The Outside Vapor Deposition Method of Fabricating Optical Waveguide Fibers

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(Invited Paper)

Abstract—**The outside vapor deposition (OVD) process for fabricating high performance glass optical waveguide fibers is reviewed. Starting metal halide chemicals, porous soot preform fabrication, sintering steps, and fiber drawing are discussed. Preform target size and its effect in obtaining deposition rates to 4 g/min is presented. Data comparisons of OVD fiber performance with other vapor deposited techniques are presented for attenuation, hydroxyl content, and strength (0.7 GPa/M^2 for 49.5 km of fiber). Single-mode fiber results including excellent geometric concentricity are also discussed.**

I. INTRODUCTION

IN the development of optical waveguides for communications, several glass fabrication methods have been reported by various manufacturers. The highest performance optical waveguides reported to date have all been made from vapor phase deposition of high silica glasses with core dopants of germania and/or phosphorous pentoxide.

The first section of this paper describes the outside vapor deposition (OVD) method of manufacturing fibers for optical communications. The second section presents some comparative fiber performance data for this process (OVD) as well as the two other major methods employed in making optical waveguides using doped deposited silica. These other methods are the inside vapor deposition (IVD) technique and the axial vapor deposition (AVD) technique which is also known as VAD. AVD forms the porous core preform by deposition on one end of the preform as compared to OVD which forms the preform on a starting target rod.

The basis for much of the chemistry employed in the OVD process can be found in the work of Hyde [1], who made vitrified silica by passing vapors of a hydrolyzable silicon compound, such as silicon tetrachloride, through a gas-oxy burner flame. A breakthrough technique, which employed the vapor deposition of silica, was developed by Keck and Schultz [2] and was used to make the first waveguide fibers with losses of less than 20 dB/km reported by Maurer *et al.* in 1970 [3]. Since that early work, much progress has been made in further lowering the optical losses and in providing other product improvements. This paper presents advances in the technology since the review done by Schultz [4] in 1980.

II. OUTSIDE VAPOR DEPOSITION PROCESS

A. Raw Materials

High silica (SiO_2) glasses are attractive for optical fibers because silica has intrinsic total losses under 1 dB/km for wavelengths from about 1 to 1.7 μm. In a vapor deposition process such as OVD it is desirable to have a silicon-containing liquid starting material with a high vapor pressure (about half an atmosphere) at a temperature somewhat above ambient. The high vapor pressure liquid permits relatively high mass transfer rates and high purity through distillation processes when impurities such as transition metal compounds are at much lower vapor pressures. Silicon tetrachloride ($SiCl_4$) is a very convenient chemical for this application because it has both the vapor pressure and purity characteristics required. It is also available commercially at relatively low cost.

The index of refraction of silica glass can be increased by adding metal oxide dopants. Germania (GeO_2) has a combination of favorable attributes as a dopant. It is a glass former and its optical transmission extends into the near infrared region where the Rayleigh scattering losses are minimized in silica. It is also relatively refractory so that it can readily be kept in the silica glass matrix. Germanium tetrachloride ($GeCl_4$) is a convenient starting material from which to form this dopant in that it also has a relatively high vapor pressure and is available in high purity. Other dopants such as P_2O_5, B_2O_3, and TiO_2 may also be added to help modify the glass physical properties or to aid in processing. The usual starting raw materials for these elements are also their chloride forms. The incorporation of florine into OVD has also been recently reported by Berkey [5].

B. Preform Fabrication

The outside vapor deposition process is very flexible and has been used to successfully fabricate a wide variety of optical waveguide preform types capable of producing high performance fibers with a range of properties. The many degrees of freedom in the process can be optimized to obtain relatively high deposition rates for the achievement of low manufacturing costs. The OVD process utilizes the pure starting chemicals described above in the "deposition" step to make a low density porous glass body referred to as a soot preform. This soot preform is "sintered" or "consolidated" in a second step, described below, which also employs a controlled atmosphere to remove hydroxyl ions from the glass. The result is a dense glass preform suitable for drawing into optical waveguide fibers.

The process starts with the chemicals which are metered to the deposition burner through a delivery system that provides precise control of the flows, mixing of components, and vaporization. There are several possible types of delivery systems. They utilize bubblers, direct chemical vaporization apparatus with a gas flow controller, or a metering pump with a subsequent vaporization chamber.

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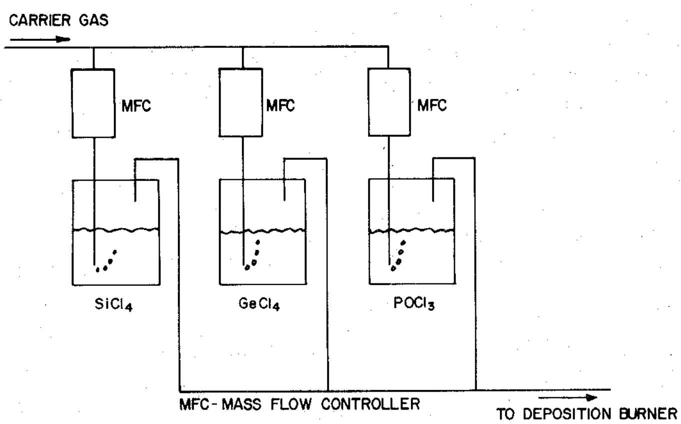

Fig. 1. Bubbler vapor generation system.

Fig. 1 shows schematically a standard "bubbler" delivery system employing mass flow controllers (MFC) to provide precise control of the "carrier gas." This carrier gas bubbles through the liquid in the container vaporizing some of the chemical. The mixture of the carrier gas plus the chemical is then sent to the deposition burner as shown. Bubbler systems have typically been operated at a fixed temperature in the 35–50°C range and with a carrier gas such as oxygen or nitrogen.

Glass forming vapors (e.g., $SiCl_4$, $GeCl_4$, etc.) are fed through a fuel gas and oxygen fired deposition burner which employs a series of concentric orifices. The center orifice is for the metal halide vapors. An adjacent orifice is used for a shielding gas which prevents premature reaction of the chlorides which could form glassy buildup on the burner face. An outer orifice is used for the fuel gas and oxygen mixture. The heat of the flame, along with the oxygen, causes the metal chloride vapors to react forming tiny spheres of the metal oxide material (doped silica glass). These spheres are directed toward a target mandrel, or soot preform, where a fraction of the glass is collected. The glass spheres, or soot, have a range of particle sizes approximately 0.1 μm in diameter as shown in Fig. 2.

A starting target rod is typically employed for deposition and removed prior to sintering the porous preform. The porous soot preform can have a wide range of densities and porosities with an average preform density of about 15–25 percent of the bulk glass density [6]. In appearance, this soot preform would resemble a cylinder of compressed talcum powder as shown in Fig. 3(a). The use of the porous glass preform as an intermediate step has several advantages over directly depositing a fused preform. The lower soot preform temperatures reduce the volatilization of dopants such as GeO_2 and P_2O_5. The separation of the laydown step from the sintering or densifying step permits removal of the hydroxyl impurity which forms because of the H_2O byproduct formed in the deposition flame.

The glass deposition rate and efficiency increase with the target size and with the amount of fuel gas over the range portrayed in Fig. 4. Average soot preform deposition rates are 1.3–4 g/min. The typical soot preform geometry is a cylindrical body that rotates as the deposition burner traverses back and forth along its length. Soot preforms as large as 1800 g (11 cm diameter by 80 cm length) have been made [7] with about 1000 layers. This large number of layers permits many changes in the vapors or deposition composition. This enables the size

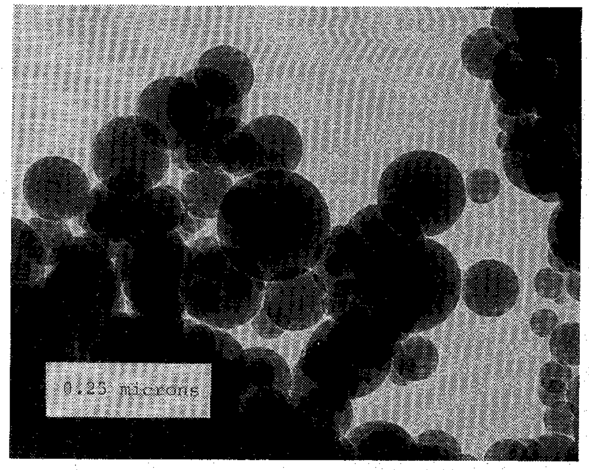

Fig. 2. Glass spheres produced by outside vapor deposition.

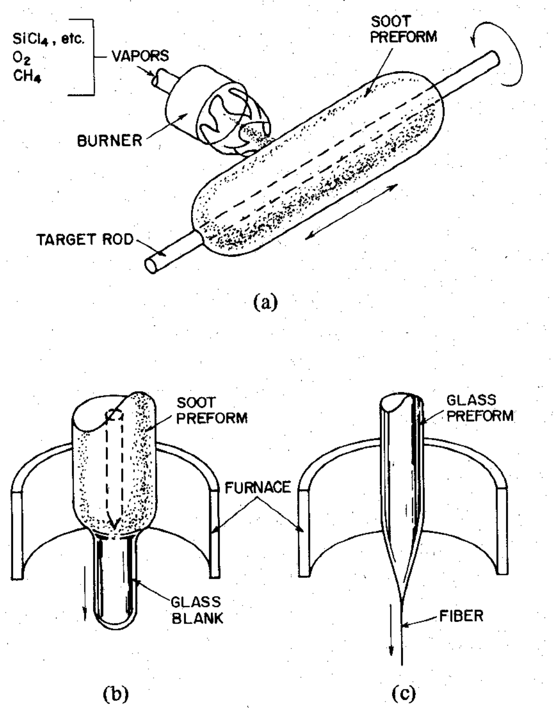

Fig. 3. Outside vapor deposition process. (a) Soot deposition. (b) Sintering. (c) Fiber drawing.

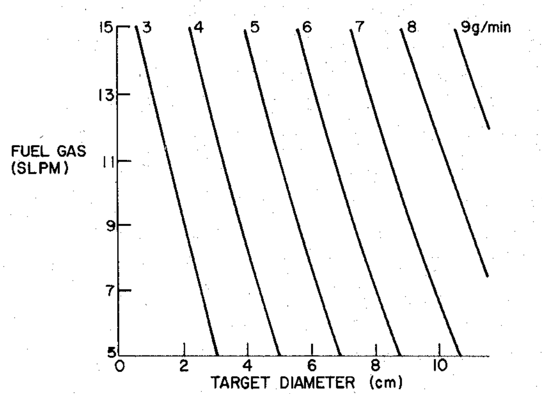

Fig. 4. Outside vapor deposition rate (g/min) as a function of target diameter (cm) and fuel gas flow (SLPM).

and index of refraction profile of the optical core portion of the preform to be tailored with precision. Since both core and cladding glass are typically deposited for each preform, there is essentially no quality difference between these regions in the resulting fibers.

C. Soot Preform Sintering

Sintering of the porous soot preform to a dense glass preform [shown in Fig. 3(b)] is done by supporting the soot preform from one end and passing it vertically through a hot zone of about 1500°C inside a refractory muffle furnace. By using helium with a few percent chlorine as the atmosphere within the muffle, the glass preform is effectively purged of hydroxyl ions. The main reaction involved in the drying process employing chlorine can be represented by (1)

$$2 \equiv \mathrm{SiOH} + \mathrm{Cl_2} \rightleftarrows \mathrm{SiOSi} \equiv + 2\mathrm{HCl} + \tfrac{1}{2}\,\mathrm{O_2} \tag{1}$$

where $\equiv$SiOH indicates a siloxyl group bound to the silica matrix by three bridging oxygens. Other drying agents such as bromine and thionylchloride have been used. Drying is an important aspect of making high transmittance glass in the 1.3-1.6 μm region because absorption due to $^-$OH is about 37 dB/km/ppm at 1.38 μm [8].

An early OVD processing problem was stress-induced glass preform breakage resulting from flaws along the inner surface where the deposition target mandrel had been removed. This has been overcome through composition changes (such as the addition of phosphorous on the center) and through improved processing. Multimode glass preforms with high core doping levels and correspondingly high thermal expansion coefficients can now be made. The glass preform center hole is closed during the sintering step, eliminating internal free surfaces that would initiate breakage.

D. Fiber Drawing

Drawing of glass preforms into fiber [shown in Fig. 3(c)] is done by using induction or resistance furnaces at about 2000°C. The glass preform is slowly fed into the furnace while the free formed glass fiber is pulled out of the bottom at a higher speed. The glass fiber is coated with protective polymers to retain its intrinsically high strength.

III. Comparative Fiber Properties

A. Attenuation Rate of Multimode Fibers

The recent advances in understanding and control of OVD processes described above have allowed increased flexibility in fiber compositions. This has permitted making fibers of a wide range of improved properties. Attenuation is still a key property of most fibers. The importance of separating "typical" values obtained in production from "champion" values obtained in laboratories should be noted. Typical values are more likely to represent the present state of the art in production and, therefore, are likely to be more available in commercial quantities. The question of how soon typical values in fact approach champion values is a function not only of technical difficulty but also of commercial need. Table I shows that each process has the same attenuation rate values at 850 nm. The 1300 nm attenuation rate data show a significant difference among processes. The OVD typical value is significantly higher (0.2-0.3 dB/km) than the other processes. The OVD champion value is 0.08-0.12 dB/km higher. The data at 1550 nm show essentially no difference between the OVD and AVD processes.

TABLE I
Multimode Telecommunication Type Fiber—Attenuation Rate

	850 nm		1300 nm		1550 nm
	Typical	Champion	Typical	Champion	Champion
OVD	2.4	2.2	0.9	.52	.30
AVD [12]	2.4	2.2	0.7	.44	.29
IVD [13,14]	2.4	2.3	0.6	.40	.34[14]

The conclusion reached is that these 1300 nm data for the OVD process are significantly affected by the residual hydroxyl content of the glass. This is from the impact of the tail of the $^-$OH absorption band located at 1380 nm. It can be reduced by lowering the residual $^-$OH content during the sintering process as described earlier.

As can be seen in Fig. 5, the understanding of the OVD drying process has progressed considerably in the recent past. Translation of laboratory knowledge and process improvements into production has proceeded quickly and the impact of very good drying (less than 50 ppb $^-$OH) should soon begin to have a major impact on typical attenuation values at 1300 nm. The drying process has been brought under control in the laboratory well enough to produce fibers which do not have a detectable water peak at 1380 nm (<2 ppb). This is a significant achievement which has the potential of providing increased fiber utility through a significantly lower 1300 nm attenuation rate and the use of wavelength division multiplexing.

B. Bandwidth of Multimode Fibers

Fiber bandwidth is a very important parameter for telecommunications applications. Comparisons between process types are somewhat complex because of the differences among fibers optimized for specific applications. First window fiber is optimized for use at 850 nm, second window fiber is optimized for use at 1300 nm, and double window fiber is optimized for use at both 850 and 1300 nm. OVD fibers can be optimized for any of these applications. In the case of first window fibers, the typical bandwidths range from 600-1000 MHz/km with champion values up to 3000 MHz/km. Second window fibers have the same typical values and the champion fibers have exceeded 3000 MHz/km. Double window fibers are typically in the 400-800 MHz/km range.

A very important aspect of bandwidth is the effect of fiber length. A detailed discussion of this aspect is beyond this paper, but can be reviewed in the work of Love [9] and Bouillie [10].

C. Data Communication Fiber

Fibers described above have been specifically optimized for use in telecommunications applications where high data rates (up to and possibly exceeding 140 Mbits/s) and long distances (up to 20-40 km) are needed. A separate class of fiber has been developed for low data rate communications over short distances as reported by Jones and Sommer [11]. This fiber is an improved short distance fiber. This fiber type has a large

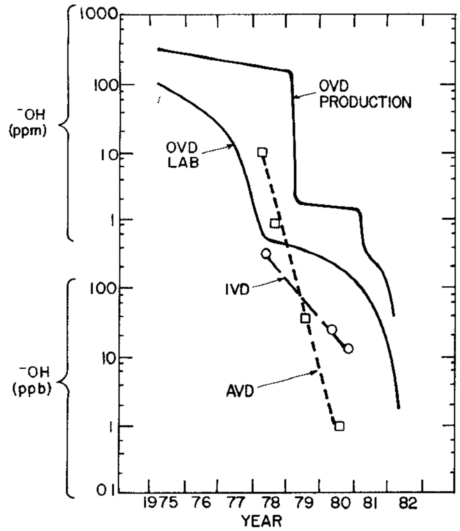

Fig. 5. Progress in reducing hydroxyl content.

TABLE II
GRADED INDEX DATA TRANSMISSION TYPE FIBER

	AVD	OVD SDF	OVD Improved SDF
Δ	2.0%	2.1%	2.0%
Numerical Aperture		0.30	0.29
Core Diameter (μm)	100	100	100
Fiber Diameter (μm)	140	140	140
Core Glass System		GeO_2-B_2O_3-SiO_2	GeO_2-P_2O_5-SiO_2
Clad Glass System		B_2O_3-SiO_2	SiO_2
Attenuation (dB/km)			
850 nm Typical	3.0	4.2	2.9
Champion			2.3
1300 nm Typical	1.0		1.0
Champion			0.7
Bandwidth (MHz/km)			
850 nm		20-40	200-400
1300 nm			200-400

core (100 μm versus 50 μm), larger OD (140 μm versus 125 μm), and a higher numerical aperture (0.29 versus 0.20) than many telecommunication type fibers. These parameters have been specifically designed to allow use of lower cost light sources and connectors. The fiber performance of these germania-phosphosilicate fibers is much improved over the older germania borosilicate short distant fiber (SDF) types as shown in Table II. It can be seen that a low attenuation rate and a bandwidth which is high for these applications is now possible at both 850 and 1300 nm. The ability of the OVD process to obtain high deposition rates during the core making process is particularly important in making these highly doped, graded index, large core fiber types.

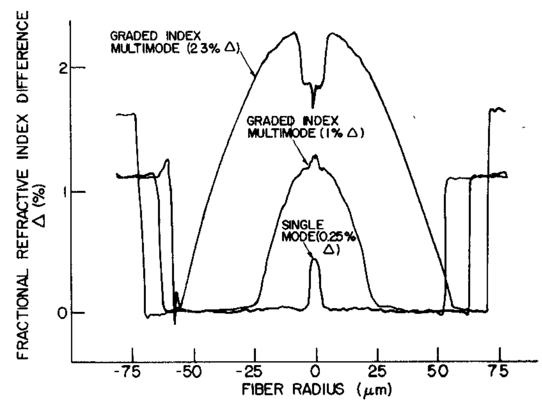

Fig. 6. Refractive near field profiles of OVD fibers.

D. Index Profile

Fig. 6 shows the index profiles of the three major types of fibers now being made by the OVD process. The improved short distance fiber (Δ = 2.0 percent) curve shows the high level of dopant required for the high numerical aperture. The rather large dip is due to the hole closing process in this composition, but is not a significant problem for the low bandwidths needed for most low data rate applications. The middle curve is typical for OVD multimode telecommunications fibers. It can be seen that there is no centerline dopant burnout, which is typical in the IVD process. This is due to the lower temperature (≈1500°C) required to sinter the OVD soot preform as compared to those required to collapse IVD tubes after core deposition has been completed (≈2000°C). The AVD process does not have a hole to collapse, but depends on controlling deposition temperature and/or fume flows to obtain gradients. The remaining curve in this figure is for an OVD single-mode fiber which will be discussed in greater detail below. These are but three examples of the fiber geometry/numerical aperture flexibility of the OVD process. Many other options are possible.

E. Attenuation Rate of Single-Mode Fibers

As interest in ever higher data rates (above 140 Mbits/s) and longer link lengths (greater than 40 km) continues to grow, the importance of single-mode fiber also grows. When suitable emitters, connectors, and detectors are available, it is expected that this class of fiber will become extremely important. A prime example is the potential for submarine telecommunication systems where very long links and high data rates are essential.

The OVD process has recently made single-mode fibers, which in some respects are superior to any reported in the literature. The attenuation data for these fibers were presented by Berkey [5] and are reproduced in Table III along with data from the AVD and IVD processes. The attenuation of the fibers made to date is excellent in all respects and indicates the exceptional prospect for making single-mode fibers by the OVD process. Fig. 7 shows the spectral attenuation curve for one OVD single-mode fiber. With the exception of a small water peak, the fiber curve approaches the Rayleigh limit. Future work based on techniques recently used to eliminate the water peak on multimode fibers is expected to further reduce the remaining water peak in OVD single-mode fibers.

The zero dispersion wavelength (λ_o) for these fibers is near 1330 nm. Although this is a somewhat longer wavelength than for IVD fibers (which typically have λ_c near 1300 nm), this is not a problem since the OH^- absorption peak is so small its tail does not increase attenuation at this wavelength.

TABLE III
SINGLE-MODE TELECOMMUNICATION TYPE FIBER—ATTENUATION

	1300 nm		1550 nm	
	Typical	Champion	Typical	Champion
OVD	.40	.27	.25	.14
AVD[11]	.47	.33	.35	.22
IVD[11]	.60	.40	.40	.20

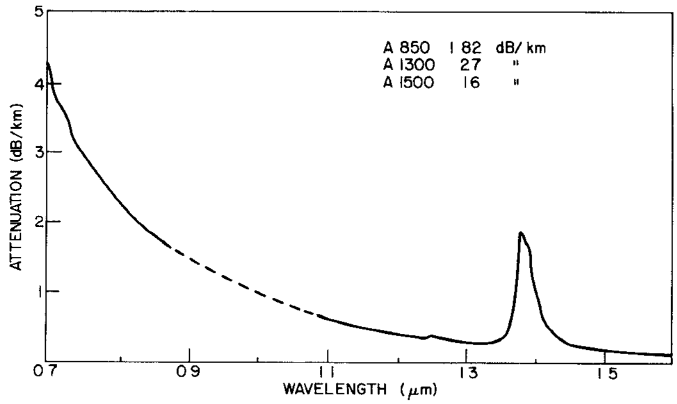

Fig. 7. Outside vapor deposition single-mode attenuation rate spectrum.

F. Splice Loss of Single-Mode Fibers

A key concern for the future utility of single-mode fibers in addition to low attenuation is low splice loss. A key factor for low splice loss is optimizing fiber parameters Δ and "*a*," where Δ is the difference in refractive index between the core and the cladding, and "*a*" is the radius of the core. As has been shown, the OVD process has considerable flexibility in this area. Single-mode fibers have been made with Δ values ranging from 0.1 to 1.3 percent and 2*a* values ranging from 3 to 20 μm. Thus, there are no fiber design limits (with respect to Δ or *a*) which would limit achievement of low splice losses. Actual data are now being generated to quantify fiber design tradeoffs.

G. Fiber Geometry

Another key to low splice loss is very stringent control over fiber geometry. OVD blanks are regularly being drawn with outside diameter variations having 1σ values of less than 0.3 μm for 125 μm OD fiber. Due to the small core size and low numerical aperture of useful single-mode fiber designs, low splice loss requires very round and very concentric cores. For those single-mode fibers evaluated to date, no core ovality or core eccentricity was detected. These evaluations were done with a microscope and are felt to be precise to less than 0.2 μm. Very good geometric control is also found in multimode fibers. This is one of the advantages of the very highly circular symmetric OVD process. This high degree of symmetry should be of considerable value in system performance since all fiber types which will be used near the theoretical loss limit will become critically constrained by excess splice losses.

Fig. 8 shows the expanded refracted near field plot of an OVD single-mode fiber. This is expanded over the one shown in Fig. 6 to show the lack of a centerline effect. The nonsquare edges are due to diffusion of germania in this binary GeO_2-SiO_2 core/SiO_2 cladding fiber design.

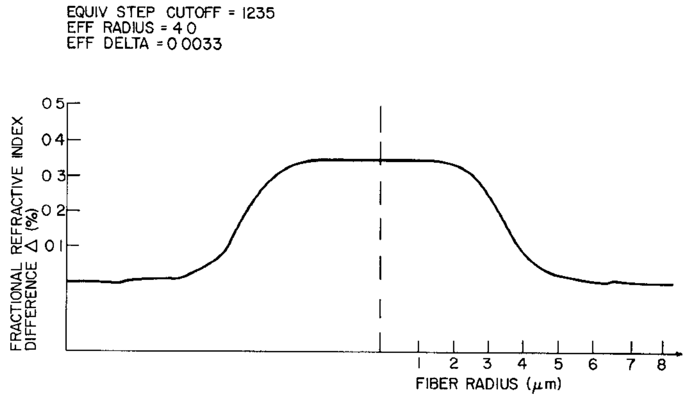

Fig. 8. Refracted near field profile of OVD single-mode fiber.

H. Strength

The strength of optical waveguide fibers is of crucial importance to users. Fig. 9 shows the complete Weibull probability plot of 49.5 km of OVD multimode fiber tested in 100 m gage lengths at 4 percent/min strain rate. These data show that over 90 percent of fiber tested in 1.1 km lengths is expected to survive an axial tensile test of 100 kpsi (0.7 GPa/M^2) when strength tested during manufacturing. This excellent strength is not unusual in that the same process and raw material which is used to produce the ultra pure cores are also used to produce the entire cladding of the fiber. This strength is similar to that obtained from the IVD process when Suprasil(TM) tubes are used.[1]

A practical advantage of the OVD process is that the same process and raw materials are used for making the core and cladding. This removes the concern inherent in the IVD process for obtaining a reliable supply of sufficiently high quality tubing of the correct geometry. In the OVD process, the cladding is applied in situ with the required high quality and concentricity. In the event that low-cost high-quality tubes do become available, less OVD cladding could be deposited and the blank put inside a tube for drawing.

IV. CONCLUSION

The basic process of making high quality optical waveguide fibers by the outside vapor deposition process has been discussed. The process demonstrates high deposition rates and a lack of dependence on high quality tubes. Recent advances have expanded the utility of the process from multimode fibers for telecommunications into long wavelength, large core, high numerical aperture fibers for data communications and single-mode fibers for high data rate long distance telecommunications. Implementation of recent ^-OH removal

[1] Suprasil(TM) tubes are synthetic vitreous silica also manufactured by vapor phase deposition techniques.

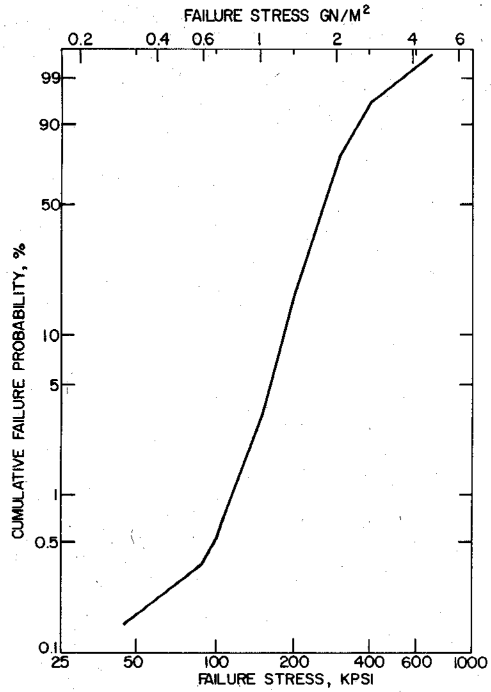

Fig. 9. Weibull probability of stress failure for 50 km of OVD fiber.

processes during sintering should further improve attenuation rates at 1300 nm. The high strength and excellent geometrical control achieved by the OVD process continue to be a benefit and should become even more attractive, particularly in single-mode applications.

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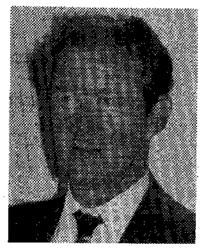

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From 1969 to 1971 he was with the U.S. Army, where he was involved in project management. In 1972 he joined Corning Glass Works, Painted Post, NY, where he is currently engaged in various technical and technical management functions. Since 1981 he has been a Portfolio Manager of optical waveguides.