# Strength and Fatigue of Silica Optical Fibers

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*(Invited Paper)*

*Abstract*—**Great progress has been made in the ability to produce long lengths of strong high-silica lightguide fibers since work first started in the early 1970's. Some important advances have also been made in the protection of the fiber surface from environmental attack through the development of new polymer coatings and through the development of hermetic (metallic) or environmentally stable (inorganic or carbon) coatings. In addition, substantial insights have been gained both in terms of simple mechanical behavior (strength) and simple environmental degradation (aging), as well as the combined behavior (fatigue).**

## I. Introduction

AT THE TIME work was being started on the mechanical properties of oxide glass fibers for lightguide applications, there was a vast body of experimental and theoretical work available generally on glass strength (see [26], [50], [59], [74]). However, there was not sufficiently detailed understanding of either the size or time dependence of fiber strength to make any extrapolations of these properties to the useful engineering lengths or times required for lightguide applications. In particular, the longest total length of fiber that had been tested was of the order of meters [1] and what appeared to be both intrinsic and extrinsic behavior was noted even in this case. In terms of time dependence, the slow crack growth model proposed to explain fatigue in glasses was known ([59]) to be inadequate to describe fatigue in high strength fibers since the fatigue parameters describing fiber fatigue and slow crack growth were found to be quite different.

Early work in the mid 1970's on both of these problems led to rapid practical progress and some theoretical progress. In this paper, a brief review of this early lightguide work will be given and a more detailed assessment of the advances since that time will be attempted. An exhaustive review will not be undertaken because several fine reviews are already available [12], [19], [34].

## II. Strength

### A. Strength Distributions

Bartenev and Izmailova [2], Metcalfe and Schmitz [50], and Proctor *et al.* [59] showed that bimodal strength distributions were usual (if any reasonable volume or length of fiber were tested) for both E-glass (aluminum-barium-borosilicate glass) (Fig. 1) and silica glass. In the case of both glasses, the total fiber length tested was meters. Since it was hoped that lightguide fibers could be used in single pieces in at least kilometer lengths, the first questions asked were[1]:

1) If the lower strength mode in the bimodal distribution is extrinsic, can it be controlled or eliminated?
2) Physically and analytically, how can the fiber breaking problem be handled? In particular, a) is a weakest-link model obeyed, and b) what kind of strength distributions are found?

Both of these problems were answered in the earliest papers. Maurer [47] showed that the short length (0.6 m) tests and long length (kilometer) prooftests formed a single distribution. Kurkjian *et al.* [41] showed in rather more detail that the weakest-link model is appropriate: that is, the data for three lengths coincide when shifted by ln $L2/L1$ (Fig. 2). Schonhorn *et al.* [70] showed, in general terms, that by taking steps to improve bulk and surface glass quality, as well as furnace atmosphere cleanliness, the frequency and magnitude of the low strength breaks could be decreased impressively (Fig. 3). In fact, by fire-polishing a synthetic silica rod and drawing it in a laser furnace, a 1-km fiber could be produced with a mean strength of ~5.6 GPa. Kurkjian and Paek [43] showed that the variance ($\nu_\sigma$) in apparent strength of fiber of the type is in the range 1–5 percent (corresponding to a value of the Weibull modulus, $m$ ($1.28/\nu_\sigma$) in the range 25–

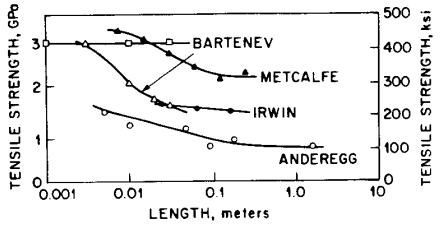


Fig. 1. Tensile strengths of *E*-glass fibers as a function of gage length. From [2], △: industrial fiber and □: laboratory fiber, ▲: [50], ●: [30] and ○: [1]. Since the Weibull slope $m$ equals the reciprocal of the slope of this log $\bar{\sigma}$ versus log $L$ plot deviations from a straight line indicate deviations from unimodality.

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[1]In fact, the first very important question which had to be solved was that of providing a mechanically protective polymer coating for the fiber in-line. See [3] and [4].

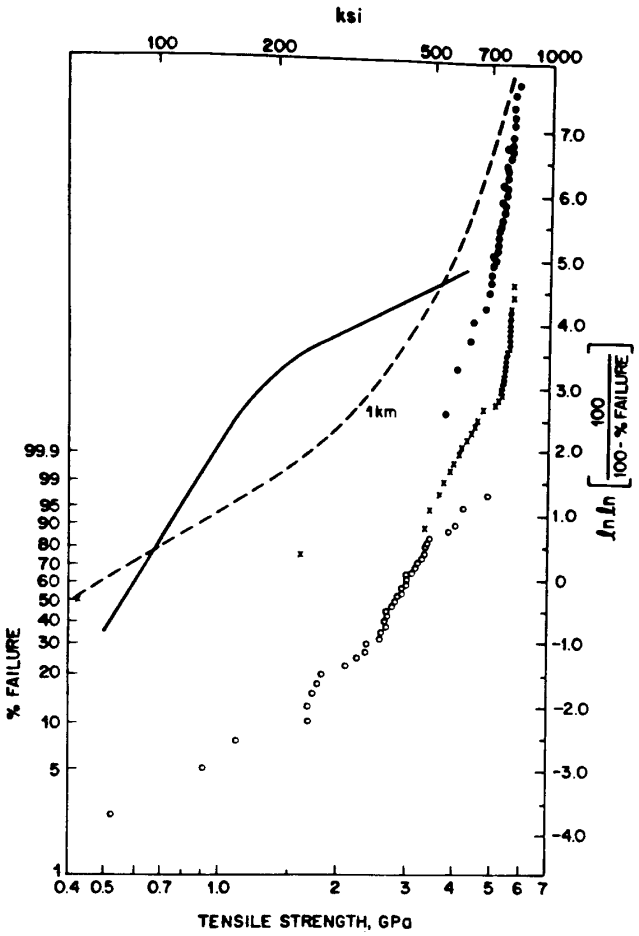


Fig. 2. Weibull probability plot for furnace-drawn polymer coated silica fiber [41]. Data are taken at gage length ○ : $L$ = 20 m, ● : $L$ = 0.04 m and ×: $L$ = 0.75 m, and shifted vertically by ln $(20/L)$. The dashed curve is obtained by shifting a smooth curve through the data at 20 m by ln $(1000/20)$. The solid curve is the data of [47] shifted by ln $(20/0.61)$.

125) and could almost be accounted for by diameter fluctuations. They suggested that this narrow high strength mode is the intrinsic strength (except for fatigue degradation occurring during measurement) of a "perfect" fiber surface.

### *B. Procedures for Improving Strength*

The rate of occurrence of extrinsic flaws was reduced by the procedures applied by Schonhorn *et al.* [70]. However, it is expected statistically that, as longer lengths are tested the probability of failure at a given stress will increase. Apparently, as shown by several investigators, the procedures which must be controlled are understood in a general way. The quality of the fiber produced then depends not only on how well these parameters are understood and controllable, but also on the quality of the fiber required since all quality improvements will add some cost. Thus, four aspects may be considered: 1) initial bulk glass quality, 2) initial surface quality, 3) cleanliness in drawing, and 4) suitability of the coating.

1) If the preform rod is of poor quality in the bulk, at the moment there is no remedy (Fig. 4).

2) If the surface is of poor quality, two procedures are normally applied. An HF etch is appropriate in order to remove foreign impurities and an etching rate of ~2–3 $\mu$m min$^{-1}$ in 48-percent HF has been found for silica [44]. While etching will also tend to reduce the seriousness of cracks, it has been found that fire polishing is more effective for this purpose [11]. Although no quantitative study of crack healing has been made, Sakaguchi [6] has found "two torch passes at 1900°C" reduces the surface roughness from 10 $\mu$m to 1 $\mu$m. Since as-received rods might be expected to have cracks of the order of hundreds of micrometers long, several passes might be required to heal such cracks.

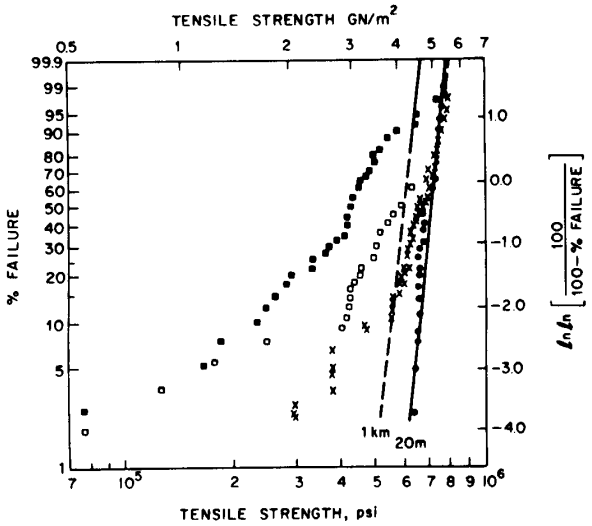


Fig. 3. Weibull probability plot for polymer-coated silica fiber tested in 20-m gage lengths [70]. ■: Furnace-drawn from Amersil TO8 road, □: same using fire-polished TO8 rod, ×: furnace-drawn from fire-polished Amersil suprasil rod, and ●: laser-drawn from fire-polished Amersil suprasil rod.

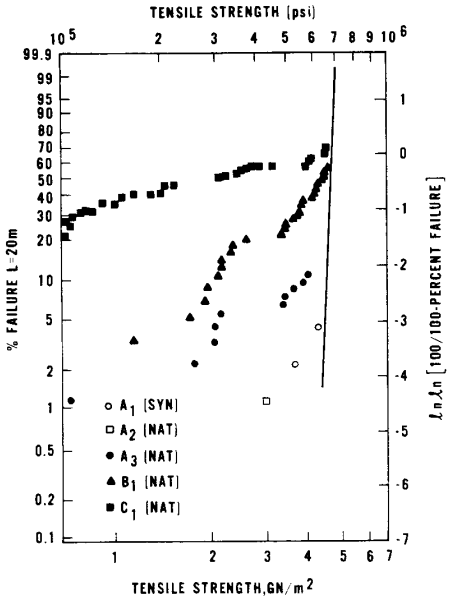


Fig. 4. Weibull probability plot for polymer-coated silica fiber tested in 20-m gage lengths [11]. 1-2 km lengths of fiber drawn from several types of collapsed tubes.

3) Maurer [48] has studied the strength of fibers in which dust particles have inadvertently contaminated the surface. Sakaguchi [67] has purposely inserted particles (0.03-$\mu$m, 0.3-$\mu$m, and 1-$\mu$m $Al_2O_3$, and 20-$\mu$m carbon) into the draw furnace and found that, within the precision of the measurement, the well-known fracture mechanics equation

$$\sigma = \frac{K_{IC}}{Yc_c^{1/2}} \tag{1}$$

(where $\sigma$ is the strength, $K_{IC}$ the fracture toughness, $c_c$ the critical flaw size, and $Y$ a factor of order unity describing the flaw geometry) is obeyed if the particle size is taken to equal the flaw size $c_c$ (Fig. 5). In Maurer's case, a minimum flaw size of 0.1 $\mu$m (corresponding to a strength, $\sigma \sim 800$ MPa) was observed, while Sakaguchi found agreement even with the smallest particle size (0.03 $\mu$m). It is clearly essential to reduce contamination of the furnace from any source whether it be from the outside air or from flaking and spalling of furnace materials [32].

4) Huff and DiMarcella [29] and Donaghy and Nicol [14] have studied the strength decrease resulting from surface damage caused by particles mixed into the coating material. Fig. 6 shows the results of Huff and DiMarcello who find no strength reduction with particles of 1–3 $\mu$m in diameter, but a substantial, continuous strength degradation with particles in the ranges 6–10 $\mu$m and 15–20 $\mu$m in diameter. Donaghy and Nicol, however, find strengths of 1.2 and 1.0 GPa when particles of ~0.05 and 0.3 $\mu$m are used. Huff and DiMarcello indicated that coating adhesion is an important parameter in determining both the mechanism of damage and the extent of damage that occurs for a given particle size. It is clear then that a reasonable precaution is the filtering of the coating liquids prior to application and curing, as suggested by Miller *et al.* [52].

### C. Long Length Strength, Prooftesting, and Splicing

Fig. 7 shows a cumulative probability plot for long lengths of some high silica lightguide fibers taken from the literature. These data span the 12 years since Maurer's first data were published, the most recent distribution by Gulati *et al.* [22]. The 1965 results of Maurer were taken in 0.6-m lengths and are combined with 1-km prooftest data. These data have been transformed to an effective test length of 40 m and are plotted together with more recent data, also taken at, or transformed to, an effective length of 40 m. The high strength portion of these distributions at ~6 GPa has been argued by Kurkjian and Paek [43] to be intrinsic. At a gage length of 40 m, all except the very early data (curve 1) show this high/intrinsic strength mode. It is interesting to note that the newest data [22] show only this mode at least to 1-percent failure at this length. Two of the other high strength fibers (curves 2 and 3) show high strength modes for which the strengths are not quite as high and, more importantly, the variance in strength (~1.28/slope) is much greater. The lower strength may be rationalized on the basis of somewhat different measurement conditions (e.g., relative humidity and/or strain rate) or possibly slightly different fiber surface composition (e.g., $B_2O_3$ doped silica [49]). The values of strength variances however (10 and 18 percent, respectively), would seem much too large to correspond

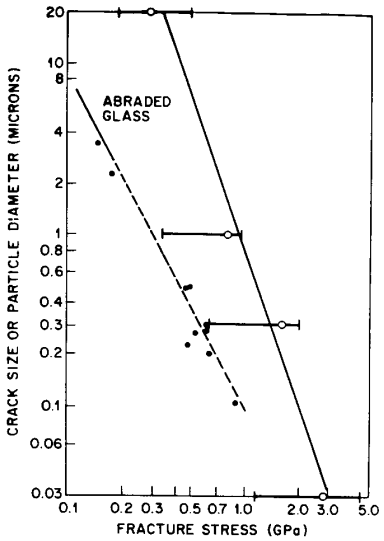


Fig. 5. Strength of lightguide fibers as a function of the size of crack or size of refractory particle responsible for failure. ● : [48] and ○ : [68].

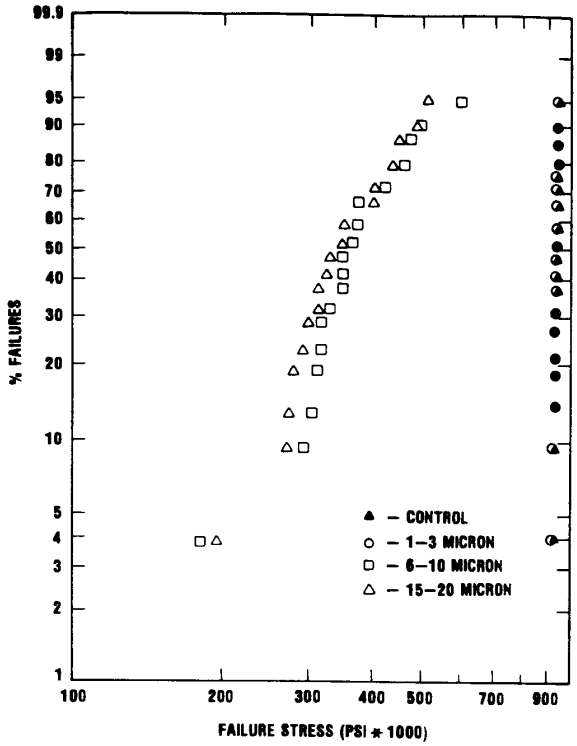


Fig. 6. Weibull probability plot for polymer-coated silica fibers. The polymer coating has been contaminated by $Al_2O_3$ particle of the sizes indicated [29].

simply to diameter fluctuations (variance (diameter) ≡ variance (strength)/2). It is suggested that these excessively large strength variances are due to combination of

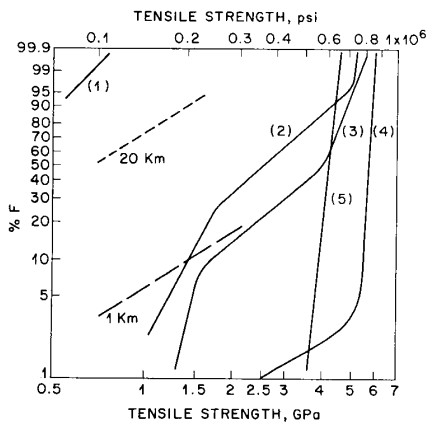


Fig. 7. Weibull probability plot for 40-m polymer-coated silica or lightguide fibers. (1): [47], (2): [25] (1982), (3): [66], (4): [12], (5): [22]. The low strength mode of curve (4) has been shifted to 1-km and 20-km gage lengths by ln ($L$/40).

experimental variables. Strengths less than this are collectively described as "extrinsic" for the reasons discussed above. An enormous improvement in quality has been made in 12 years. While less than 10 percent of Maurer's original fiber had a strength of more than 750 MPa in a 40-m gage length, each of the four newer fibers shown have a similar failure rate at about 5 GPa. Indeed, fiber number 5 may have no extrinsic flaws in a 10-km length.

Although the fiber quality has improved markedly, the demands have increased even more. For instance, for an undersea trial [5], it was required that gage lengths of 19 km pass a 1.2-GPa prooftest. With the fiber available at that time (curve 4), this corresponded to a failure rate of 90 percent, as shown by the dashed curve, Fig. 7. This very high failure rate may be avoided by joining the prooftested lengths, which will have no "flaws" weaker than 1.2 GPa. If these fibers can be fusion spliced at a strength greater than the prooftest then, although the initial "failure rate" will not be changed, the net yield will be 100 percent. It has been shown that splices can be made with no reduction in strength (i.e., 5.5 GPa) [38], using $H_2/O_2/Cl_2$ flame fusion or with strengths of 4.8 GPa using a modified oxy-hydrogen torch [39]. Alternatively, splice strengths in the 1.5 to 3 GPa range are readily attained by conventional oxy-hydrogen or arc fusion methods [54]. Fiber handled during splicing is then reproof tested together with the recoated splice to assure reliability of the span.

### *D. Flaw Character*

As mentioned, it has been suggested that the normal high strength mode found in a silica fiber is characteristic of a perfect, flaw-free surface. Credence is lent to this interpretation of the statistical behavior if the apparent crack size is calculated by means of the standard Griffith–Irwin equation (1). Failure of a sample with a crack of

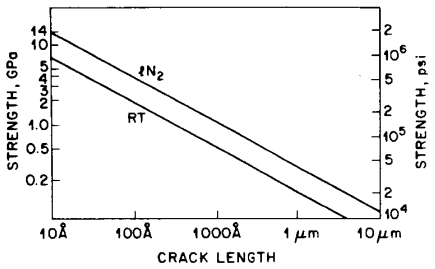


Fig. 8. Strength *versus* crack length calculated from (1) for strengths measured with (room temperature, 10 s) and without (liquid nitrogen temperature, independent of time) slow crack growth.

size $c_c$ will occur at liquid nitrogen temperatures when the applied stress is $\sigma$, independent of time or stress (or strain) rate. Failure of a similar sample will occur at room temperature in a water-containing ambient environment if the time of stress application is of the order of a microsecond. If the loading time is longer than this, failure will occur at some lower stress after the crack has grown at a slow, subcritical velocity and "fatigue" is said to have occurred. Then, if $K_{IC}$ for silica is 0.81 MPa $\cdot$ $m^{1/2}$ [76] and $Y = \sqrt{\pi}$, then if $\sigma$ = 14 GPa (the liquid nitrogen strength of a "perfect" fiber), $c_c \sim 1$ nm the size of a few silica tetrahedra. On the other hand, if a similar fiber is tested under ambient conditions, failure will occur at ~7 GPa in a testing time of ~10 s. In this case, the flaw will have grown from 10 to 35 Å for the fiber to fail at ~7 GPa. In the discussions of flaw sizes given here, the initial flaw size $c_i$ (calculated from the liquid nitrogen strength) will be quoted rather than the critical flaw size—that at which failure actually occurs (at liquid nitrogen temperatures $c_i = c_c$.). These are plotted in Fig. 8.

An interesting question arises if one considers the details of one of the apparently continuous strength distributions shown in Fig. 7. We have argued that no flaws exist in fibers with an ambient environment strength of ~6 GPa. On the other hand, it is quite clear that sharp cracks do exist and are responsible for failure at the 300 MPa strength level [9]. The correlations of particle size with crack size down to 0.03 μm argue that sharp cracks also exist to this level, though the correlation is marginal at the 0.03-μm level. In any case, at some sufficiently small particle size, sharp cracks will cease to be formed, yet a reduced strength (e.g., less than 6 GPa) will be observed. Several possibilities exist:

1) The entire fiber surface has a different composition with a lower intrinsic strength [63].
2) Regions of different composition are formed with resulting residual stresses, thus lowering the apparent strength.
3) Small impressions resulting from the indents result in stress concentrations.

None of these possibilities need give rise to cracks though at some stage of seriousness they may.

## III. The Strength Degradation

### A. High Strength Fiber

The intrinsic strength of silica lightguide fibers is 14 GPa. Under ambient environment conditions (temperature, $T \sim 25$°C, and relative humidity, $R_H \sim 50$ percent), the stress corrosion susceptibility factor $n$ (defined by the negative reciprocal of the slope of the log $t$ versus log $\sigma$ fatigue curve) of this fiber determined over a time from $10^{-3}$ to say $1.5 \times 10^7$ s (~6 months) is approximately 20. Given this information, is it possible to quantitatively predict the lifetime of a commercially available silica fiber under conditions expected in normal service? At the moment, the answer is almost certainly no. To anyone familiar with the mechanical properties of these fibers, this is not a particularly sensible question. On the other hand, it is not completely clear, even to so-called experts in the field, what are the relevant questions to ask. In this section, we will attempt to describe the problems associated with predicting the lifetime, or assessing the reliability of silica-based lightguide fibers, and suggest what additional information is needed. At the same time, we will try to provide some guidance to those who must make predictions, given the incomplete nature of the data and understanding at the present time.

### B. Fatigue

As indicated earlier, if a stress is applied to a sample containing a crack in an atmosphere containing water or water vapor, the crack will grow. If the crack is of critical size, that is if the product of the applied stress $\sigma_a$, and the crack severity (actually $Yc^{1/2}$) equals the fracture toughness $K_{IC}$, the crack will grow at its critical velocity (of the order of the sound wave velocity) and failure will occur essentially instantaneously. If a stress less than the critical stress is applied, the crack will grow at a subcritical velocity. The value of this subcritical velocity depends on the ratio of the applied to the critical stress intensity factor $\sigma_a Yc^{1/2}/K_{IC}$ or $K_I/K_{IC}$. Although the exact relationship between the subcritical crack velocity $v$ $K_I$ is not known, it is often assumed to be power function [17]:

$$v = AK_I^n. \tag{2}$$

It has been argued above that almost certainly the high strength (~7 GPa) as-drawn fibers have no "real" flaws and perhaps other weaker fibers have flaws which are not sharp. Even so, it has been common practice to describe and treat the flaws in these fibers as if they were sharp cracks. The justification for the implications of this will be discussed later.

As indicated in the introduction, in "reasonable" times (~6 months) and under "reasonable" environmental conditions, fatigue of the high strength mode is well-behaved (a good power law dependence). Although the details of the mechanism giving rise to the fatigue of this mode are not completely understood, it is clearly due to

a reaction of the following type:

$$-\overset{|}{\underset{|}{Si}}-O-\overset{|}{\underset{|}{Si}}- + H_2O \quad -\overset{|}{\underset{|}{Si}}-O-H \quad H-O-\overset{|}{\underset{|}{Si}}-.$$

Duncan *et al.* [16] have studied the behavior of the strength (and fatigue) as a function of both temperature and humidity. The following equations can be used to predict the failure strain $\epsilon$ (or stress) and fatigue susceptibility ($n$) as a function of relative humidity ($Z$) and absolute temperature ($T$):

$$\epsilon = 2.28\, Z^{-0.093} \exp \frac{2400}{RT} \tag{3}$$

$$n - 1 = -10 \Big/ \left[ -0.9 - 0.093 \log Z + \frac{2400}{2.3RT} \right]. \tag{4}$$

The results are summarized in Figs. 9, 10, and 11.

An improvement in fatigue resistance has recently been described by Gulati *et al.* [22]. Instead of consisting of pure silica, the fiber surface is doped with a small amount of $TiO_2$. While this results in a 20-percent reduction in short time strength, the improvement in fatigue resistance is impressive:

1) the $n$ value for static fatigue is increased from 34.6 for the standard fiber, to 130 for the new "Titan" fiber;
2) the $n$ value for dynamic fatigue shows an increase (22.5 to 29.5) though not as striking; and
3) the "knee" to be described in the following section, is not observed after 170 days in 80°C water.

Although these results are not completely understood, they hold great promise for substantial system improvement.

### C. Fatigue "Knee"

The discussion so far has been concerned with ordinary conditions, at temperatures of 25–50°C in air or water, and the fatigue or aging tests have been carried out for reasonable times, say 100 days. Under more severe environmental conditions, say 90°C distilled water or at higher values of pH ( >7), a "knee" in the log $\sigma$ versus log $t$ plot occurs and a rather precipitous decrease in $\sigma$ with $t$ occurs and the value of $n$ falls from its more usual value of ~20 to a value around 5. This knee originally was observed by Wang and Zupko [75] at 32.6°C and 90 percent relative humidity, but under these less severe conditions, the knee appears at much longer times. Several other investigators have verified this behavior, and shown that its existence is strongly influenced not only by temperature, relative humidity, and pH, but perhaps even more so by the presence or absence and type of coating [6], [36], [46], [64], [71]. Fig. 12 summarizes some of these results. In those situations where the knee is observed there seems to be some disagreement as to the effect of temperature [40]. Certainly, the possibility of this knee occurring must be kept in mind when predicting life-

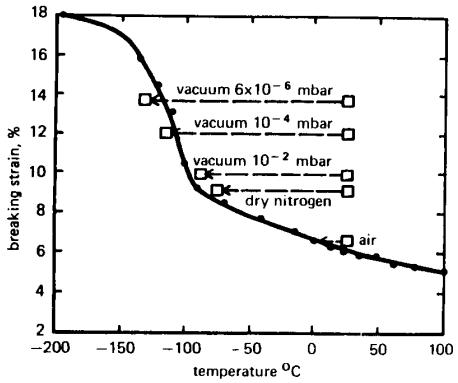


Fig. 9. Strength of silica fiber at different temperatures and humidities. ●: Strength in 100-percent $R_H$, □: strength at 20°C and low humidites, □: humidity data replotted as dewpoint temperature. From [16].

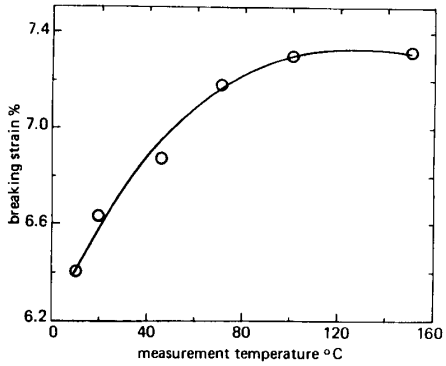


Fig. 10. Strength of silica fiber in an environment of constant moisture content. From [16].

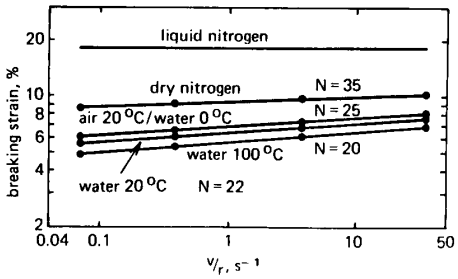


Fig. 11. Dynamic fatigue on silica fiber. From [16].

times. Also, since it appears to be so strongly influenced by the chemistry of the coating, it is clear that more work needs to be done both on understanding the reason for this major coating effect and in developing a coating material that removes the knee, or at least postpones it for very long times.

This knee behavior has only been observed in high strength fibers. A possible explanation suggested by [10] is that the knee is the result of crack "pop-in." However,

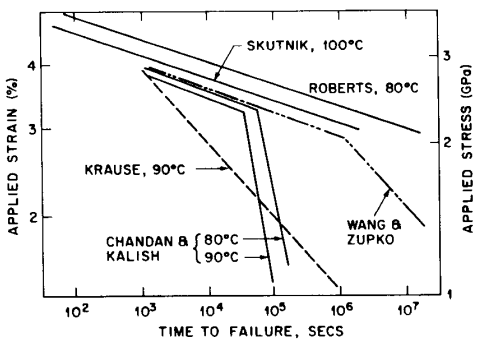


Fig. 12. Static fatigue of silica fiber in water at temperature indicated, except for [75]—$R_H$ = 90 percent, $T$ = 32.6°C. Krause [37] fiber stripped of coating, Chandan and Kalish [6] polyurethane-acrylate coating, [75] epoxy-acrylate coating, Roberts *et al.* [64] two-layer silicone coating, Skutnik *et al.* [71] fluorinated acrylate coating.

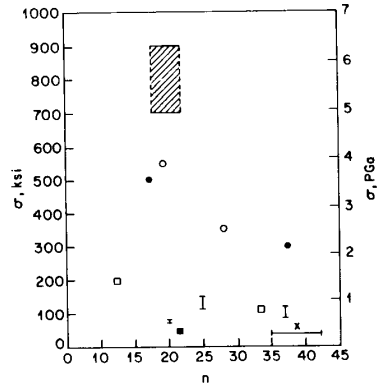


Fig. 13. Strength fatigue susceptibility ($n$) plots. Data and references in Table I.

Matthewson and Kurkjian [46] show that extrapolation of pop-in data [57] gives times to pop-in of $\sim 10^{12}$ s under conditions that show a knee at $\sim 10^6$ s. Further, they argue that there would need to be unreasonably large number of flaws of the type that lead to pop-in in order to produce the knee observed for their bend-test specimens which only have an effective tested length of tens of micrometers.

### *D. Low Strength Fiber: $\sigma < 300$ MPa*

At the other end of the strength distribution, at least where the short-time room temperature strength of "fresh" cracks is 300 MPa or less, the fatigue is probably once again well behaved, but this time $n \sim 35$–40 [10], [67]. Again, these data are taken under moderate time and environmental conditions. The reason for the $n = 20$ and $n = 35$ for the high and low strength modes, respectively, presumably has to do with the absence or presence of real stress-concentrating cracks in the two cases.

### *E. Intermediate Strengths: 300 MPa $< \sigma <$ 1.5 GPa*

While it seems relatively clear that samples having strengths less than 300 MPa contain true cracks (e.g., post-threshold flaws in the Dabbs and Lawn nomenclature), apparently, one reason for strengths of the order of 600 MPa is the presence of stress-concentrating indents without the presence of true cracks. This is shown by the data of [10] and also presumably is the reason for a value of $n \sim 20$ measured in [8].

The literature contains many $n$ values estimated from various kinds of strength test, both static and dynamic, on various kinds of silica fibers and rods as well as from subcritical crack velocity measurements on macroscopic fracture mechanics samples. Tabulations of this sort have been given in [20], [25], [42], [49], and [62]. In both [53] and [33] it is argued that there should be, and is, a relationship between $\sigma$ (or $A$ in equation (2)) and $n$. Thus, the available data on silica have been plotted in this way in Fig. 13 and listed in Table I. It can be seen that although the high strength data are reasonably well behaved (except for the knee which is not included), $n$ values for samples with strengths less than about 2 GPa result in a scatter plot: Thus, if $n = f(\sigma)$, it is not a single-valued function. A review of Section II-A on flaw sizes may provide a possible explanation. We suggest that a variety of flaw sizes and shapes, as well as a variation in residual stresses and inert strength (due to impurity inhomogeneities), results in a similar variability in fatigue behavior.

### *F. Fatigue Limit*

It has been proposed by several workers that a fatigue limit should exist [7], [51], [55]. It is suggested that no degradation occurs below this level of stress, and in fact strengthening should be possible. While in soda-lime glass there is reasonable evidence for such a limit [51], such is not the case for silica. Although there is some suggestion of strengthening of low strength samples, it is not clear if this is associated with crack healing or blunting or if it reflects a relaxation of residual stress. While the existence of this is of considerable scientific interest, it is not clear if it is practically important. In Fig. 14, we have sketched the behavior of fibers fatiguing with $n = 20$ or $n = 40$. It has been suggested that the fatigue limit might be expected at a stress in the neighborhood of $\frac{1}{3} - \frac{1}{5}$ of the intrinsic strength [56]. In Table II we have listed the liquid nitrogen strength $\sigma_{N_2}$ (calculated at $t = 10^{-7}$ s), the ambient environment strength $\sigma_{RT}$, taken on a 10-s time scale, the fatigue limit strength $\sigma_{FL}$, taken as $\frac{1}{3}$ of the intrinsic or liquid nitrogen strength, and the 20-year strength $\sigma_{20\text{yr}}$, at $6 \times 10^8$ s. With fatigue occurring with $n = 20$, the fatigue limit strength $\sigma_{FL}$ is reached at $t_{FL} = 10^7$ s ($\sim 100$ days). These values are within 20 percent of the 20-year strengths. With fatigue occurring at $n = 40$, on the other hand, the 20-year strengths are twice as great as the fatigue limit strengths which are not shown in the figure since they occur at $t = \sim 10^{22}$ s ($\sim 10^{14}$ years). Thus the discussion as to the existence of a fatigue limit seems as though it may be irrelevant since it may only be reached at quite long times. It is also of interest to note that the 20 year strength is 40 percent of the room temperature

TABLE I

| Reference | Strength Level GPa | Strength Level ksi | $n_s$ | $n_d$ | Remarks |
|---|---|---|---|---|---|
| [ 8] | 0.35 | 50 | 21.5 | | Abraded, $Al_2O_3$ slurry |
| [21] | 0.55 - 0.85 | 80-120 | | 36.8 | |
| [67] | 0.2 | 30 | 35.6 | 42.6 | Abraded with Emery paper |
| [61] | 0.05 - 0.1 | 7.5-15.8 | | 37.8 | Abraded rods |
| [14] | 0.5 - 0.6 | 70-85 | | | $Al_2O_3$ particles in coating |
| [25] | 3.5 | 300 | | 17 | Commercial fiber |
| | 2.1 | | 37.6 | | |
| [72] | 8-1 | 110-150 | ~25 | | 13% $B_2O_3$ |
| [31] | 0.55 | 115 | 12.5 | | |
| | 1.4 | 200 | 33.6 | | |
| [15] | 3.85 | 550 | 18.9 | | |
| | 2.45 | 350 | 28 | | |
| [24] | 2.1 | 300 | | 15 | Natural Flaws - |
| | 3.5 | 500 | | 19 | Probably borosilicate jacket |
| [16,59] | 5-6.3 | 700-900 | 20 | 20 | High strength fiber |
| [65,67,76] | | | ~40 | ~40 | Crack velocity |

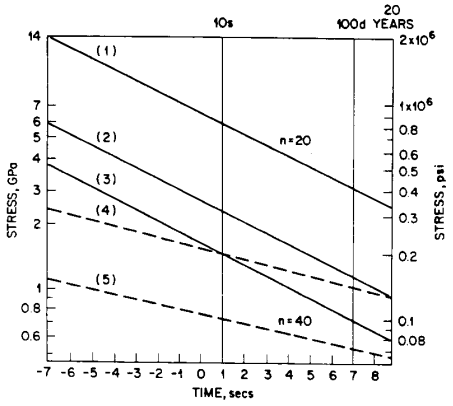


Fig. 14. Schematic stress versus time plot for two values of fatigue susceptibility, solid line $n = 20$, dashed line $n = 40$. Data and references in Table II.

TABLE II

| | Curve # | $\sigma_{fN_2}$ GPa (ksi) | $\sigma_{RT}$ GPa (ksi) | $\sigma_{FL}$ GPa (ksi) | $\sigma_{20yr}$ GPa (ksi) |
|---|---|---|---|---|---|
| $n = 20$ | 1 | 14 (2000) | 5.6 (800) | 2.8 (400) | 2.3 (330) |
| $t_{FL} = 10^7$ s | 2 | 5.6 (800) | 3.5 (500) | 1.12 (160) | 0.91 (130) |
| = 100 days | 3 | 3.5 (500) | 1.4 (200) | 0.7 (100) | 0.56 (80) |
| n = 40 | 4 | 2.1 (300) | 1.4 (200) | 0.42 (60) | 0.875 (125) |
| $t_{FL} = 10^{22}$ s | 5 | 1.05 (150) | 0.7 (100) | 0.21 (30) | 0.455 (65) |
| $= 10^{14}$ years | | | | | |

strength for $n = 20$ and 65 percent for $n = 40$. The assumptions involved in these calculations are, of course, that the strength at liquid nitrogen temperatures can be estimated by extrapolating to $t = 10^{-7}$ s and that the fatigue is a power function from $10^{-7}$ to $10^9$ s. This is clearly not the case if a knee appears. This calculation has been used only to illustrate certain factors and is suggested as a valuable exercise, along with other calculations, in trying to evaluate lifetimes.

### G. Aging and Fatigue

The models suggested by both [18] and [25] to account for a fatigue curve which is not a power function on the one hand, or which gives different values for $n$ for static and dynamic fatigue on the other, are similar although they attempt to explain different trends. They postulate that aging and crack growth occur simultaneously but at different rates. However, while crack growth, as shown by measurements of subthreshold crack growth, can be adequately represented by a power function, perhaps aging may not obey a power function, and may, for instance, show a linear relation. However, Krause [37] and Matthewson and Kurkjian [46] have shown that aging and fatigue show similar behavior, though perhaps the fatigue is shifted to shorter times due to the effect of stress enhancement. Thus considering them as separate phenomena seems inappropriate and aging should perhaps be considered as the limit of fatigue as the applied stress approaches zero.

### H. Hermetic Coatings

It has been pointed out above that not only does strength degradation occur at a relatively rapid rate due to interaction with water, but more importantly, its exact behavior is uncertain and unpredictable. Because of this it is extremely important that coatings be developed which

TABLE III
HERMATIC COATINGS

| Coating Material | Ave. Strength Ambient, GPa (ksi) | | n | Reference |
|---|---|---|---|---|
| Al | 6.3 | (900) | ∞ | [58] |
| In | 3.5 | (500) | 32 | [69] |
| SiON | 2.8 | (400) | 100 | [27] |
| HP[2] unspecified | 3.9 | 550 dynamic 45 static | 500 | [28] |
| $Si_xO_yC_2$ | - | 47.256 | | [23] A range of composition in patent. No strength values quoted. |
| $Si_xO_yN_zC_{(1-x+y+z)}$ | - | 40.330 | | |
| C | - | 8 | | |
| C | 4.2-4.6 | (600-650) | 23-25 | [60] |
| SiON | 1.4-1.75 | (200-250) | 90 | |
| C-SiON | 2.1-2.8 | (300-240) | 70 | |
| SiC | 2.8-3.5 | (400-500) | 90-95 | |
| TiC | 2.5-3.2 | ( 90-100) | 90-100 | |
| C-TiC | 3.2-3.5 | (450-500) | 90 | |
| C | 3.5 | (500) | 110 | [45] |
| C | 4.2 | (600) | 200 | [13] |

isolate the fiber surface from the environment. Several of these so-called "hermetic" coatings have been described in the literature. These, as far as their compositions are known, are listed in Table III. Although details of the manner in which these coatings affect the fiber strength and fatigue properties are not known, the following models may be proposed.

In the case of metal-coated fibers, or at least aluminum, a real hermetic seal is probably formed. In general, the strengths of these fibers are somewhat less than those of polymer-coated fiber presumably because of coating reactions with the silica surface.

Inorganic coatings (SiON, SIC, TiC, etc.) are desirable since they are stable toward most environments—HF as well as most common acids and bases, steam, etc.. A disadvantage, however, is that in every case known to the authors substantial lowering of the measured strength is observed—levels of 2.5–3.5 GPa are normal. On the other hand, quite reasonably high values are quoted for $n$, though the validity of some of the quoted values may be questioned. In particular Hiskes *et al.* [28] have shown data for an unspecified coating (probably SiC) in which the $n$ value measured by static fatigue is 45 while the $n$ value under dynamic fatigue is 500. The failure mode of fibers coated with these materials is not known. It might be supposed that they are brittle, have higher moduli and are physically less perfect than silica and are impermeable to water. Because of this, it might be expected that the coatings will experience brittle failure before the silica fiber. Any failure of the coating can cause failure to propagate through the fiber since a fracture in the coating will concentrate stress at the silica surface. The extent of this concentration is determined by the size of the fracture in the coating which is limited to the coating thickness, thinner coatings therefore produce less severe stress concentrations than thicker ones, though the thinness may compromise the coating's hermeticity. Alternatively, if the interface is weak then a fracture in the coating may propagate along the interface rather than through the fiber. Kendall [35] considers the energy involved in crack propagation both across and along an interface between two similar materials and finds a transition from cohesive to adhesive failure when the interfacial strength falls below some critical fraction of the cohesive strength. Clearly a weak interface promotes interfacial failure which reduces the stress concentrations at the fiber surface, however, any such interfacial failure could lead to exposure of large areas of the fiber surface to the environment, again compromising hermeticity. Therefore the design of a coating in terms of its thickness and adhesion is a compromise between strength and hermetic properties. The optimum design is yet to be established.

Recently, hermetic carbon coatings have been developed at AT&T Bell Laboratories [13] as well as at Corning Glass [45]. These coatings appear to have the desirable qualities of the inorganic coatings while not suffering such severe initial strength reduction. A possible reason for this is that the carbon coating probably has a lower modulus and thus experiences a smaller stress than the silica fiber at the same strain.

There hermetic coatings hold great promise for providing adequate strength under severe environmental conditions. However, as far as the authors are aware, a simple in-line proof testing procedure for hermeticity has not yet been developed. Since even the presence of the smallest defect in the hermetic coating can have a profound effect on long-term strength, a proof test would seem to be of considerable importance to the general acceptance of these coatings.

## IV. SUMMARY

Enormous progress has been made in the development of long-length high-strength fibers. The development of

high strength fusion splicing techniques essentially allows any strength level to be chosen.

Fatigue and aging occur as a result of the reaction of silica with water. The details of the time dependence are not known and firm extrapolations are not possible.

A promising development is the appearance of several "hermetic" coatings, although detailed data are lacking. The development of a simple on-line prooftesting procedure for hermeticity is desirable.

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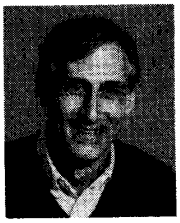

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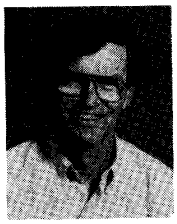

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During the following year he was a Research Assistant in the Department of Physical Chemistry at the University of Oslo, Norway, before joining Bell Laboratories, Murray Hill, NJ, in 1956. His research has included studies of the acoustic and acoustooptic properties of ceramics and glasses and the development of specialized glasses for isopaustic and acoustooptic devices. He is presently a Member of the Technical Staff in the Glass Research and Development Department and is currently involved with the mechanical properties, the strength, and the static fatigue characteristics of glass optical fibers. His recent work has been in the area of fiber splices where he is co-inventor of a process for achieving intrinsic splice strength through a novel flame fusion process. Current activities have focused on hermetic fibers and splices as well as on other fatigue resistant fibers.

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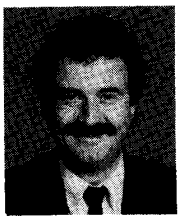

**M. John Matthewson** received the B.A. degree in theoretical physics from Cambridge University in 1975. He received the Ph.D. degree from Cambridge in 1978 for work on the subject of impact erosion and fracture. He continued his work on this area as the Goldsmiths Junior Research Fellow at Churchill College, Cambridge University.

He spent two years at AT&T Bell Laboratories as a Postdoctoral Member of the Staff before moving to the Magnetic Recording Institute at the IBM Almaden Research Center in San Jose in 1986. He has been an Assistant Professor in the Fiber Optic Materials Research Program at Rutgers University since March 1989 and is working on mechanical reliability issues for optical fibers.