQ-91 operations center by two ten-conductor triaxial cables (figure 17). One of the cables carries range and IFF beacon returns from the radar to the center; the other carries eight height bits and a strobe, in parallel, over nine of the ten conductors. There are also separate multiconductor cables for mode control and communications, and a heavy grounding wire.

Two problems are encountered with this form of radar cabling. First, the separation between the radar and the operations center is limited to 400 feet by signal attenuation in the triax. This poses a severe constraint on deployment flexibility, and the close proximity makes the operations center vulnerable to damage from ARMs homing in on radar emissions. The second problem is the heavy weight of this cabling, approximately 1200 pounds, and its impact on transport requirements, and ease and rapidity of deployment. Furthermore the triaxial cable is rather fragile with respect to crush resistance and kinking.

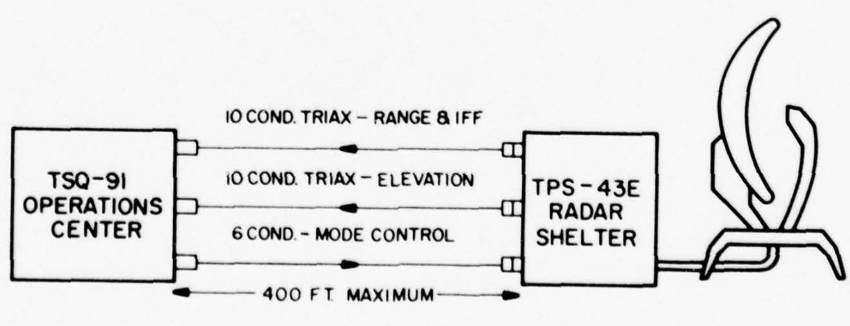


Figure 17. Existing 3-D Radar AN/TPS-43E

The need to increase the radar/operations center separation led to development of the AN/GSQ-120 microwave radar data transfer system (figure 18), which permits radar remoting up to 10 miles. But while the GSQ-120 does increase the deployment flexibility of the radar, it imposes severe weight, cost, and manpower penalties. The GSQ-120 system weighs five tons (each end consisting of shelter, electronics, mast, and dish weighing two and a half tons), and costs on the order of $1M. The users are concerned about the additional trucks and personnel required to install, operate and maintain this equipment.

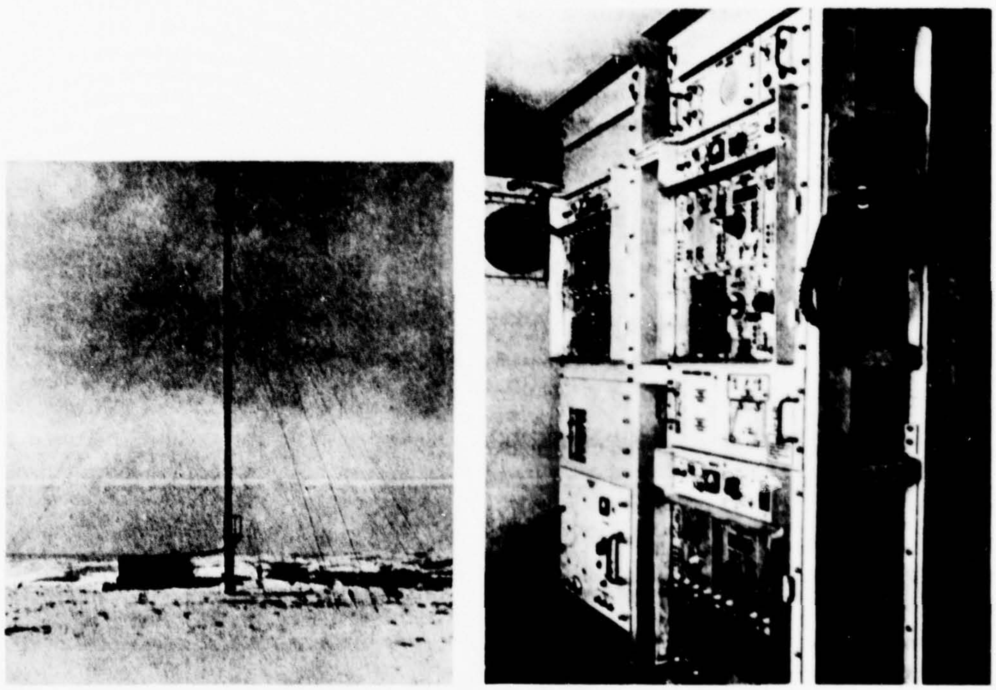


Figure 18. AN/GSQ-120 Microwave System

A fiber optic alternative to the microwave system could significantly reduce the weight and cost of the link. State-of-the-art fiber optics technology allows repeaterless links of up to 5 miles. An estimated cost comparison between the microwave system and a five-mile (8-km) fiber optic remoting link is given in Table I. Present-day cost of fiber cable ($10 per meter) have been used. Fiber cable cost for the link is $80K. Light sources, photodetectors, fiber optic connectors and electronics are estimated at $40K. This results in a total of $120K for the fiber optics link, less than one-eighth of the cost of the microwave system. In addition, weight is reduced by almost a factor of 12.

Table I. Technology Comparison for Radar Remoting

Microwave Radar Link (GSQ-120): 10,000 lbs			**$800K**
Fiber Optic Link Estimated Costs:			
cable, 8km (5 miles) at $10/M		=	$ 80K
REC, XMIT, MUX, connectors			40K
	Total		$120K
Fiber Optic Link Weight			
cable, 8km at 80 lbs km		=	640 lbs
electronics			200 lbs
	Total		840 lbs

There are, of course, situations in which the microwave system is definitely needed, such as transmission over large bodies of water or across uncontrolled territory. A fiber optics remoting link is therefore not a replacement for, but rather an attractive adjunct or supplement to the GSQ-120 system. In particular, where only modest separations of one or two kilometers are necessary, even greater cost and weight reductions are achieved, since both the cost and the weight of the fiber optic system are proportional to link length. With the microwave system, however, the full cost is paid and the full weight must be carried, regardless of the separation.

SECTION V

DEMONSTRATION MODEL DESCRIPTION

SYSTEM ARCHITECTURE

To illustrate the advantages and feasibility of fiber optic technology applied to ground-based C^3 systems, a demonstration model was developed. As originally conceived, the demonstration system was designed to interconnect the TRC-97 radio and the TSC-62 technical control van.

As a matter of expediency, vintage 12-channel tactical multiplexers (AN/TD-352/G) were borrowed from the Army and used at the ends of the link. The multiplexers digitized the 12 analog channel inputs using pulse code modulation (PCM) and time division multiplexing (TDM). The electronic digital and timing outputs of the multiplexer are converted to optical pulses for transmission on the fiber optic cable. At the receiver the optical pulses are converted back to electrical current by photodiodes. The digital electronic signal is then demultiplexed back into twelve analog signals and transferred to the TRC-97 van for radio transmission.

Figure 19 illustrates one end of the communications link. Each of the twelve channels is sampled at 8K samples/sec, and each sample is encoded into six bits. The PCM output of the multiplexer is therefore 12 x 8K samples/sec x 6 bits/sample = 576K bit/sec. The PCM output data is in non-return-to-zero (NRZ) format, and the same format is used to intensity-modulate the continuous-wave injection laser diode (ILD) sources.

The multiplexer also transmits 150 nsec-wide timing marks at each bit interval. These timing marks are also converted to optical pulses through an ILD.

Two fibers were used for an orderwire circuit. The voice signal on this orderwire was transmitted by analog modulation of an LED. AN/TA-341 telephones were used as end instruments for the orderwire.

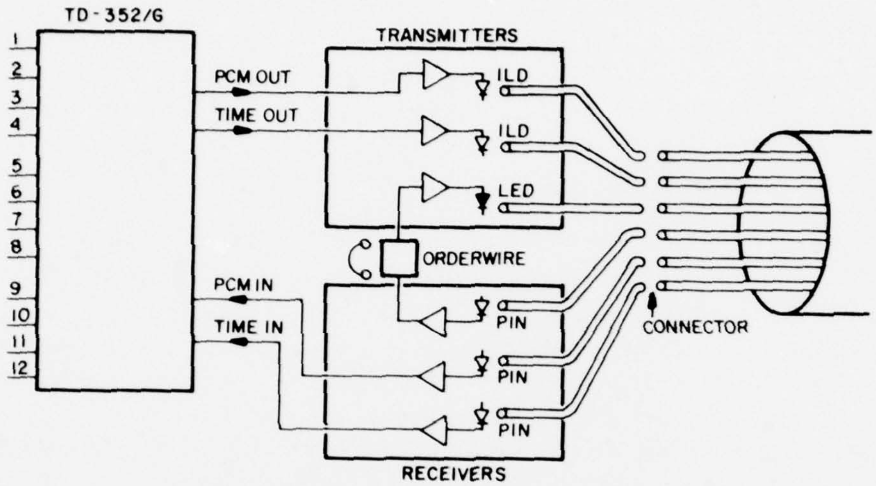


Figure 19. Optical Converters

OPTICAL SOURCES

The ILD source used for the PCM data and timing channels was a laser diode model LCW-5 (table II) manufactured by Laser Diode Laboratories of Metuchen, N.J. It has minimum total radiant power of 5mW with 3-dB intensity angles at 2^{o} and 27^{o} in the plane parallel and perpendicular, respectively, to the PN junction. The percentage of total power as a function of half-angle of collection for this diode is shown in figure 20. The step-index optical fiber used for this system has a numerical aperture of 0.25, providing an acceptance cone half-angle of 14.5^{o}. From figure 20 one finds that an acceptance cone of 14.5^{o} will collect about 30% of the total optical power from the source. This yields a numerical aperture loss of 10 log 0.3 = 5.2 dB.

A method of reducing this loss is to form a small lens on the input end of the "pigtail" fiber. The "pigtail" is a length of fiber optically aligned with the emitting area of the source. To make the lens, the fiber is first cleaved flat. A small flame is used to heat the end of the fiber and, as the glass begins to melt, the surface tension forms a nearly hemispherical lens. The lensed pigtail typically increases the power accepted by the fiber by a factor of 1.8 to 2 – that is, gives a 2.6 to 3 dB coupling improvement over the flat-ended fiber.

Table II. Characteristics of LCW-5 Injection Laser Diode

		Min.	Typ.	Max.
Total radiant power	(mW)	5	7	10
Forward current	(mA)	150	250	350
Threshold current	(mA)	100	200	300
Peak wavelength	(nm)	800	820	880
50% spectral width	(nm)		2.5	
Source size	(mils)		.01x.5	
Rise time	(ps)		100	
Operating temperature	(^{0}C)	0	27	65

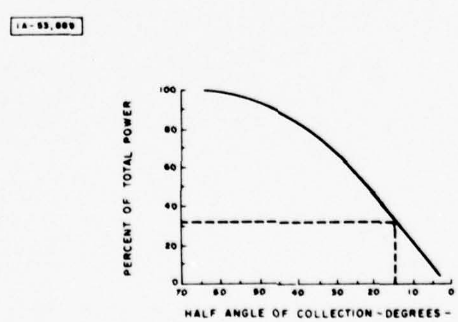


Figure 20. Angular Emission Characteristic of LCW-5 ILD

The source package assembly is illustrated in figure 21. The prepared fiber is cemented in a trough in the anvil. With the source under power, the anvil is micro-positioned to maximum light coupling and is then cemented to the heat sink under the pellet. Figure 22 is a photograph of the source assembly; figure 23 shows a closeup view of the coupling region, and the lens on the end of the fiber can be seen.

The digital and analog circuits used to drive the sources are described in another document.

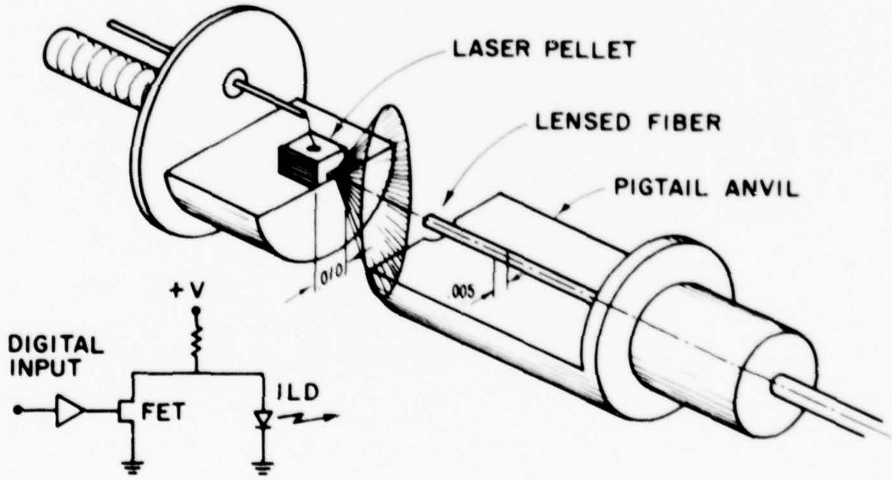


Figure 21. Injection Laser Diode Source

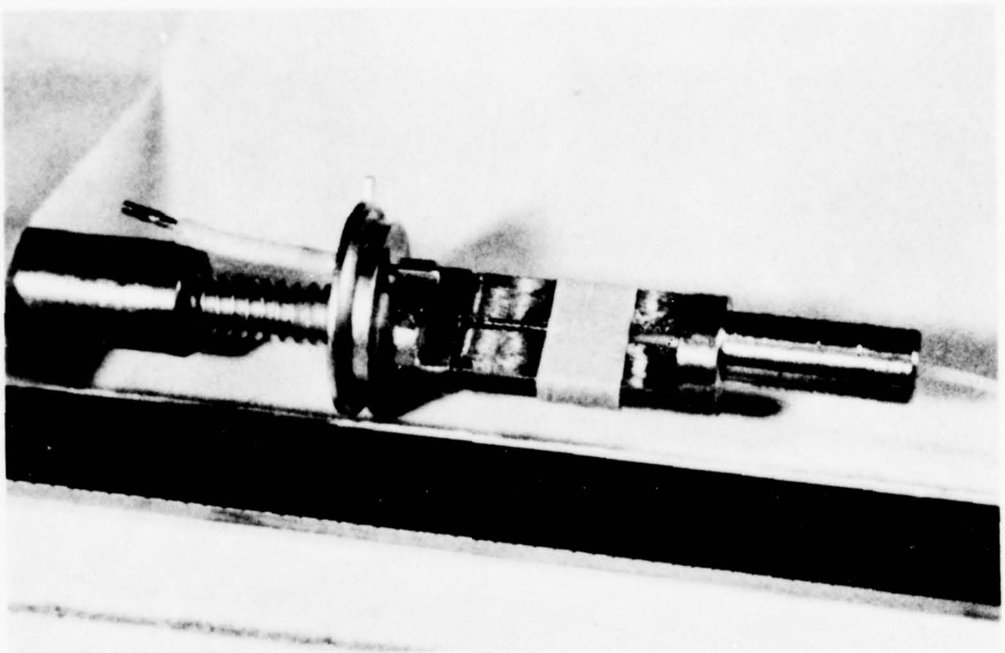


Figure 22. Source Package

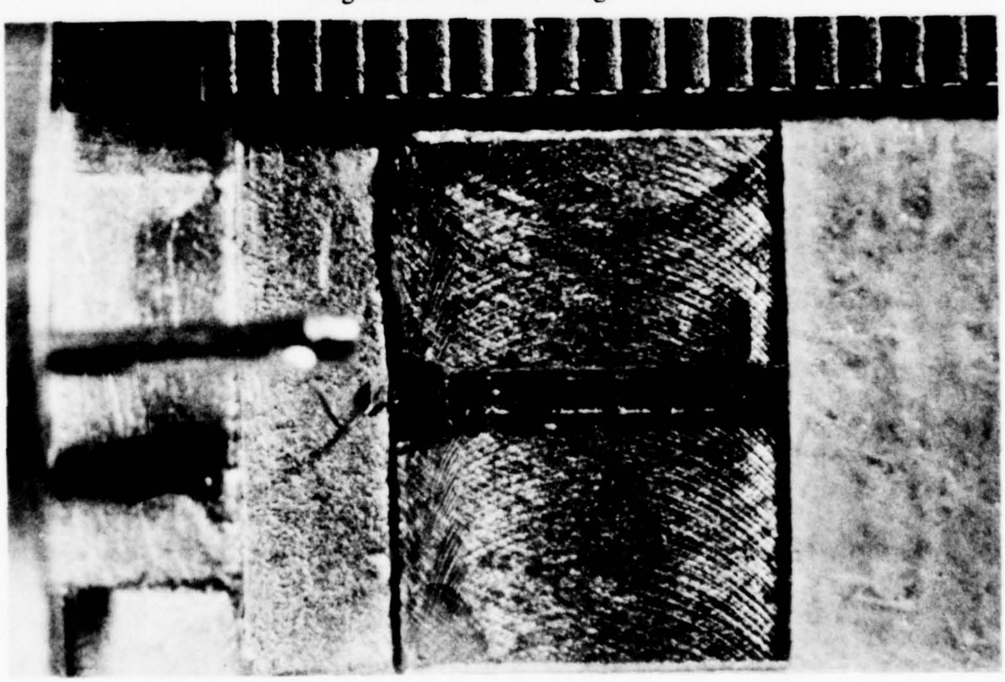


Figure 23. Source Package, Closeup

OPTICAL FIBER

The optical fiber used in this system was type T-101, manufactured by ITT. This is a multimode step-index fiber consisting of a doped silica core and a borosilicate cladding. A plastic jacket is extruded onto the fiber to provide mechanical and environmental protection. A cross-sectional view of the fiber, its refractive index and attenuation profiles are shown in figure 24, taken from ITT product literature. ITT specifications for this fiber are given in table III.

OPTICAL FIBER CABLE

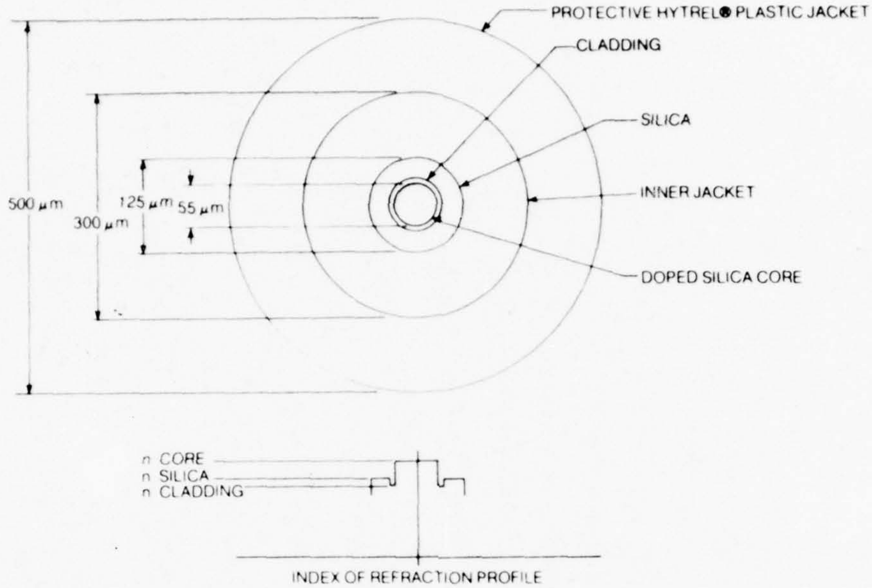
Siecor (a Siemens-Corning affiliation) and ITT fiber optic cables were evaluated for ruggedness in a roadway test at the MITRE Bedford facility. As shown in figure 25, the four specimens (two- and six-fiber versions from both manufacturers) were laid across an asphalt driveway with a traffic counter. Simple continuity checks were made periodically. The cables were exposed to an average of 5000 cars and trucks per week during the six-week (summer) test period.

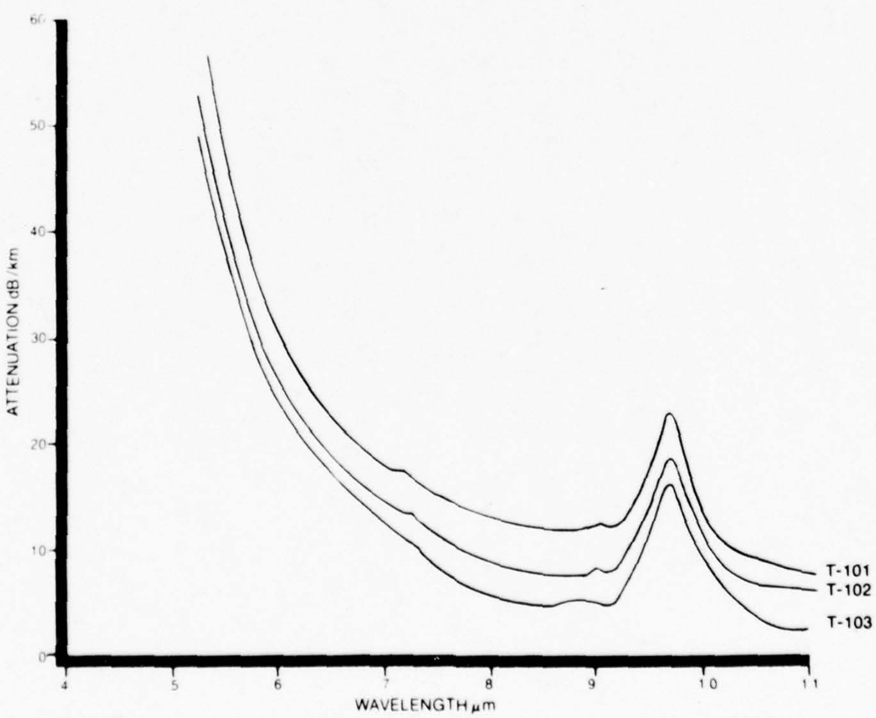
The Siecor and ITT cable constructions differed significantly (figure 26). The ITT external strength member cable employs a tightly bound fiber containment in which the jacketed fibers are embedded within an extruded polyurethane jacket. This is surrounded by helically laid Kevlar® strength members and an outer extruded polyurethane jacket.

The Siecor cable uses a loosely bound fiber containment in which the fibers are laid within a tube of much larger diameter. The rationale for this construction was to decouple external stress on the cable from the fiber itself. The containment tubes are then surrounded by two layers of Kevlar® separated by a polyurethane sheath. The entire structure is contained within a polyvinylchloride outer jacket.

At the end of the roadway test (approximately 30,000 vehicles) all fibers within both the two- and the six-fiber ITT cables remained continuous. All fibers, except two, within the Siecor cables had failed; the first Siecor fiber (one within the two-fiber cable) failed after 500 traffic counts. The second failure (same cable) occurred at approximately 1500 counts. Because of its superior performance with respect to crush resistance and durability, the ITT cable was chosen for the MITRE demonstration system.

STEP INDEX MULTIMODE FIBER
DIMENSIONS SHOWN ARE NOMINAL VALUES





TYPICAL SPECTRAL ATTENUATION- STEP INDEX FIBER

Figure 24. Fiber Characteristics

Table III. Nominal Specifications for ITT T-101 Fiber

Attenuation	@ 0.85 microns	12dB/km
	@ 1.06 microns	8dB/km
Numerical aperture		0.25
Dispersion	10dB width	30nsec/km
	3dB width	15nsec/km
Core index		1.48
Core diameter		55μm
Cladding diameter		125μm
Jacket O.D.		600μm
Tensile strength (1/2 meter gauge)		500Kpsi
Min. bend radius		0.5 cm

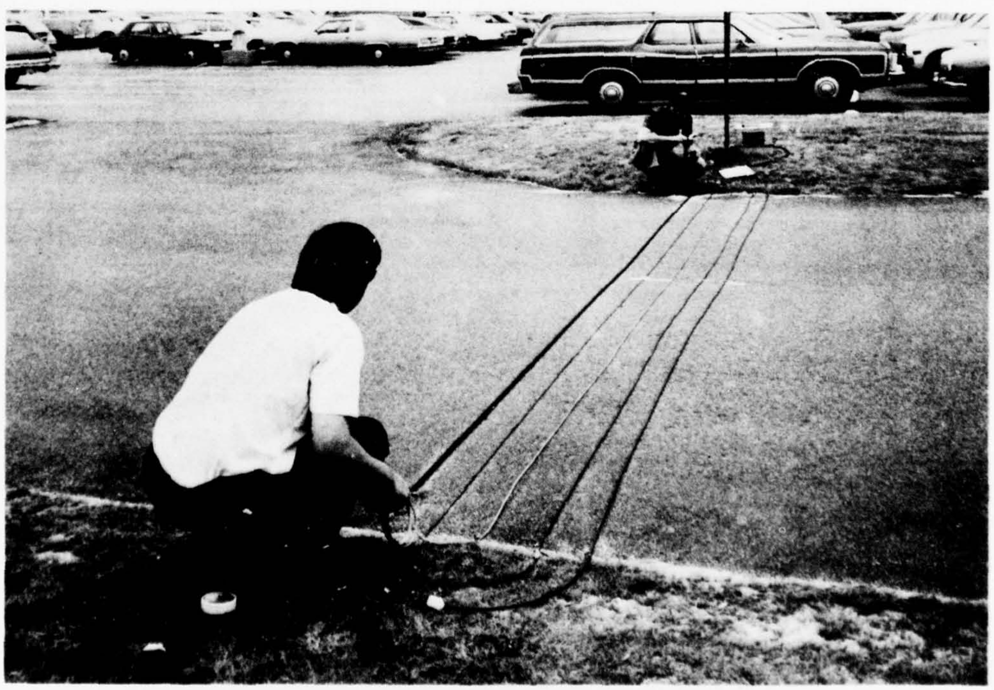


Figure 25. Roadway Test

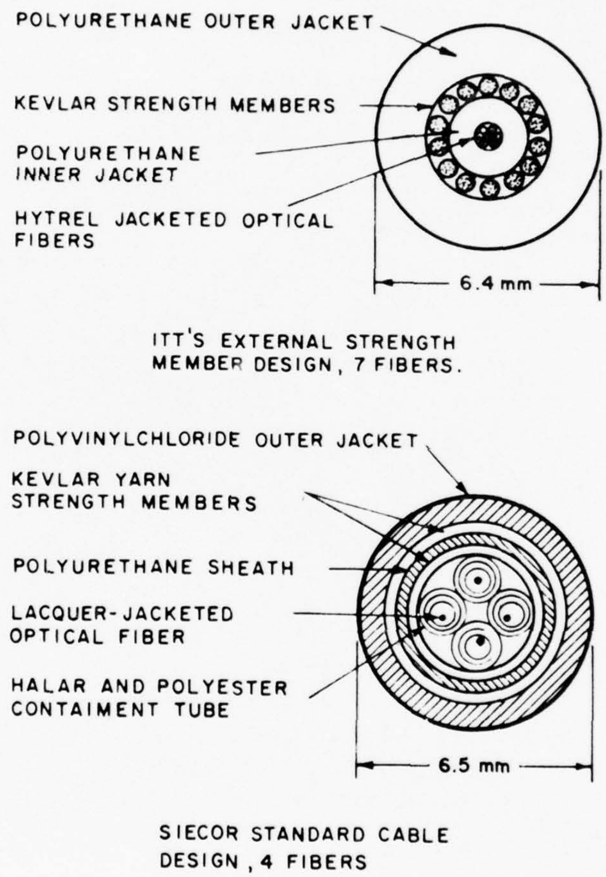


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Figure 26. Fiber Optic Cable Constructions

CONNECTORS

At the outset of the program there was only one commercially available single-fiber connector for 125-micron-diameter fibers. Its high cost ($200 per fiber) and high insertion loss forced MITRE to invent its own connector.

Alignment is achieved in the MITRE connector by an extension of the familiar three-rod alignment principle discussed in section III. Three small rods are sized so that the fiber fits snugly into the interstice formed when the rods are in tangential contact. To accomplish this, the diameter of the rods must be approximately 6.5 times the diameter of the fiber.

After stripping, cleaning and cleaving, the fiber is inserted completely through the interstitial gap. The cleaved end of the fiber is placed nearly flush with the end faces of the rods; to prevent end abrasion, it is recessed about 25 microns. The fiber and rods are secured by applying low-viscosity cement to the assembly. A protective ferrule fits over the end of the assembly to prevent fiber breakage. This unit, illustrated in figure 27, will be referred to as an "insert".

For a single-channel connector, two inserts must be aligned. The alignment is accomplished by enclosing the inserts in another three-rod arrangement (figure 28). The three larger connector alignment rods are sized so that the inserts fit exactly within the interstice. To do so, the connector alignment rods must be made approximately 9.9 times the diameter of the insert rods.

The three larger connector alignment rods, held together with an 0-ring, are used to guide the inserts to a homing position which keeps the fibers aligned. The inserts may be gripped tightly by choosing the connector alignment rods slightly undersized. Since the forces at the points of contact are radial, they tend to self-center the fiber.

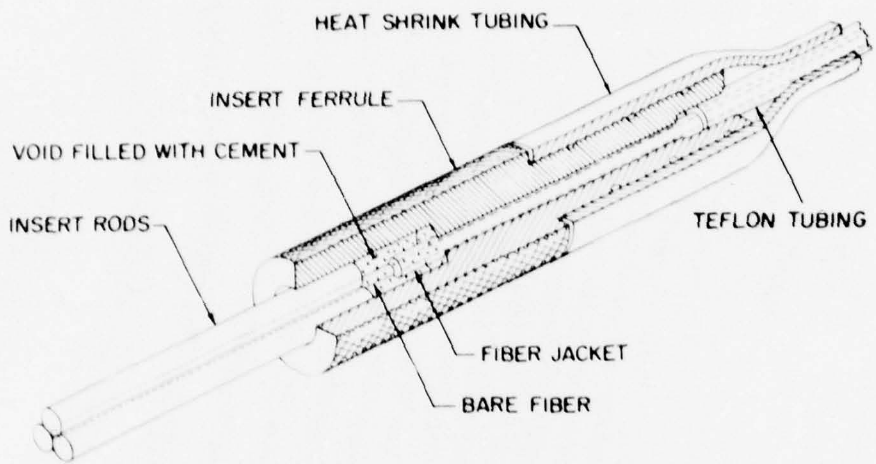

Figure 27. MITRE/ESD 3-Rod Insert Assembly

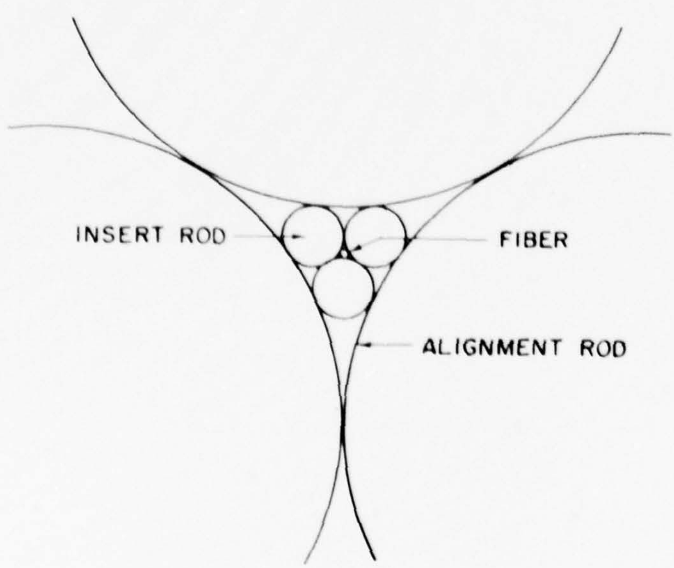

Figure 28. Dual Three-Rod Geometry

Since the small fiber alignment rods are 6.5 times larger in diameter than the fiber, and the large connector alignment rods are 9.9 times the diameter of the fiber alignment rods, the dimensional sensitivity of the large rods is almost 64 times less sensitive than the tolerances required in fiber alignment, creating a desensitization factor. This dimensional range is easily achievable using inexpensive drill blanks.

This arrangement can be extended to accommodate multiple-fiber cables by using more connector alignment rods. A multifiber connector for a standard six-fiber cable is made with a closely-packed hexagonal arrangement of seven rods forming six interstices – refer to figure 29. Tightening the ring nut uniformly squeezes the O-ring in the shell flanges, centering the inserts within the larger alignment rods. A photograph of a cutaway version of the connector is shown in figure 30.

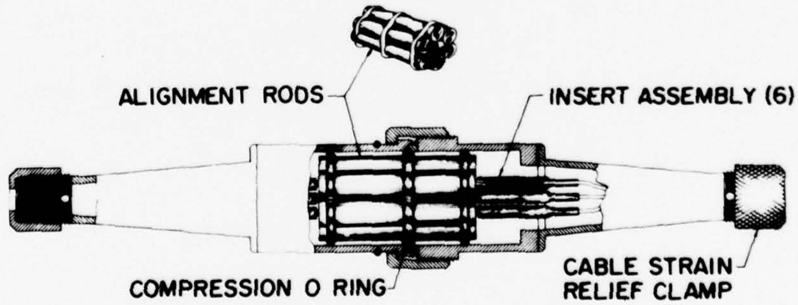

Figure 29. MITRE/ESD Dual 3-Rod 6 Fiber Connector

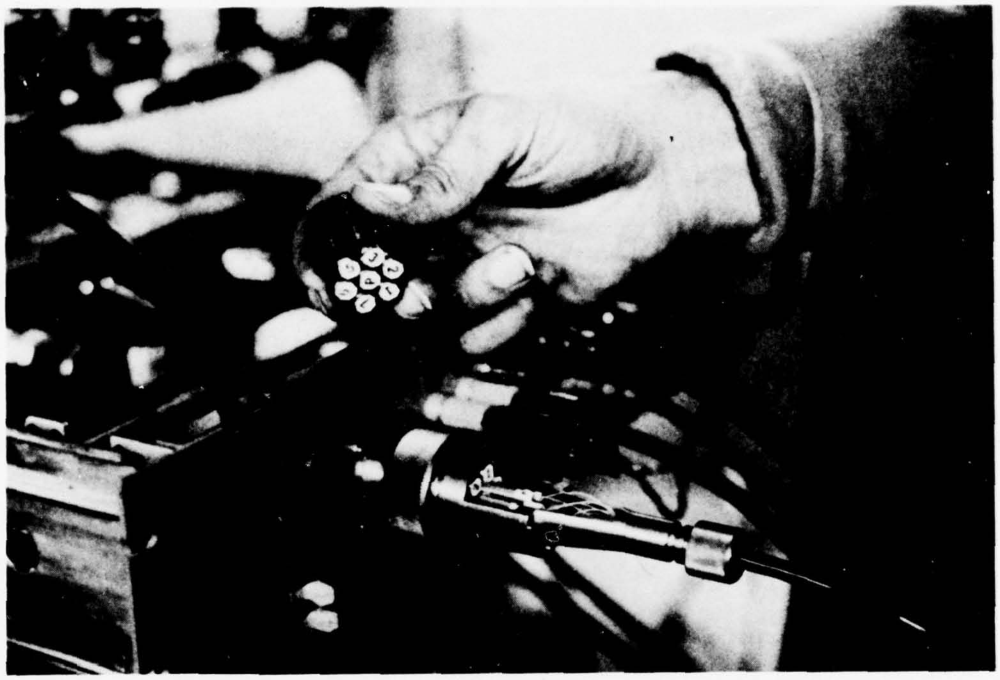

Figure 30. ESD/MITRE Chassis Mount Connector

Measurements were made on the insertion loss of a single-channel version of this connector. A continuous-wave gallium arsenide injection laser diode source was used. The step-index fiber used in the measurements was nominally 125 microns in diameter and had a numerical aperture of 0.25. Inserts were made with 66-gauge (0.838 mm) drill blanks, and connector alignment rods were P gauge (8.204 mm). The free end of the source pigtail was terminated in an insert. Six inserts were prepared on each end of a six-fiber cable approximately 300 meters long. Power measurements were made with a radiometer at the output of the pigtail and then after connecting the 300-meter fiber. The known loss of the fiber was then subtracted to determine the connector insertion loss.

Measurements were made for each of the twelve inserts on the cable connected to the pigtailed source. Each of the three possible insert orientations were measured, yielding 36 loss measurements in all. Individual losses ranged from 0.8 to 2.4 dB, with an average loss of 1.5 dB and a standard deviation of 0.4 dB.

PHOTODIODES

Silicon PIN photodiodes were used for the optical detectors. The photodiode selected for use in the demonstration system was EG&G model SGD-100A (table IV). In the receiver circuitry these diodes were operated into a Texas Instruments TIXL152 transimpedance amplifier. Details of the digital and analog receiver circuits are given in another document.

Table IV. Typical Specifications for SGD-100A PIN Photodiode

Rise time	4 nsec
Dark current (100v @ 25°C)	10 nA
Capacitance (@100v)	4 pf
NEP	10^{-13} watts/$\sqrt{Hz}$
Active area	5.1 mm^2

The photodiode pellet is housed in a TO-5 package. The pigtail assembly for the photodiode is illustrated in figure 31. A drilled metal cap fitting over the photodiode package serves to hold the fiber in alignment with the photosensitive surface of the diode.

Figure 32 is a photograph of the electro-optic transmitter/receiver unit used for the demonstration system. The front panel contains the six-fiber connector and the electrical input/output connectors for the orderwire (binding posts) and multiplexer data and timing marks (BNC connectors). The front of the chassis drawer contains power supplies. The back of the drawer contains six circuit cards for data, timing and orderwire transmit (left three cards) and receive (right three cards), respectively. Connected to the chassis is a 1000-foot spool of ITT heavy-duty six-fiber cable.

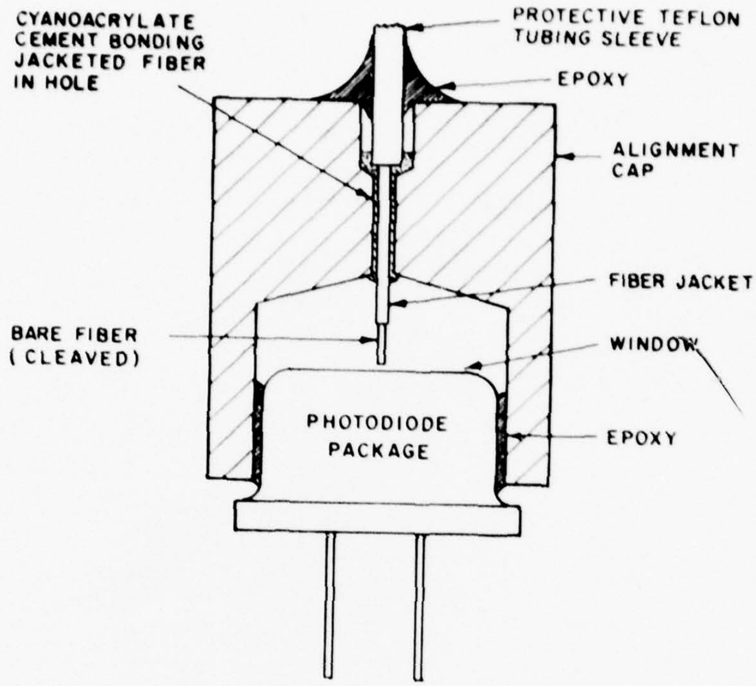

Figure 31. Photodiode Pigtail Assembly

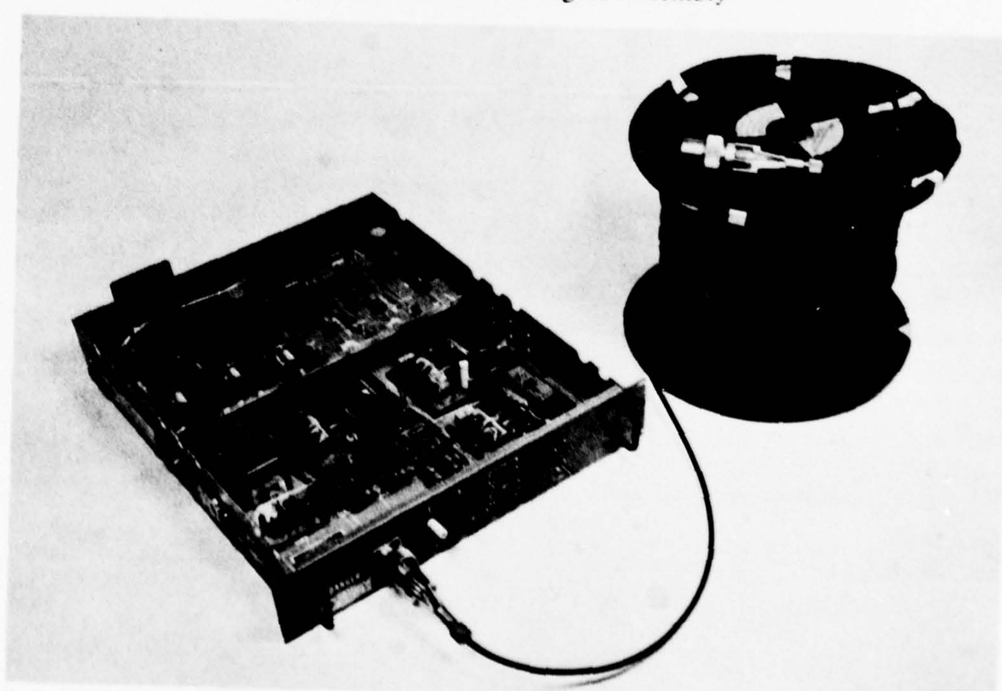

Figure 32. 26-Pair Cable Replacement Hardware

SYSTEM CAPABILITY

The optical receiver sensitivity was examined. It was found that the received data pattern, as viewed on an oscilloscope, was stable at an average received optical power of 2μW, but began to exhibit jitter at lower levels. The required received optical power is therefore taken to be 2μW (-27 dBm).

LCW-5 injection laser diodes emit a typical peak total radiant power of 6.5 mW (8 dBm), so that the average power emitted by the source when modulated by a random NRZ data pattern is 5 dBm.

The loss margin for the link is the difference between the average source power and the required power at the receiver. This turns out to be 5-(-27)=32 dB; this loss must be budgeted among all the system losses, including input and output coupling, fiber cable attenuation and connector losses.

System losses were measured on the demonstration model as follows:

Input coupling loss = 3.3 dB

Output coupling loss = 0.2 dB

Connector losses = 2 x 1.5 = 3 dB

Total = 6.5 dB.

The worst-case fiber attenuation in the cable was 6 dB/km. Thus the power-limited length (L) is determined from 32=6.5+6L, which gives a length of L=4.3 km (=2.7 miles).

This estimate of the power-limited length of the link is based on a PIN diode receiver which, for simplicity and economics, was used in the demonstration model. However, it is known that the more sensitive avalanche photodiode (APD) could add approximately 15 dB to the loss margin. If the APD were used, the power-limited length could be increased to 6.8 km = 4.2 miles.

At the modest transmission rate of 576 kb/s, dispersion length limits far exceed power limits.

SECTION VI

FIELD TEST AND DEMONSTRATION

After the link was completed and laboratory-tested, it was taken to a Rhode Island Air National Guard (ANG) installation for preliminary field tests. No difficulties were encountered. In October, 1977 the system was successfully deployed at the Bold Eagle tri-service exercise at Eglin AFB, Florida.

PRELIMINARY TESTING

During September 1977 the 102nd Tactical Control Squadron at the North Smithfield Rhode Island Air National Guard Station cooperated in conducting preliminary field tests. The van-mounted fiber optic terminals, cable, and multiplexers evaluated during these tests are seen in figure 33.

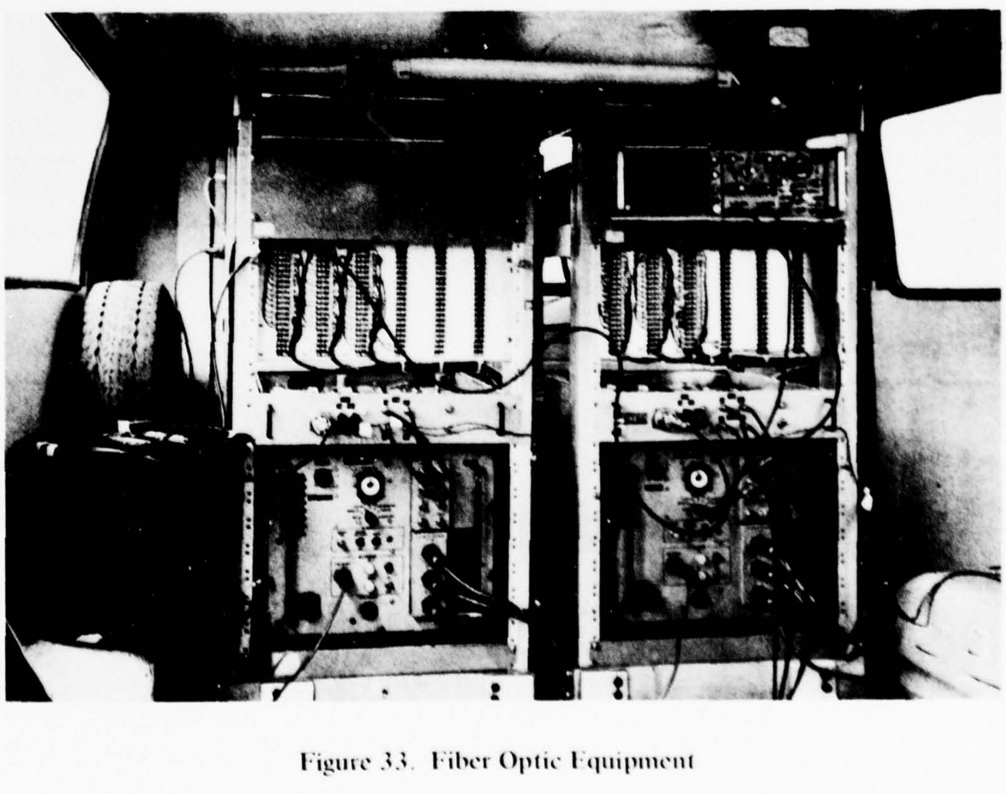

Figure 33. Fiber Optic Equipment

To facilitate field deployment, the multiplexers at each end of the fiber optic link were terminated with short lengths of 26-pair cable and standard connector hocks. The connectors were attached to the entry panel of a TSC-62 technical control facility and terminated inside on the patch panel. Except for the directional nature of the fiber optic link, the demonstration system was treated during the tests as if it were a 26-pair cable.

The tests were designed to determine the ability of the fiber optic link to handle voice and several other types of quasi-analog signals normally generated, transmitted and processed by an operational CRC. The signals under investigation during this test series included dual-tone multiple-frequency (DTMF) and AC supervisory signals used in the telephone switching system, low-baud-rate frequency-shift-keyed (FSK) signals used for teletype communications, and high-baud-rate FSK signals used in digital communications links. The test loop is diagrammed in figure 34.

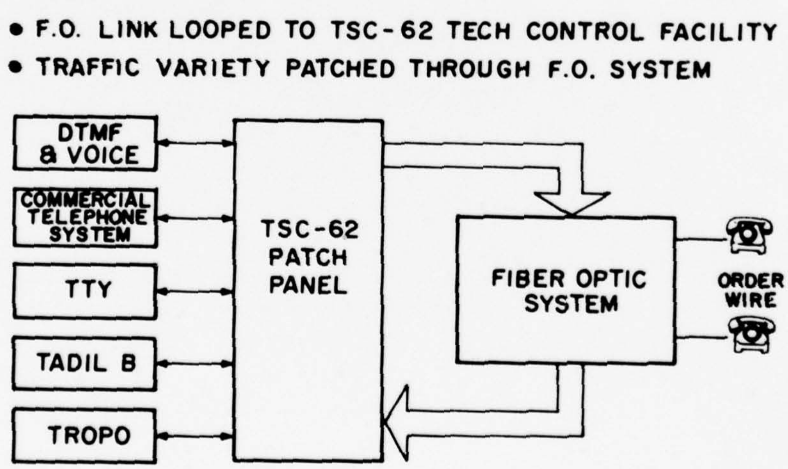

Figure 34. Test Set-Up At Rhode Island Air National Guard

Dual Tone and Voice Signals

These tests were to determine if the AN/TTC-30 switching system could interpret dual-tone signaling and supervising inputs transmitted from a TA-341 telephone over the fiber optic data link. AC supervisory signaling was used.

Of particular concern was the signal distortion developed by the analog/digital and digital/analog converters used in the 6-bit pulse code modulation (PCM) multiplexing system (TD-352) associated with the fiber optic link. It was felt that such distortion might be manifested in supervisory signal rejection in the TTC-30 supervisory control cards, or in misinterpretations of digits by the DTMF decoders.

This test was successful and no misinterpretations were observed. For each channel of the system "off-hook" signals were received and correctly interpreted by the switch. Each DTMF digit was dialed and correctly interpreted. The voice signature of the speaker was clearly identified.

Teletype Signals

These tests were designed to determine the quality of teletype signals passed through the fiber optic link. Teletype characters are converted from DC current loop to FSK signals in the TSC-62 van. The FSK signals were patched into the fiber optic link. At the receiving end, the reconstructed FSK signal was converted into DC current loop form to drive a TTY printer.

The fixed test sequence "The quick brown fox jumps over a lazy dogs back 1234567890" was transmitted many times with no errors. The signal path was then daisy-chained back and forth ten times through the fiber optic link and associated multiplexers. No errors were recorded in the diagnostic test messages.

TADIL B Modem Signals

The purpose of this test was to measure the performance of the fiber optic link in transmitting high-data-rate FSK signals. The HM-4118 computer in the TSQ-91 operations center was used as the test data source and detector. Upon operator initiation, the computer generated a continuous data stream based on a stored test message. The data then passed through the automatic data link buffer to the TADIL-B modem. The FSK signals developed by the TADIL-B modem were patched through the TSC-62 into the fiber optic link. The output of the link was patched back to the TADIL-B modem and into the computer. The loop quality test, normally used to verify tropo radio channel performance, was employed to determine a figure of merit for the fiber optic link.

All tests were run at 1200 b/s, which is the highest rate available on the TADIL-B modem. The transmission level, at the output of the TADIL-B modem, was set at -16 dBm. Normal operating transmission levels are in the range of -12 dBm to -16 dBm. Two modems were used over two separate channels of the fiber optic link. Three thousand messages were exchanged and no errors were counted.

In reducing the transmission level, it was found that errors were recorded at a transmission level of -20 dBm. Seventy-two errors were counted in 5,439 transmitted messages. This gives a message error rate (MER) of 1.3×10^{-2}. The bit error rate (BER), however, may be considerably lower than the MER since the TADIL-B message is 48 bits in length, and a single bit error causes the entire message to be counted as erroneous. If one assumes a single bit error per counted erroneous message, then the BER could be as low as 72 bit errors in $5439 \times 48 = 2.6 \times 10^5$ transmitted bits, or 2.8×10^{-4}. The BER of this test is then in the range of 2.8×10^{-4} to 1.3×10^{-2}, at a transmission level of -20 dBm.

As a control test, a hardwire patch was substituted for the fiber optic link. At the same level of -20 dBm, eight errors were counted in 16,838 transmitted messages, giving an MER of 4.8×10^{-4}.

As a test on multiple passes through the multiplexer, 6 fiber optic channels were daisy-chained together. With the transmission level at -16 dBm, only 3 errors in 4,882 messages were recorded (MER = 8.3×10^{-4}).

A loop-around test through the TRC-97 tropo radio was conducted. With the signal level at -16 dBm, 2 errors were encountered in 2,400 messages (MER = 8.3×10^{-4}).

The results of the TADIL-B transmission tests show that at a normal operating modem transmit level of -16 dBm, the fiber optic link operates essentially error-free. Lower-than-normal transmit levels (-20 dBm), or multiple passes through the multiplexer, begin to give a measurable BER in the range of 10^{-4} to 10^{-2}. This is probably due to an insufficient input level to the multiplexer, and the accumulation of quantization noise from the repeated PCM process, respectively. This completed the preliminary field tests.

BOLD EAGLE 78 DEMONSTRATION

During the period 17 through 28 October 1977 the fiber optic communication system was demonstrated to Air Force users at exercise Bold Eagle 78, held on Eglin Reservation in Florida. The purpose of this exercise, involving some 20,000 troops, was to test U.S. force readiness against a tank force occupying a friendly country.

The Tactical Air Control Center (TACC), located on Hurlburt Field, was the locale of the demonstration. As shown in figure 35, the fiber optic link was used in place of a 26-pair cable for interconnection between two TSC-62 communication centrals operated by the 5th Combat Communications Group (CCG) and the 507th Tactical Air Control Wing (TACW).

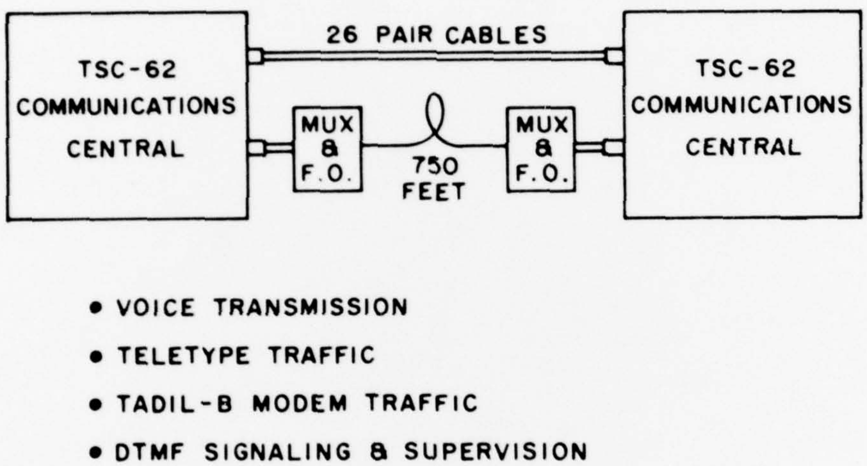

Figure 35. Bold Eagle Demonstration

A portion of the TACC communications complex at Hurlburt Field is seen in figure 36. The 5th CCG technical control van is located slightly forward of the tower. One terminal of the fiber optic link was located in the Jamesway hut, the semicircular cylindrical shelter in the approximate center of figure 36, associated with the TSC-62. The fiber optic cable ran to the right from this hut along the roadway to the 507th CCG shelter (not shown). The cable run was approximately 750 feet in length.

It is interesting to note that the 200-foot Army tower seen in figure 36 was used to site ten TRC-97 tropo horns and is vulnerable to high wind velocities. In the course of the exercise, this tower had to be retracted for several hours during a tornado alert. Long-distance, lightweight fiber optic links could of course be used to ease deployment in a case such as this by remote-siting the radio vans on distant natural elevations.

Figure 36. Bold Eagle TACC Communications Complex

During the demonstration period, the fiber optic link carried a variety of operational communications traffic including trunks interconnecting tactical switches, point-to-point telephone lines, secure teletype and narrowband secure voice. Table V provides a communications traffic log for day-to-day operation of the 12 channels on the system. System operation was interrupted twice by malfunctions of the 15-year old multiplexer. There were no malfunctions of the fiber optic link.

Figure 37 illustrates the electromagnetic immunity advantage of fiber optic cable. The metallic 26-pair cable must be looped or bridged up over power cables to minimize the 400-Hz pickup into the communications system; and still hum pervades the system. In the Bold Eagle demonstration the fiber optic cable was laid directly on top of the power lines; there is no possibility of interference from the electromagnetic field to the dielectric optical fibers. Furthermore, there is essentially no crosstalk from one fiber to another within multifiber cables. Crosstalk poses another limitation in the use of 26-pair metallic cable for modern digital communications. The copper braid and wires required for the grounding network illustrate the serious consequences to metallic conductors of ground loops and lightning strikes. These problems, along with the nuclear EMP threat, are completely eliminated with fiber optic communication links.

Table V. Traffic Log, Bold Eagle 78 Fiber Optics Demonstration

18 Oct.	0900	Established link, checked performance
20 Oct.	0915	Operational traffic carried: 3 TTC-30 trunks 5 TA-341 phones, point-to-point 2 KW-7 secure teletype 1 test tone monitor 1 fiber optic station phone
20 Oct.	2135	TD-352 Multiplexer malfunction
21 Oct.	1600	Operational traffic carried: 10 TTC-30 trunks 1 test tone 1 fiber optic station phone
23 Oct.	0815	TD-352 Multiplexer malfunction
23 Oct.	1115	Operational traffic carried: 4 TTC-30 trunks 2 TA-341 phones, point-to-point 3 KW-7 secure teletype 1 KY-65 secure voice 1 test tone 1 fiber optic station phone
26 Oct.	1500	Operational traffic changed: 5 TTC-30 trunks 2 TA-341 phones, point-to-point 2 KW-7 secure teletype 1 KY-3 secure voice 1 test tone 1 fiber optic station phone
28 Oct.	1415	Terminated demonstration

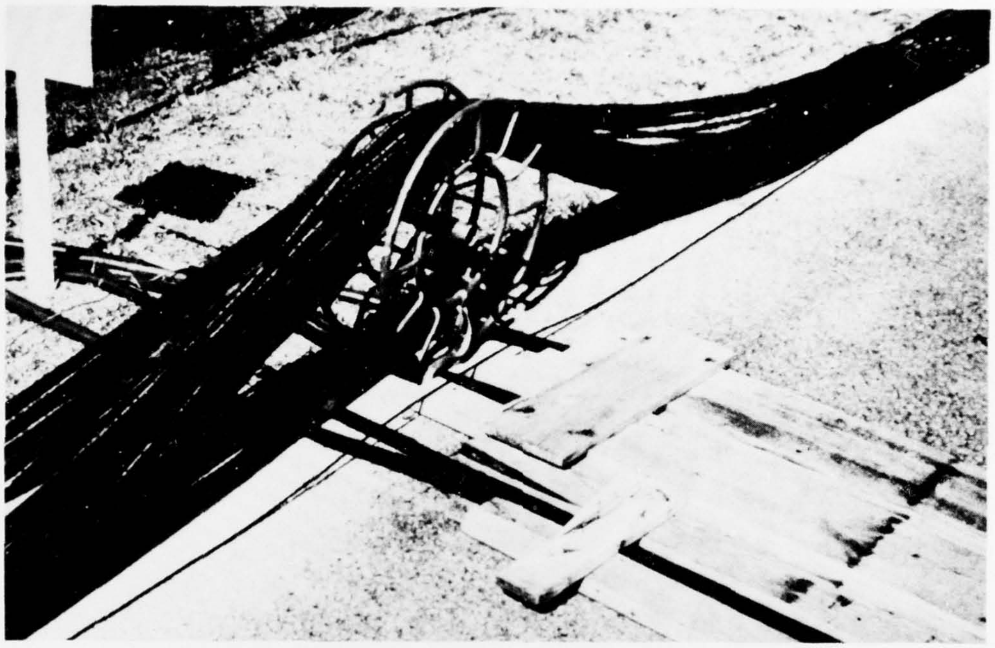

Figure 37. Electromagnetic Immunity of Fiber Optic Cable

The deployment techniques used with conventional cabling and fiber optics are compared in figure 38. Deployment of a thousand-foot spool of 26-pair metallic cable weighing about 300 pounds requires two men and an A-frame despooler. The same length of fiber optic cable weighs only eight pounds and is deployed with little effort. Even more dramatic, the fiber optic cable shown in figure 38 has information carrying capacity for almot 700 voice channels at distances of several kilometers. If fully exploited, this fiber cable could replace all the 26-pair cables as seen in the ground raceway.

The ruggedized fiber optic cable withstands the abuse of traffic roll-overs (figure 39) without fiber breakage. The 26-pair cables must be protected with wooden bridges to prevent vehicle stress from shorting the metallic conductors.

The system demonstration given at the Bold Eagle 78 exercise served to stimulate high-level Air Force user interest. During the demonstration, the fiber optic system was inspected by many senior officers responsible for ground communications. In figure 40, Major General Robert Sadler, Commander, Air Force Communication Service, is seen making the first telephone call to the Pentagon over a field deployed fiber optic link. This call was being transmitted via the fiber optic link to a tactical switch and there connected into AUTOVON. The demonstration was highly successful in establishing the feasibility of fiber optic technology for use in ground-based tactical communications.

Figure 38. Deployment Comparison

Figure 39. Fiber Optic Durability

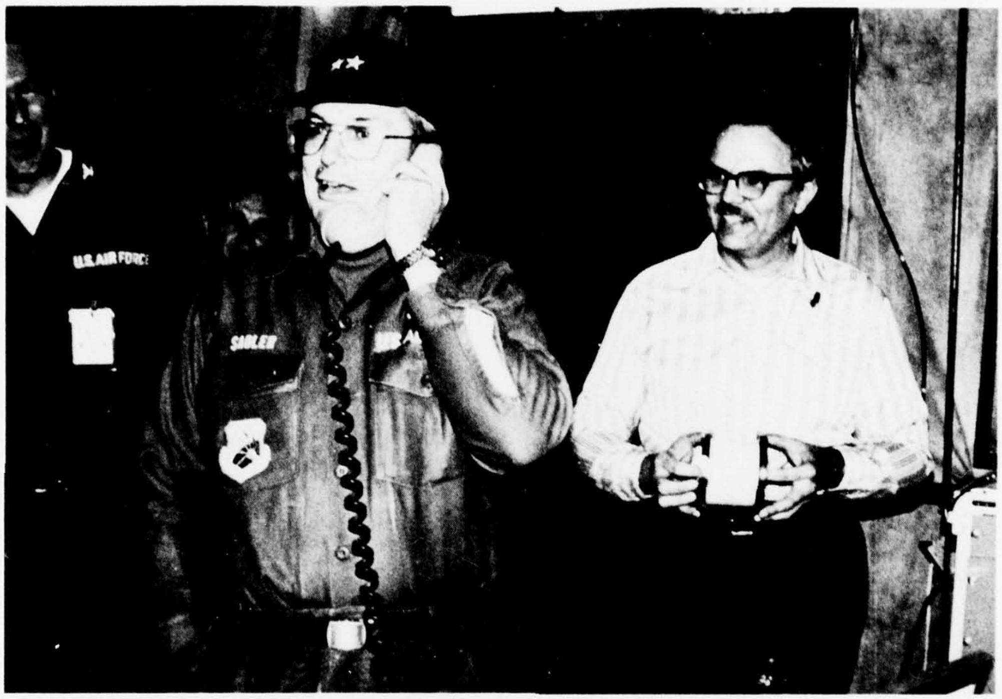

Figure 40. First Fiber Optic/AUTOVON Call to Pentagon

SECTION VII

CONCLUSIONS AND RECOMMENDATIONS

TECHNOLOGY CONCLUSIONS

Before operational fiber optic systems can be implemented, a number of refinements to the components are required; however, no new breakthroughs in the technology are needed. Now is the opportune time to establish standards and specifications; otherwise, system components will soon begin to proliferate and intensify the logistic support problem. It is our opinion that specifications can be organized to allow for future improvements in the technolcgy, that is, can be upward-compatible. This could assure near-term implementation while minimizing obsolescence.

Fortunately, fiber optic cable is the most advanced component at this time. Although it is at least as rugged as its metallic counterpart, and probably more so, further evaluation with regard to low temperature, moisture and nuclear radiation effects is required. Expendable cables could be developed for rapidly moving or "leapfrogging" command centers. Test equipment such as optical time domain reflectometers need to be fully developed to locate breaks or poor connector joints. Tools for repair splices will be required. Cable structures must be defined for a variety of applications (1, 2, 3, and 7 conductors) so that connector manufacturers can design their tooling to accommodate the fibers and terminate strength members.

Connectors to withstand the military environment must be developed. A 2 dB insertion loss specification is well within current practice; however, the connectors must be hermaphroditic in nature, easily cleaned and field replaceable. A family of shell sizes to accommodate the various numbers of fibers and also different glass fiber diameters (125, 150, 200, 300 and 400 microns) should be specified.

Source and detector devices must be ruggedized and packaged with short pigtails for easy replacement. As the technology advances, the operating wavelength should be extended to the 1.1 to 1.3 micron range to maximize power budgets and minimize pulse dispersion and nuclear dosage effects. Integrated circuit gain controls and chopper power supplies are needed to lower the cost (from a few thousand dollars to a few hundred dollars) of optical transmitter and receiver modules.

Additionally, lower-loss (and higher-performance) fibers could be specified in the same cable configurations. Furthermore, if dramatic connector improvements (cost and performance) are made in the near future, the old connectors could be cut off and new ones installed, thus adding lifetime to the expensive cables in inventory. Likewise, higher-performance sources and detectors could be used as replacements for earlier versions. Thus we should be able to take advantage of existing technology and yet implement improvements as they become available.

26 PAIR CABLE REPLACEMENT

Development Concept

The fiber optic system deployed at Bold Eagle 78 was successful in demonstrating the feasibility of utilizing fiber optics in tactical ground communications. For operational deployment, however, certain enhancements are necessary. To efficiently use the available bandwidth of the fibers, signals must be multiplexed before transmission. In the demonstration model this function was performed by the TD-352 multiplexer. These multiplexers, because of their age, were large and heavy, offsetting the size and weight advantages offered by fiber optics.

State-of-the-art integrated circuit technology can alleviate this difficulty through the development of a miniaturized multiplexer. In a retrofit application of fiber optics to 407L equipment, an ideal location for the miniature multiplexer would be within the standard 26-pair cable connector (figure 41). This would avoid any modifications to existing shelter constructions. It is envisioned that a 12-channel multiplexer, composed of hybrid or LSI circuitry, along with light source and photodetector chips, would fit in the 4.7" x 1.6" space within the connector shell (figure 42). Source and detector pigtails would attach to the fiber optic cable by a two-fiber connector on the end of the shell. In this manner the multiplexer would fit on existing shelter connector panel walls.

Monolithic circuits which convert voice signals to the digital continuously variable slope delta (CVSD) format already exist (examples are the Motorola XC3418 and Harris HR-3210). A 12-channel miniature multiplexer would require 12 such chips, along with timing/combining chips, and source and detector circuits.

Development Phases

The development options/phases of a fiber optic replacement for 26-pair cable are illustrated in figure 43 along with the associated hardware developments needed, requirements and limitations.

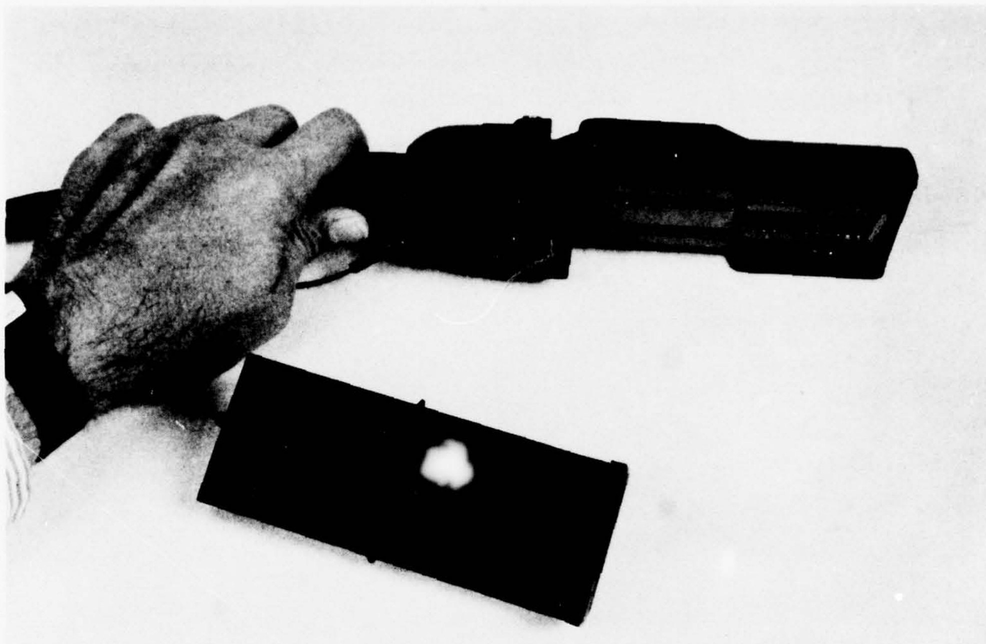

Figure 41. 26-Pair Cable Connector

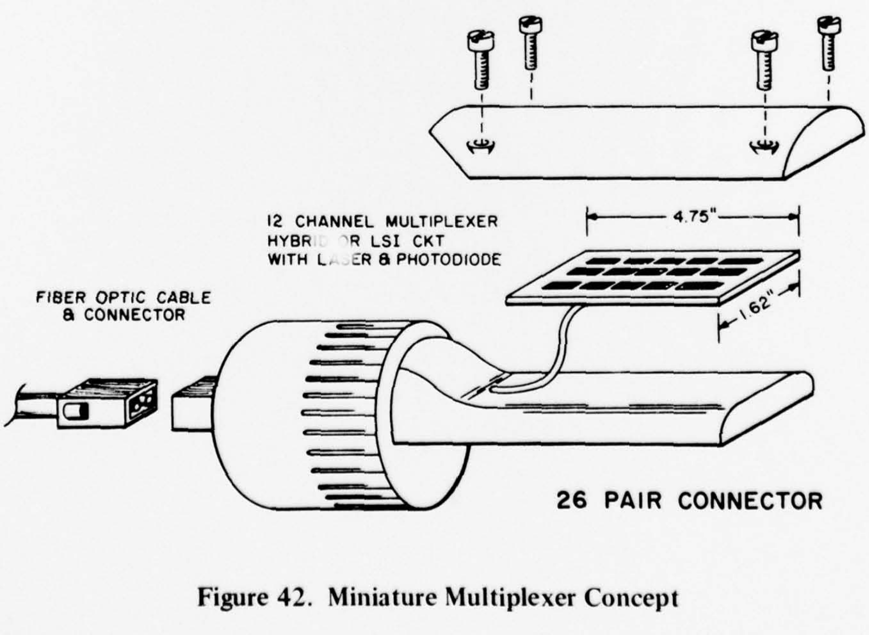

Figure 42. Miniature Multiplexer Concept

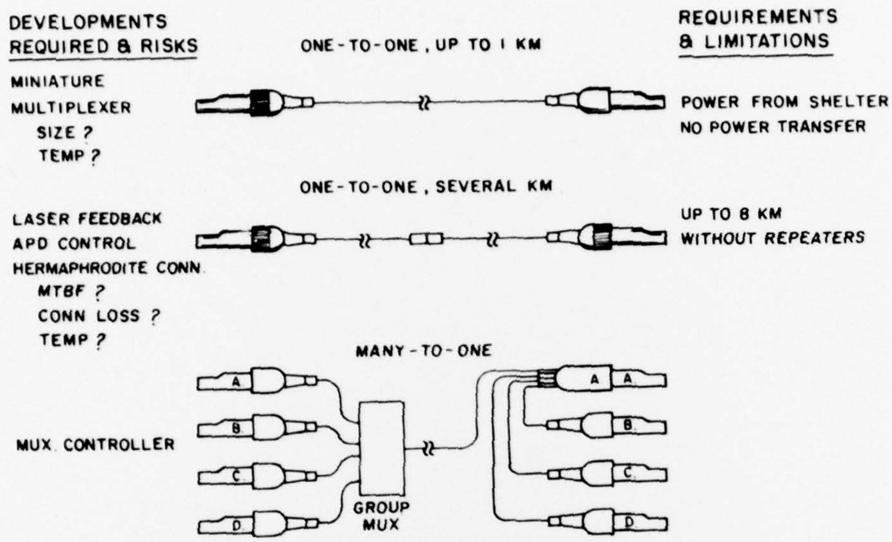

Figure 43. 26 Pair Cable Replacement Concept

The first option is a *one-to-one replacement*, in which a twin fiber cable is used to replace a 26-pair cable up to a kilometer in length. This configuration would accommodate interconnection of shelters in relative close proximity (technical control, switching, teletype centers, etc.). For these lengths the simple LED sources and PIN photodiode detectors could be used. The main development item in this phase is the miniaturized 12-channel multiplexer. The development risks are the size of the multiplexer, and its operation over military-specification temperature ranges. Power for the multiplexer/transmitter/receiver module, required from the shelter, could possibly be supplied through unused pins in the connector on the shelter wall (12 four-wire circuits require 48 pins, and the 26-pair connector has 52 pins). The system is limited by the fact that no electrical power can be transmitted over fiber optics.

The second option is also a *one-to-one replacement*, but would be capable of deployment ranges of several kilometers and could be applied to distant remoting of radio units such as the TRC-97 tropo. For such long-distance links the injection laser diode source and avalanche photodiode receiver are appropriate. These components require further refinements for bias control as a function of temperature. Development of a low-loss, low-cost hermaphroditic connector is also required. Links up to 8 km without repeaters should be possible.

The third development option most effectively exploits the bandwidth capacity of fiber optics. Here a many-to-one configuration is proposed. Higher-level multiplexing combines 12N channels for transmission on a two-fiber cable. For example, combining ten 12-channel units of 32 Kb/s CVSD would require a data rate of approximately 3.8 Mb/s. This type of link would be used for high-traffic-density routes, for example, between a technical control van and switching center. Development of the group multiplexer could directly follow from either the first or second option.

This cable replacement program must also address such questions as:

- Can multiplexers be made to fit within the standard cable connector and be qualified for military use?
- What are the risks associated with high ambient temperatures?
- What is the best method for powering the multiplexers?
- Since the fibers cannot transmit power, how will common battery instrument power be provided?

This effort should also develop design guidelines to ensure that fiber optic 407L retrofit systems would be compatible with TRI-TAC equipment.

CONCLUSION

The success of the fiber optic system demonstration at Bold Eagle 78 proves clearly that fiber optic technology is no longer a laboratory curiosity. Fiber optics are now in widespread use in industrial and commercial applications. The technology needs only refinement for use within the military environment. It is recommended that the cable replacement program discussed here be initiated immediately so as to insure rapid introduction of this technology to the field.

REFERENCES

1. C.W. Kleekamp and B.D. Metcalf, "Designers' Guide to Fiber Optics", Parts 1-4, EDN Magazine, 5 Jan, 20 Jan, 20 Feb, 5 Mar 1978.