LA-UR -80-667

CONF-800322--2

TITLE: FIBER-OPTIC TECHNOLOGY REVIEW

MASTER

AUTHOR(S): Peter B. Lyons, P-14

SUBMITTED TO: DNA (Invited Paper) Symposium on Fiber Optics in the Nuclear Environment 25-27 March 1980

University of California

LOS ALAMOS SCIENTIFIC LABORATORY

Post Office Box 1663 Los Alamos, New Mexico 87545

An Affirmative Action/Equal Opportunity Employer

Form No. 836 R3
St. No. 2629
12/78

UNITED STATES
DEPARTMENT OF ENERGY
CONTRACT W-7405-ENG. 36

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

FIBER-OPTIC TECHNOLOGY REVIEW

P. B. Lyons
Los Alamos Scientific Laboratory
Los Alamos, NM 87545

I. Introduction

Fiber-optic technology is not quite into its teenage years as the decade of the 80s begins, but the promise of fiber optics to revolutionize communication technology is already quite clear. As the decade of the 70s began, this conference would have been, to say the least, premature. In fact, in 1970 this conference might have been without attendees. Now fiber optics represents the only topic of several major conferences and is included as a subtopic in twenty or more major annual conferences.

This paper is intended as a broad, nontechnical, introduction to this DNA conference on Fiber Optics in the Nuclear Environment. It is, in fact, the only largely nontechnical talk scheduled for this conference. But any conference participant who now doubts the technical impact and promise of fiber optics should be adequately convinced by the conclusion of this conference.

II. The History of Fiber Technology

Many ancient cultures were well aware of the utility of glass objects and the principles of total internal reflection and light guiding may well have been known to these early artists. It is believed that in the first century B.C., the Palestinians made glass portraits with techniques resembling fused fiber bundles.[1]

Optical communications were in use long before fiber optics were developed. In 1790, the French developed an optical semaphore system capable of transmitting a message 200 km in 15 minutes.[2] And in 1880, Alexander Graham Bell demonstrated speech transmission via a light beam with his photophone.[3,4]

John Tyndall,[5] in 1854, demonstrated light guiding in a water stream for what is generally believed to have been the first published record of the phenomenon. Fiber technology actually began with J. L. Baird's patent in 1927 for coherent fiber bundles.[6] By the early 1960s, fibers were used for fiber optic tube faceplates, punch card readers, medical imaging, and decorative purposes. The glass fibers available before 1960 were characterized by very severe attenuations, exceeding 1000 dB/km.* With such attenuation, any communications applications were confined to shouting distances.

In the 1960s, much better understanding of fiber optic attenuation mechanisms was developed. In their paper in 1966, Kao and Hockham[7]

*At 1000 dB/km, only 1% of the light remains after a 20-m distance.

reported attenuation below 200 dB/km in bulk quartz and discussed the requirements (~ 20 dB/km) for fiber optic utilization in telecommunication. They predicted that a loss of 20 dB/km should be attained with further purification. In 1969, Jones and Kao[8] reported attenuation below 10 dB/km in bulk fused quartz.

In 1970, Corning Glass scientists broke the critical 20 dB/km attenuation barrier.[9] Figure 1 charts the history of fiber attenuation over several decades with the critical milestone shown by the starred value.[10] Later progress is shown in Fig. 1 and any new attenuation records tend to be short-lived. Recent work in Japan resulted in a value of 0.20 dB/km at a wavelength of 1.55 μm.[11] At this level of attenuation, a 50-km line length will still deliever 10% of the incident coupled light. Very high purity materials are required to realize these low-loss fiberas. Figure 2 summarizes the attenuation contributions of several contaminants and scattering mechanisms.[12]

Low fiber attenuation is necessary but not sufficient for an effective telecommunications system. High volumes of data transfer require that each data bit be transmitted in a very short time, μs or even ns. Fiber pulse dispersion (or time spreading) thus is of critical importance. The first fibers were constructed with the simple index profile shown in Fig. 3a, a step index profile. With the constant index of the core region, pulse spreading results simply from the difference in path lengths for limiting rays. Typical step fibers offer a bandwidth of about 20 MHz for a one-km line.

The graded index fiber of Fig. 3b utilizes a varying material index as a function of radius to compensate the transit times for varying ray paths (and lengths). A central ray, shown in Fig. 3b, propagates at a lower velocity over a shorter path length than a ray propagating in outer regions of the core region. Fibers with a graded-index profile were proposed in Miller's patent of 1969.[13] Important contributions toward understanding the index gradient which optimizes the pulse distortion have been made by several groups including Gloge and Marcatelli at Bell Labs,[14] and Keck[15] and Olshansky at Corning. These contributions have dealt with determination of the exponent α for an index profile varying with a power law dependence on radius. The value of α which minimizes the pulse width is a function of fiber composition and wavelength. Fig. 4 from Ref. 15 demonstrates such calculations. For a wavelength near 800 nm and an α near 2.3, pulse dispersion well below 100 ps/km is calculated.

Graded index fibers are now available from several commercial sources. The highest bandwidth specified as a standard product is now 1500 MHz-km from Corning. The current published record for graded-index bandwidth is now set at 3.0 GHz-km.[16]

Fiber fabrication must involve a technique that minimizes the impurities and allows precise control of an index profile (or alternatively, a dopant profile to produce a variation in index). Most low loss fibers made in the US today use some form of a CVD (Chemical Vapor Deposition) process to fabricate a preform--a greatly enlarged version of the final fiber. The preform is subsequently heated and drawn into a thin fiber.

ROUGH DRAFT

ROUGH DRAFT

History of Fiber Attenuation

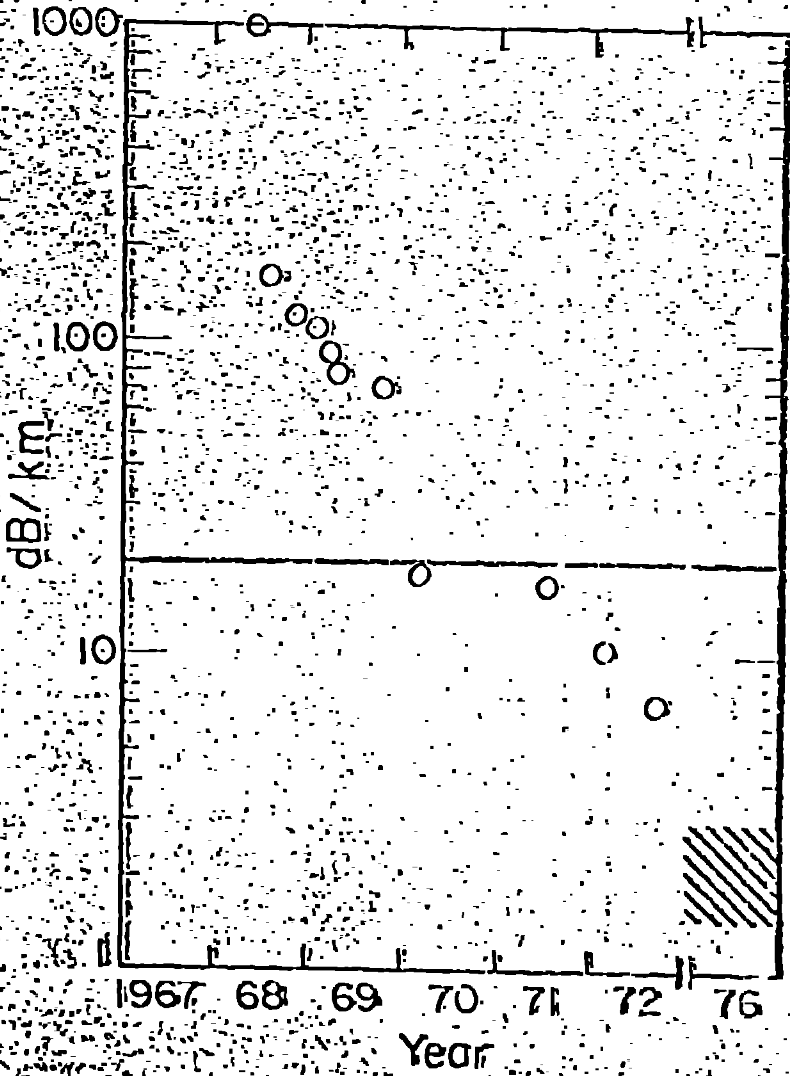
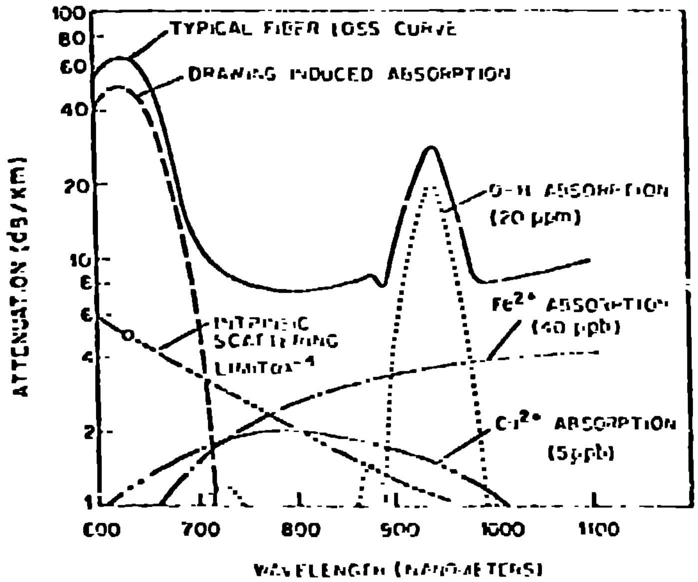


Fig 1

Fig 1

ROUGH DRAFT

DRAFT



Origin of loss in glass fiber waveguides

Fig 2.

ROUGH DRAFT

Fig. 3

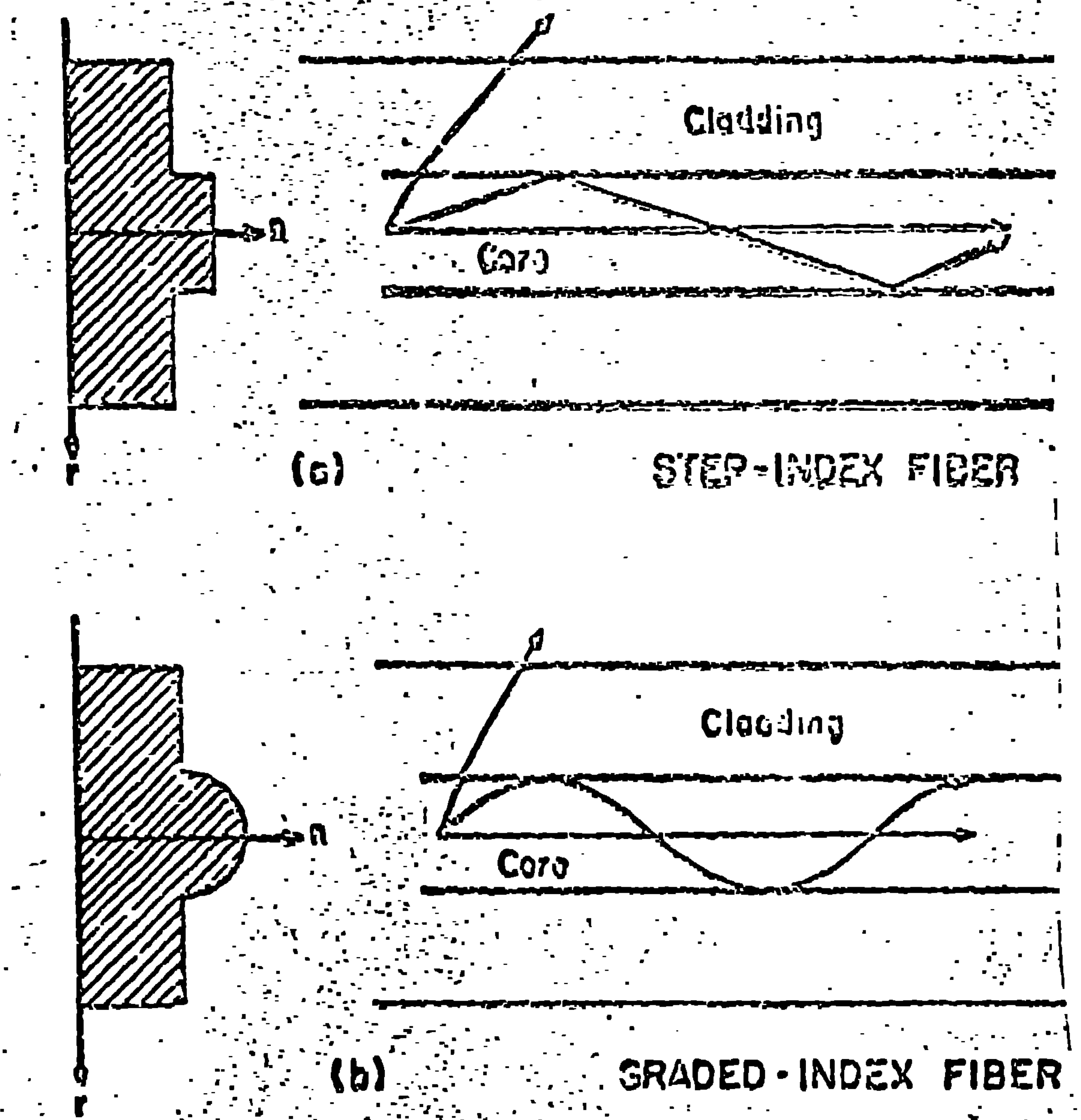


Fig 3

ROUGH DRAFT

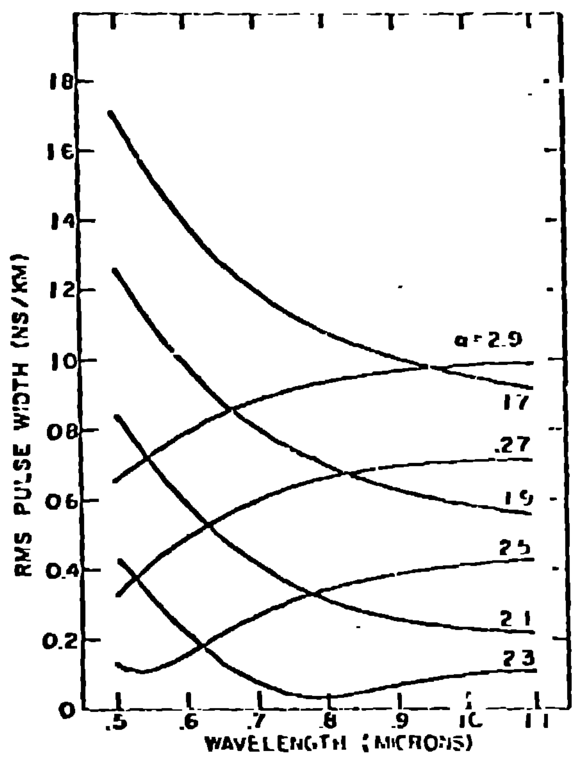


Fig 4
~~Fig. 3.2~~ RMS pulse width as a function of wavelength for several values of the index gradient parameter α.

Fig 4

ROUGH DRAFT

ROUGH DRAFT

Fig. 5 shows one type of CVD process. A tube of fiber cladding material is rotated and heated by a high-temperature flame. Various dopant materials, $SiCl_4$, and oxygen are introduced into the tube. In the presence of the high temperature, the materials react to leave an oxide soot on the inside of the tube. By varying the dopant/$SiCl_4$ ratio the soot composition can vary from pure SiO_2 to the desired doping level. Many layers of soot can be built up. The hollow tube is subsequently collapsed to form a solid rod of varying composition. In modern fiber drawing operations, precise control of temperature and draw speed is coupled with complex monitors in a closed loop system to obtain fiber with tight dimensional tolerances.

III. The Advantages of Fiber Optics

Each participant in this conference probably recognizes at least one potential advantage of fiber optics in their own specialty. The examples used below represent those recognized by the Los Alamos weapon testing program and surely are not an all-inclusive list. Since the fiber lengths in weapon testing involve distances $\lesssim 1$ km, one very critical advantage, increased repeater spacing, is not of importance in this application.

III.A. Bandwidth

Coaxial cables are quite limited in bandwidth performance. Very special cables are required to realize even a few tens of MHz over kilometer distances. Depending on the type of fiber used, much greater bandwidth with fibers can be achieved. Table I collects bandwidth data for several types of high-performance coax cable and various fiber cables. Any long-distance application that involves transfer of large quantities of data should consider the larger bandwidth potential of fiber systems.

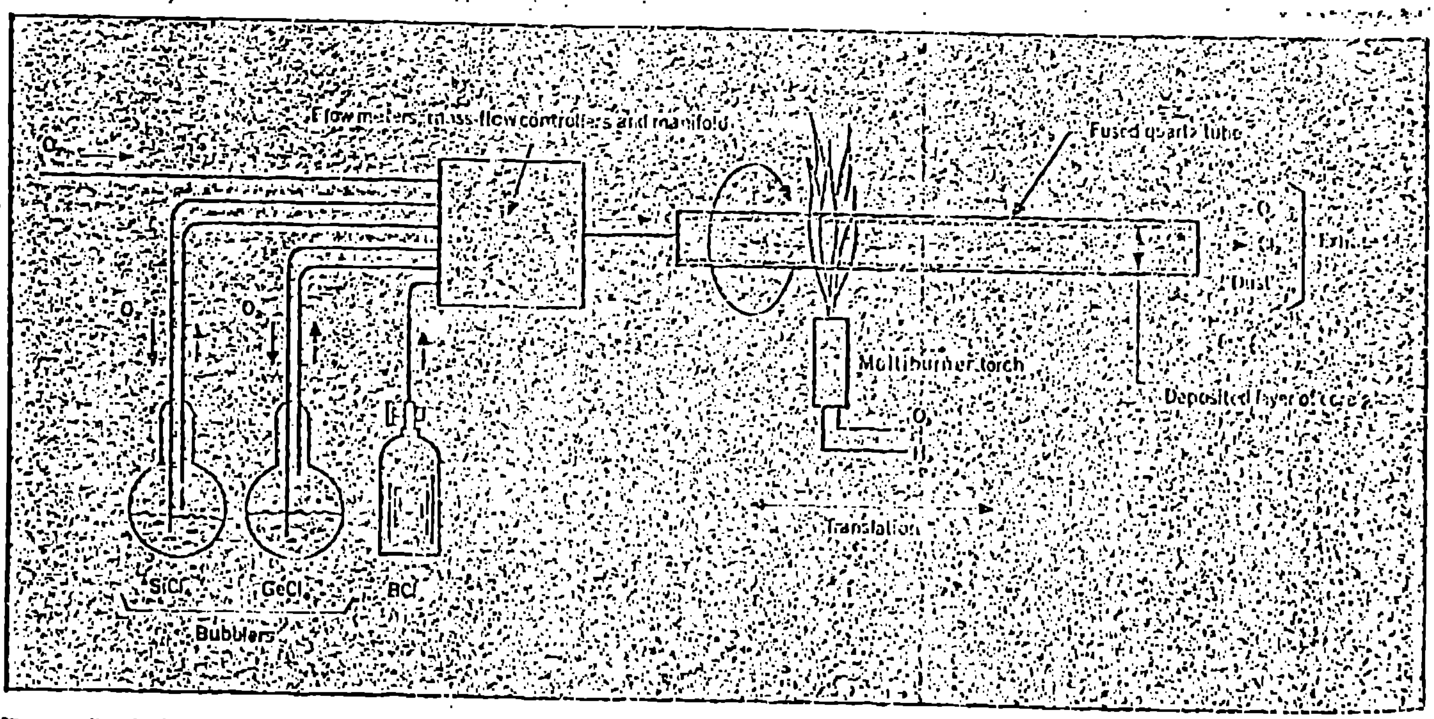
III.B. Cost

The costs of fiber optics have been greatly reduced over the last five years as R&D laboratory or pilot plant operations were replaced by full-scale manufacturing operations. For example, Table II records fiber cost per meter for two grades of Corning fiber as a function of time. Costs have dropped dramatically while attenuation has improved with time.

The cost of fiber optics in a specific application is a strong function of the environmental and physical requirements of the final cable. For applications at the Nevada Test Site[17] the cable is emplaced in a vertical hole, up to 2000 feet deep, and subjected to backfill material (sand, gravel, and epoxy) dropped into the hole from the top. The cable must be gas-tight to prevent migration of radioactive gas into the atmosphere and extensive test and documentation procedures must be completed by the vendor to guarantee this performance. A partial list of cable specifications is given in Table III. The most recent bid on this cable was about \$1.75 per fiber-meter (fiber bandwidth was 200 MHz-km at two wavelengths). From Table II it is evident that no coax can be considered as a direct replacement, however in the absence of fiber cable, the 0.88 inch coax would be used. The last order of this cable was priced at about \$4 per meter.

ROUGH DRAFT

(5)



The modified chemical-vapor deposition process for preparing the preforms from which fibers are drawn. In this process, developed by J. B. MacChesney and P. B. O'Connor, the first layers deposited become the cladding and the last layers, the core.

Fig 5

ROUGH DRAFT

TABLE I

LINE LENGTH VS BANDWIDTH

	100 MHz	200 MHz	1000 MHz
RG223/55	21 m	15 m	5.5 m
RG214/9b	42 m	29 m	10 m
RG218/17	113 m	76 m	24 m
1/2 in. Foam Heliax/ Gas Blocked	113 m	76 m	27 m
7/8 in. Foam Heliax/ Gas Blocked	191 m	127 m	46 m
Corning 1053	4,000 m	2,000 m	400 m
Corning 1054	2,000 m	1,000 m	200 m
Corning 5021	2,000 m	1,000 m	200 m
Corning 5101	10,000 m	5,000 m	1,000 m

ROUGH DRAFT

TABLE II

COST HISTORY OF OPTICAL FILBERS

Date	200 MHz Attenuation	200 MHz $/m	800 MHz Attenuation	800 MHz $/m
1975*	10	~2.50		
5/76	10	1.50	N.A.	
	6	2.25		
6/77	10	.90	N.A.	
9/78	10 dB/Km	.50	8 dB/Km	1.00
	5 dB/Km	.90	4	1.90
3/79	8 dB/Km	.35	6	.75
	5 dB/Km	.50	4	1.25
3/80				

Prices: 100 Km < L < 500 Km

Corning Glass Work Price Lists

N.A.: Not Available as standard product

*: Extrapolated from Corning graphs--not published price

ROUGH DRAFT

ROUGH DRAFT

TABLE III

NTS FIBER OPTIC CABLE SPECIFICATION

Fiber Number:	6 - 8
Cable Diameter:	< 20 mm
Temperature Range:	-40° C to 74° C Shipping/Storage
	-29° C to 85° C Operation/Installation
Gas Block Pressur	125 psig - 24 Hours
Bending Test:	Radius < 25 cm
	50 Bends
Tension Test:	250 Pounds
Impact Test:	400 Impacts - 1ft^lb
	Hammer Diameter 2.5 cm
Construction:	Non-Metallic
Jacket:	Abrasion Resistent

III.C. Weight And Size

The fiber cable construction completely dominates the weight and size of the finished product. Again, the example of the NTS cable may be used. The fiber cable weighs 12 kg per channel-km while 0.88 inch coax weighs 650 kg per km. The coax cable is 2.7 cm in outer diameter while the NTS fiber cable is 1.0 cm in outer diameter for the eight channel cable. The fiber cable requires 60 times less cross-sectional area per data channel. Labor costs easily double the cost of coaxial cable in the NTS environment, while the fiber cable is far simpler to handle. This statement is tempered by our present situation where both coax and fiber cable are used on the same test--the heavy bulky coax and the massive equipment required to handle it can, and has, damaged fiber cable.

III.C. Nonmetallic Construction And Isolation

The fiber is completely nonmetallic and potentially free of any EMI effects. The NTS cable is specified to be nonmetallic to maintain the EMI advantage. For other special applications, metallic strength members, power lines, or data channels may be added to the total cable package--thereby compromising the EMI benefits.

The electrical isolation allows complete freedom from ground loops. Furthermore, an electrical line can radiate some information (depending on details of its shielding), whereas a fiber cable should not radiate any data to the outside environment. Security implications are obvious. Channel-to-channel crosstalk can be negligible with well-designed cables.

Fiber cables also lend themselves to several more complicated intrusion-proof scenarios--for those applications where cable integrity could be compromised.

In some applications, the fact that a cable is present must be protected from discovery by remote techniques. The nonmetallic cable cannot be detected. In other applications, the presence of a metallic member can compromise measurement accuracy.

IV. The Disadvantages of Fiber Optics

Fiber-optics technology is rapidly evolving and it is not surprising that some penalities may be expected in a transition to the new technology. Some potential, or real, disadvantages of fiber systems may be listed.

IV.A. Fiber and Cable Availability

The tremendous potential of the optical telecommunications industry has driven enough vendors into the market. While state-of-the-art technology is required in fiber and cable production, almost any requirement can be met with todays commercial capabilities. No more than three years ago this was a real problem.

IV.B. Fiber Components

Many components (connectors, splices, terminators, test instrumentation, couplers, etc.) required invention within the last few years. All component needs are now addressed somewhere in the industry, although some items (like wavelength selective couplers) are still research tools, not yet available commercially.

Fiber connectors are a particularly critical component. Many different techniques have been adopted to satisfy the precise alignment tolerances of the small fiber cores. Table IV lists several of the general categories of fiber connectors commercially available today. These different connectors differ radically in ease and simplicity of installation. In the Los Alamos NTS programs, several connectors have been used extensively (ITT and Hughes precision ferrule connectors and the Deutsch index-matched/self-centering connectors). For example on a recent test 32 Deutsch connections were made under trying field conditions with an average loss of 0.9 dB. Average time per connector was well below five minutes, including all fiber preparations. The list of Table IV will probably be reduced as the best designs are determined.

Several splice systems are in commercial use now. The present systems use either a fiber-to-fiber weld or a V-groove alignment. Reports of splice loss below 0.25 dB are not uncommon.

Test instrumentation (fault locators or time domain reflectometers, system loss monitors, etc.) is now available commercially from several sources. Only two-three years ago, each laboratory was forced to construct all its own instrumentation.

IV.C. Radiation Effects

Fibers suffer from both radiation-induced absorption and luminescence. This conference may represent the most extensive survey of radiation effects to date. The reader is referred to the conference sessions organized by G. Sigel for an in-depth treatment of this concern.

IV.D. Receivers and Transmitters

In most applications the fiber is not the limiting element in system performance. Great progress has recently been made in both receiver and transmitter performance, but system dynamic range approaching 40 dB is very difficult to obtain. The phenomenon of laser modal noise[18] has only recently been identified as a major concern in injection laser diode systems and several papers in this conference will present state-of-the-art systems. System bandwidths approaching 1 GHz have been reported.

IV.E. Material Dispersion

In some applications, the light source is not monochromatic and material dispersion becomes a major contributor to system bandwidth. Material dispersion data on several fiber types is collected in Ref. 19. A plot of material dispersion for pure SiO_2 and 13.5% GeO_2/86.5% SiO_2 is given in

TABLE IV

COMMERCIAL FIBER CONNECTORS

TYPE	VENDOR
Precision Ferrule	Meret
	ITT
	Harris
	Hughes
	Seicor
	Bell Northern
	Infoptic
Elastic/Self Centering	Thomas & Betts
	AMP
	Radiall
Eccentric	Opto-Micron
Multi-pin Alignment	Amphenol
	Thomas & Betts
Index-Matched/Self-Centering	Deutsch
Lens-Coubled	Nippon Electric
V-Groove	Bell Labs
	Plessey

Fig. 6. A solution to this concern is discussed elsewhere in this conference.[20]

V. Directions in Fiber Technology

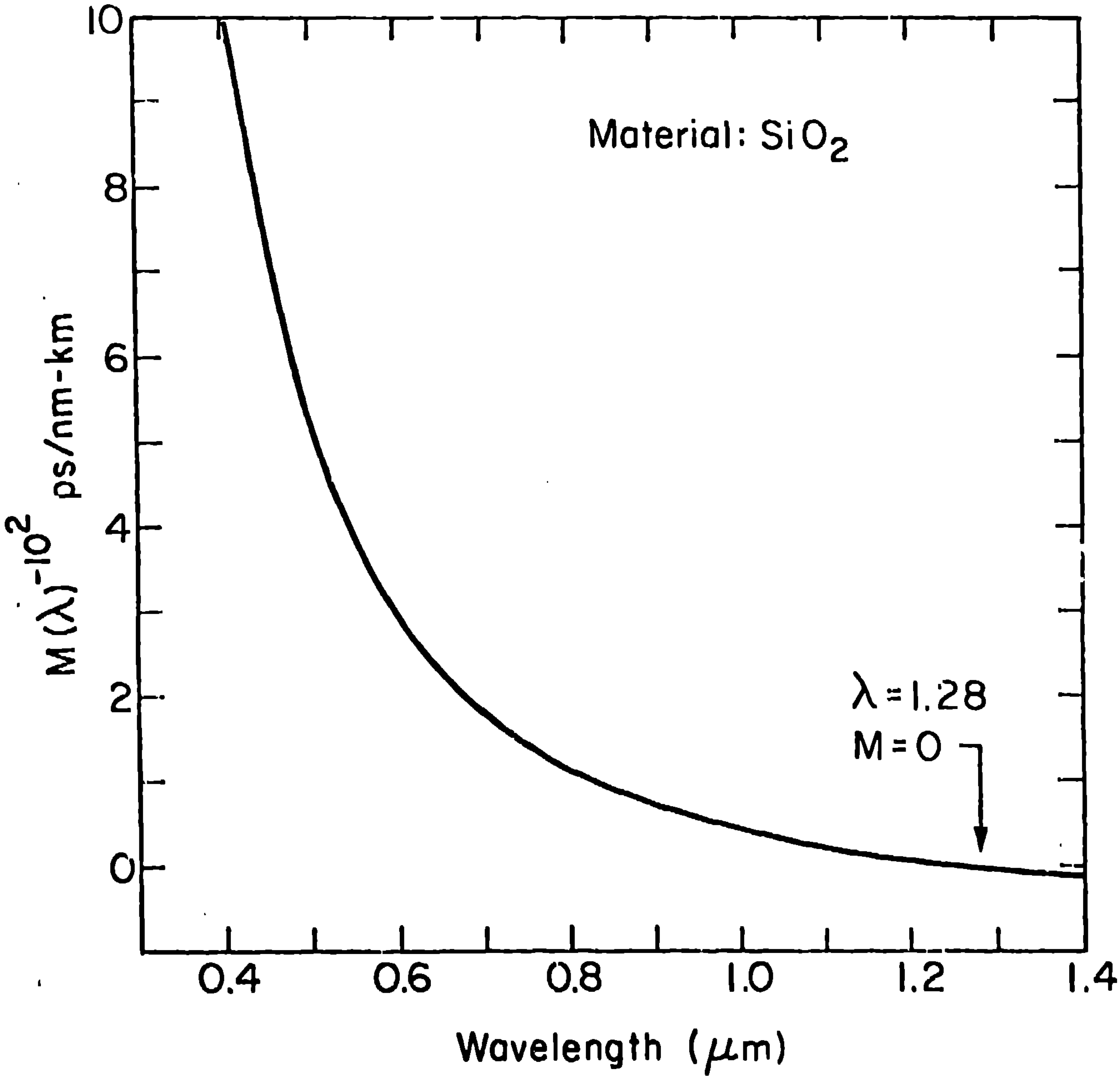
Many commercial marketing surveys have attempted to chart the future course of the fiber optics market. Details of the surveys may disagree, but all concur on the tremendous growth prospects of the industry. J. D. Montgomery[21] forecasts a worldwide dollar value of \$119 x 10^6 in 1980 for fiber systems, versus \$4.5 x 10^6 in 1976. In 1990 he forecasts a \$1.58 x 10^9 worldwide market. For the US alone, the production of fiber systems is shown in Fig. 7. While commercial communications accounted for only 16% of the 1976 dollar value, the figure should change to 77% in 1990.

This growth in the overall industry will benefit the more limited market represented by the present conference attendees. Fiber costs will drop, parameters will be standardized, and better components and instrumentation will be available.

Two areas of particular emphasis in the next few years will involve: 1) development of fibers and systems optimized for use at wavelengths near 1.3 µm (where material dispersion vanishes, cf. Fig. 6); and 2) development of wavelength multiplexers for simultaneous system operation at several wavelengths.

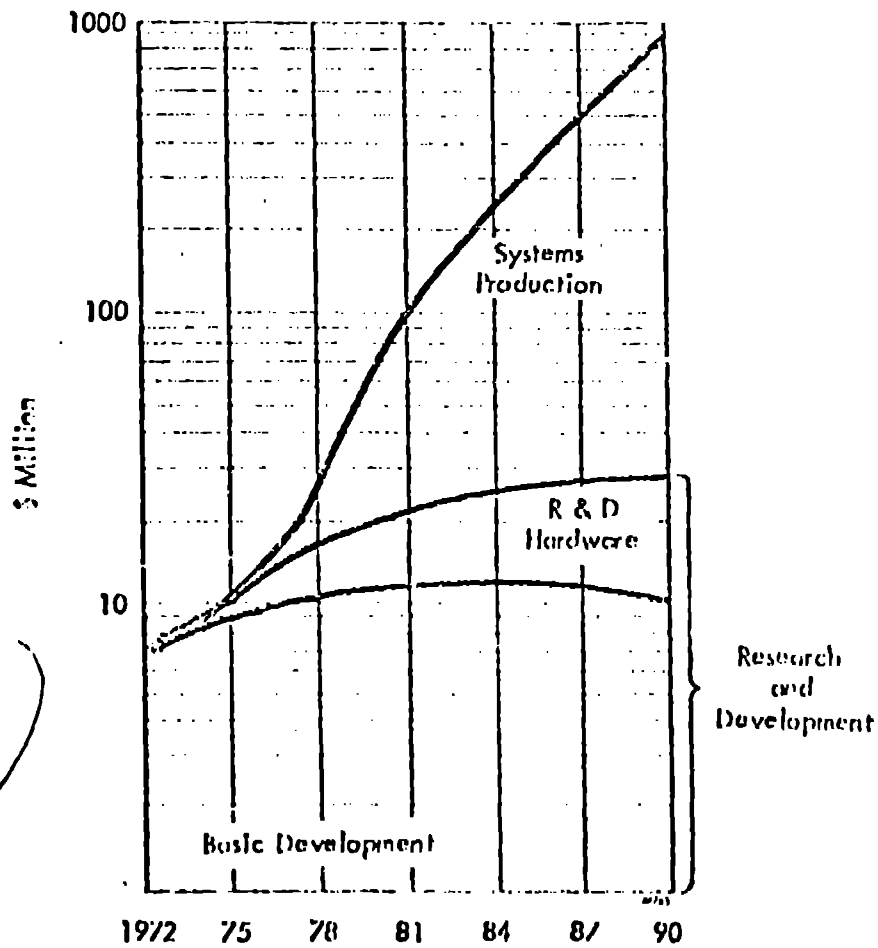
As this conference will demonstrate, fiber optics has already impacted many applications in the nuclear environment. The future is bright for both the fiber systems industry as a whole and for increased utilization of fibers in nuclear environments.

ROUGH DRAFT



LASL

ROUGH DRAFT



United States production of fiber optic intelligence transmission systems.

Fig 7

REFERENCES

1. R.J. Potter and C.E. Beasor, in Fiber Optics SPIE Vol 14, (1968) p. 9.

2. W.S. Boyle, Scientific American 237 (1977) p. 40.

3. A.G. Bell, Phil. Mag. 11 (1881) p. 510.

4. F.M. Mims, Optics News 6 (1980) p. 8.

5. J. Tyndall, Phil. Mag 8 (1854), 74.

6. J.L. Baird, British Patent 285738 (1927).

7. K.C. Kao and Hockham, Proc. Inst. Elec. Eng. 113 (1966) p. 1151.

8. M.W. Jones and K.C. Kao, J. Sci. Instr. 2 (1969) p. 331.

9. F.P. Kapron, D.B. Keck, R.D. Maurer, Appl. Phys. Lett. 7 (1970) p. 423.

10. M. Barnoski, TRW Corp., private communication (1980).

11. T. Miya, Y. Terunuma, T. Hosaka, T. Miyashito, Elec. Lett. 15 (1979) p. 106.

12. M.D. Rigterink, Ceramic Bulletin 5 (1976) p. 775.

13. S.E. Miller, US Patent #3434774, 1969.

14. D. Gloge and E.A.J. Marcatelli, Bell. Sys. Tech. Jrnl. 52 (1973) p. 1563.

15. D.B. Keck, "Optical Fiber Waveguides," in Fundamentals of Optical Fiber Communication by M. K. Barnoski, Academic Press, 1976.

16. D.B. Keck and R. Bouillie, Optics Comm. 25 (1978) p. 43.

17. P.B. Lyons, J.E. Golob, L.D. Looney, R.E. Robichaud, M.A. Nelson, T.J. Davies, "Fiber Optic Utilization at the Nevada Test Site," Los Alamos Scientific Laboratory Report LA-7029-MS, November 1978.

18. E. Miskovic and P.W. Casper, Proceedings of the Electro-Optics/Laser 79 Conference (Anaheim, 1979) p. 174.

19. S.H. Wemple, Applied Optics 18 (1979) p. 31.

20. P.B. Lyons, E.K. Hodson, L.D. Looney, L. Franks, L.P. Hocker, S. Lutz, R. Malone, J. Manning, M.A. Nelson, R. Selk, D. Simmons, "Applications of Optical Fibers in Nuclear Test Diagnostics," DNA Symposium on Fiber Optics in the Nuclear Environment, March 1980, Washington, DC.

21. J. D. Montgomery, Fiber and Integrated Optics 1 (1977) p. 101.