Reliability of Hard Plastic Clad Silica Fibers

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ABSTRACT

New formulations of cladding materials have become available in recent times for Hard Plastic Clad Silica (HPCS) fibers, Initial data showed gains in some properties, particularly dynamic strength, especially for high numerical aperture (NA) fibers. A systematic study has been undertaken to determine the full strength and fatigue behavior of these HPCS fibers and to make comparisons to earlier HPCS fibers. Preliminary results, now confirmed, has shown improved median dynamic strength and higher Weibull slope. Full results are presented below including fatigue behavior and optical properties. These fibers have many applications and benefits in the high power delivery and medical laser uses as highlighted below. High power diode laser systems with their laser diode bars and arrays not only require special fibers to couple directly to the diode emitters, but also require special fibers to couple from the laser to application sites. These latter power delivery fibers are much larger than the internal fibers but still must be flexible, and have not only good strength but also good fatigue behavior. This particularly important industrial systems using robotic arms to apply the high power laser energy at a treatment site. The optical properties of HPCS fibers are well suited for the needs of the delivery of high power from diode laser bars and arrays to an application site. Benefits of strong median dynamic strengths and tighter flaw distributions in such cases will be discussed. Many medical applications, especially endoscopic ones, can benefit from the use of highly flexible, high NA, cost effective, HPCS optical fibers. Benefits of high strength and good fatigue behavior for such fibers in endoscopic procedures, including laser surgery, are discussed briefly including implications for mechanical reliability in medical and industrial settings.

1. INTRODUCTION

A number of the properties of HPCS fibers make them very desirable for medical applications, both for in-Vivo sensing/endoscopy and for laser surgery. These are summarized in Table I for the common advantages. High core/clad ratios, low loss, small/large core sizes and broad transmission window are of value for different reasons in each of the application areas. Numerous papers, primarily by Ensign-Bickford and by 3M at SPIE meetings, have presented and discussed how the different properties are important in various medical applications[1-10].

It has been over 25 years since the invention of the class of Hard Plastic Clad Silica (HPCS) fibers by one of us. In the early experiments and developments availability of low index compounds which remained low upon curing was not great. Thus in developing the higher Numerical Aperture (NA) fibers some compromises were struck to achieve NA of about 0.45-6. Different developers had different materials to drawn upon. Some introduced combination cures leading to upper limits of about 0.43-44 NA values. Others worked on developing prepolymers for cladding compositions. Optically all approaches seemed to lead to good results. In many cases though the higher NA fibers often were not as rugged or mechanical reliable as the standard NA fibers. Status of this early work by the various groups was summarized at an American Chemical Society program in 1999[11]. In the past several years additional suppliers and developments

In the biosensing/endoscopic applications, for example, there are three areas where limitations become evident. A large NA is advantageous for these applications, however, in the past, for the higher NA HPCS fibers, the hardness, wear resistance and overall robustness were typically reduced from that of the "standard" NA product, making these fibers more susceptible to damage from handling. Developments in improving these aspects are demonstrated by the results presented below.

Smaller dimensioned optical fibers also permit the use of smaller catheters enabling associated surgery procedures to be less invasive. Small systems also can require broader illumination from optical fibers which may be minimized in number and/or in size as well. Some benefits in industrial applications are mentioned in the discussion section below.

In this paper we describe newer products, which address reliability and reproducibility of the spectral behavior particularly in the VIS-NIR regions. Strength/reliability results are presented below showing the latest information on HPCS fibers from our company's Optran[12] fiber optic line, especially featured are the High NA versions of the HPCS.

2. EXPERIMENTAL

The fibers used in the experiments referred to below were drawn using essentially standard techniques. The basic core/clad structure employed a pure undoped silica for the core and a proprietary hard plastic cladding, HPCS fibers as a class. High-OH fibers typically have $\geq$600 ppm of OH, while low-OH fibers typically have <2-4 ppm of OH. The emphasis in this paper is on the low-OH HPCS fibers. The NIR and VIS spectral losses of low-OH HPCS fiber with nominal core diameter for both types was 600 µm.

A "cutback" method was employed using a Monolight Optical Spectrum Analyzer (OSA), manufactured by Macam Photometric Ltd of Livington, Scotland. The system includes a scanning monochromator, a 3-channel controller, a power supply, two light sources (deuterium and tungsten), and input and output blocks to handle fiber from 70 µm to 1000 µm in diameter.

The "cutback" method consisted of using two pieces of same-type fiber with a length ratio of about 1:4 or 1:5. Long lengths of over 25 m were measured via a Tektronix ODTR, and shorter lengths were manually calculated (i.e. the number of loops were counted and multiplied by Π times the diameter of the spool.) The "cutback" length (in meters) was calculated by subtracting the shorter length from the longer length of fiber. More complete details on the spectral measurements were reported earlier[13].

The numerical apertures for the different fibers in this study were made using a set up which involved taking diameter measurements of the projections onto a black surface shielded from direct ambient light at five different distances from the fiber end. A white light source was over-launched and overfilled into the input end of the fiber. Meter long samples were used with about a 180 degree angle bend relative to the output end. The bend radius was on the order of a 40-50 cm. The ends were secured to metal blocks to guarantee stability of placement during testing and to improve reproducibility. NAs calculated at the five distances were averaged to yield the reported NA.

The primary mechanical property reported is the dynamic strength as measured by a universal testing machine and plotted on a Weibull plot. Gauge length was 1 meter. The fiber is stretched while horizontal and anchored at the two ends by wrapping several loops around a tapped mandrel of approximately 10 cm diameter. About 1.7 meters of fiber is consumed per trial. Results

presented below are generally from one or two fibers where 15-20 samples are taken from a specific fiber run. Tests were made at ambient temperature and relative humidity. Temperatures ranged in the 20-27 C, and relative humidity [RH] primarily was 30% ± 7%, although some samples were tested with RH at 72%. Strength data are plotted according to the generally accepted Weibull approach.

Additionally the static fatigue behavior has been measured also. Tests use half meter gauge lengths with the fiber wrapped snuggly around a metal rod, anchored at the ends with waterproof tape. The wrapped samples are then immersed in room temperature water and the time to failure is recorded. Typically at least five fiber samples are measured for each rod diameter, i.e. bending stress level. Affects of fiber jacket thickness are incorporated into the stress calculations. The data are plotted based on the power law, which is still the most generally accepted approach to presenting static fatigue data.

3. RESULTS

Figure 1 shows the typical spectral loss of standard, low-OH HPCS fiber (HWF) with core/clad geometries of 600µm/640µm and a numerical aperture (NA) of 0.37 (standard NA) from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the 'standard' hard plastic cladding.

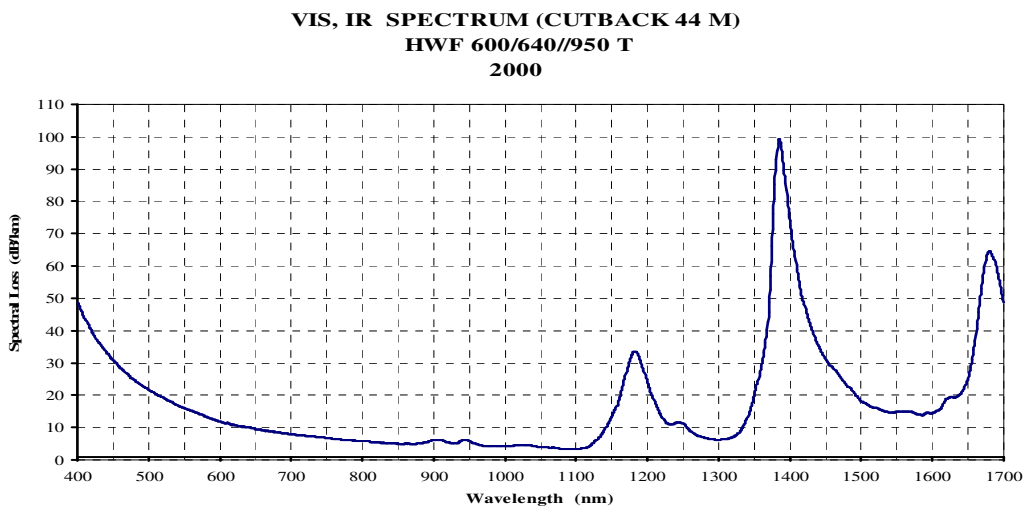

Figure 1: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.37

Figure 2 shows the typical spectral loss of standard, low-OH HPCS (HWF) fiber with core/clad glass geometries of 200µm/230µm and the new high numerical aperture (NA) of 0.48 from the wavelengths 400 nm to 1700 nm. This fiber has pure undoped silica as the core material and the 'Hi NA' hard plastic cladding. Jacketing is same material and relative thickness as for the standard NA HPCS fiber.

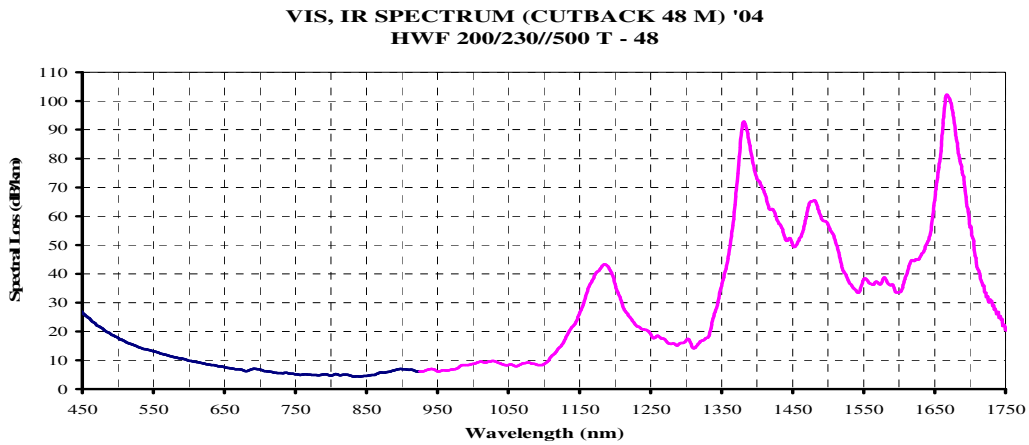

Figure 2: Full spectrum (VIS, NIR) low-OH fiber, NA = 0.48

In the next series of spectra, transposed onto the same grid, we demonstrate the relative stability of the spectra for the Optran Hi NA HPCS fibers by comparing in Figure 3 three fibers using different core glass lots and the same hard plastic cladding lot. Note that the jacketing material here is a nylon not Tefzel® and the jacketing is much thinner than for fibers in the prior two figures. Both these points lead to many of structural differences observed in the NIR region versus the prior figures. Also note that the run with the lowest near uv losses also has the highest peak at 1385 nm, indicating somewhat more OH in that silica rod than the other two. Otherwise little difference is seen between the three runs with three different silica cores.

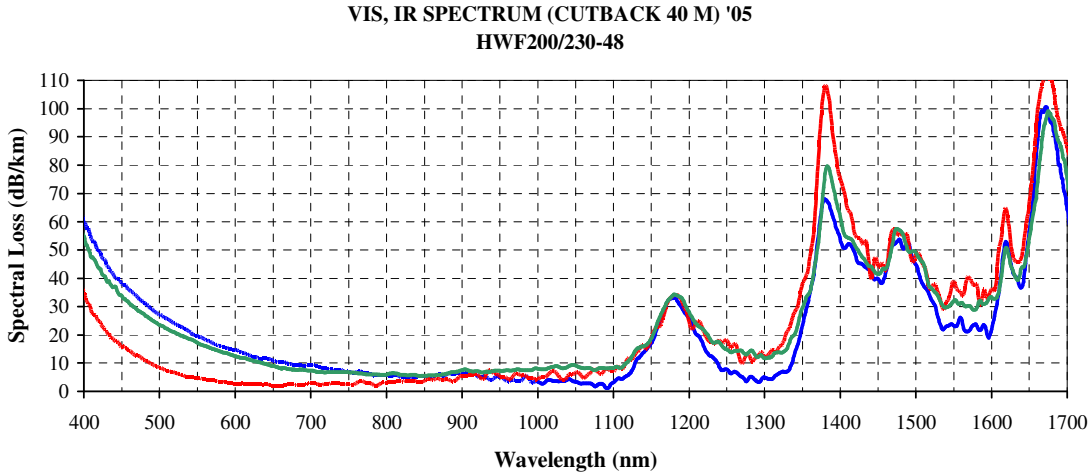

Figure 3: Overlaid spectrums three lots of low-OH fiber, NA = 0.48

In the next figure, Figure 4, we present spectra collected on the Monolight spectrometer for Optran Hi-NA And compared to results obtained for the similar fibers from two competitors. The variations in the NIR region may be attributable to the detailed chemical differences between the 'flavors' of HPCS[14] by the different providers.

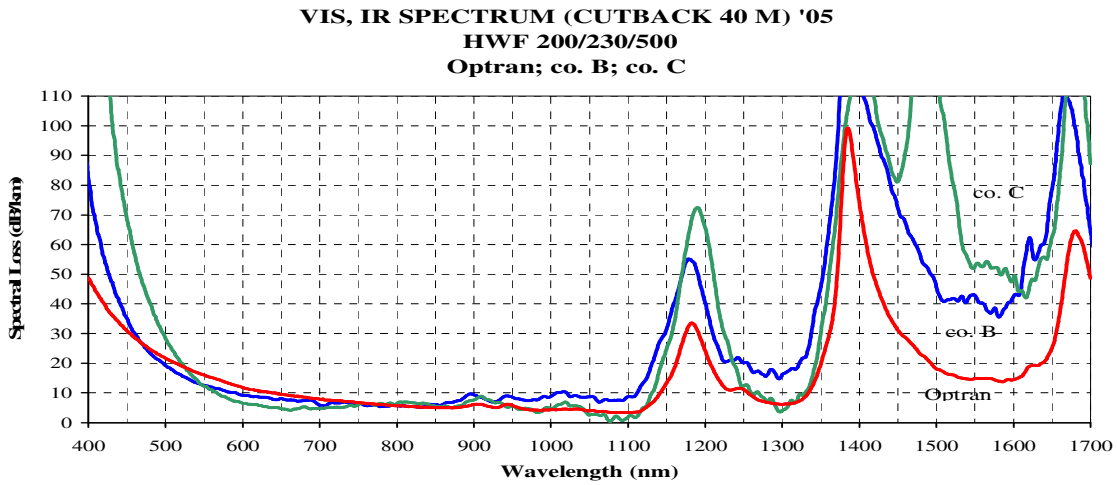

Figure 4: Overlaid spectra, Optran and competitor of HPCS fibers.

As a measure of the mechanical reliability of these fibers, we present dynamic strengths measurements for fibers made over a 5 year period and including a fiber tested and retested during this period. In Figure 5 the Weibull plot compares fibers drawn in 1999 [left points black], and in 2004 [right points, shaded].

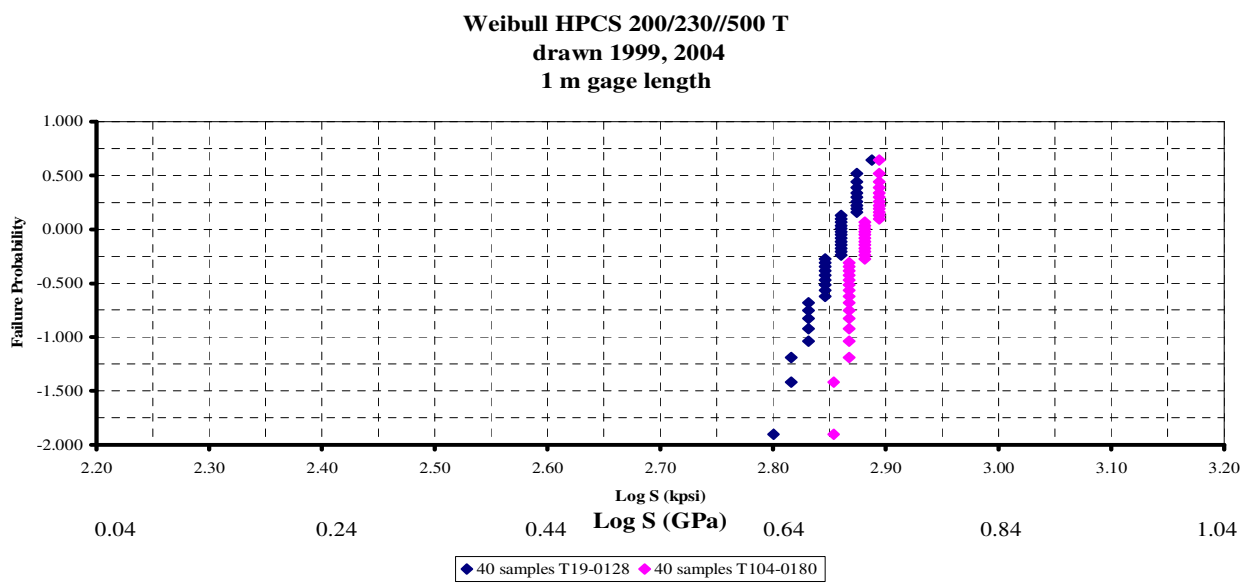

Figure 5: Weibull Plot of std. Optran HPCS fiber; drawn '99[left], drawn '04[right]

In Figure 6, the Weibull plot compares strength for a fiber drawn in 1999, tested in 2000 [diamonds] and again in 2004 [shaded boxes] after storage in varying humidity (10-80% RH) on spools under about 0.1 GPa (15 kpsi).

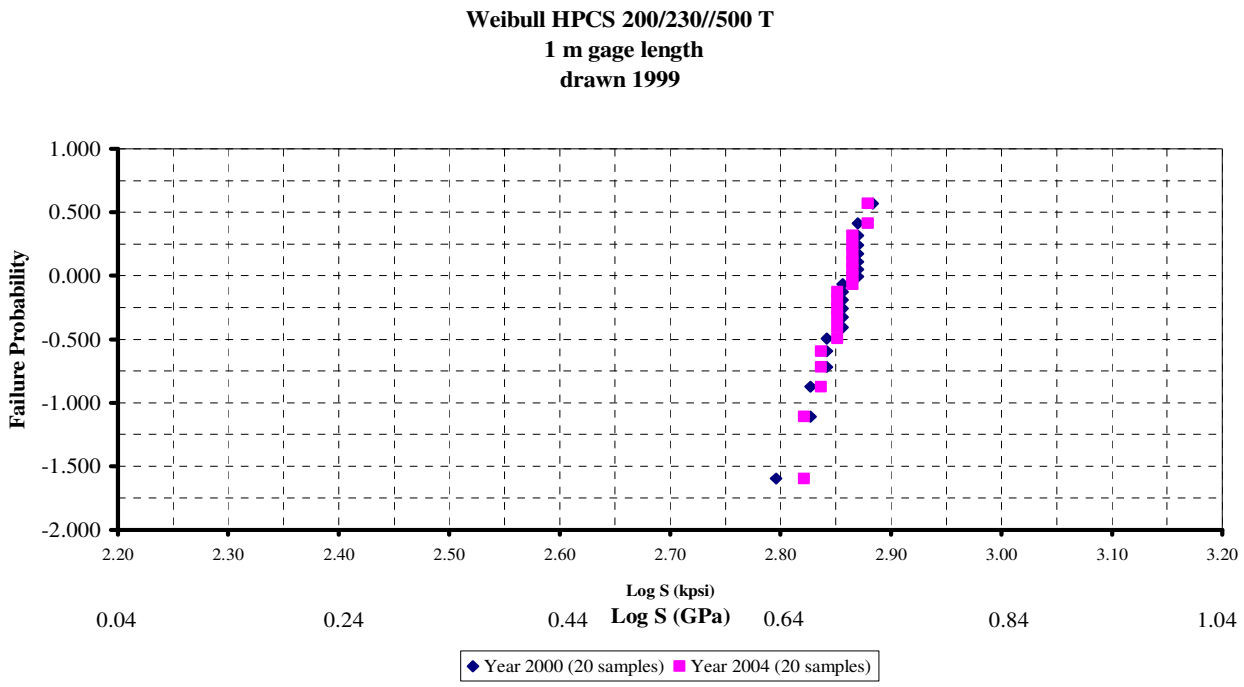

Figure 6: Weibull Plot of std. Optran HPCS fiber; test '00[diamond], test '04[box]

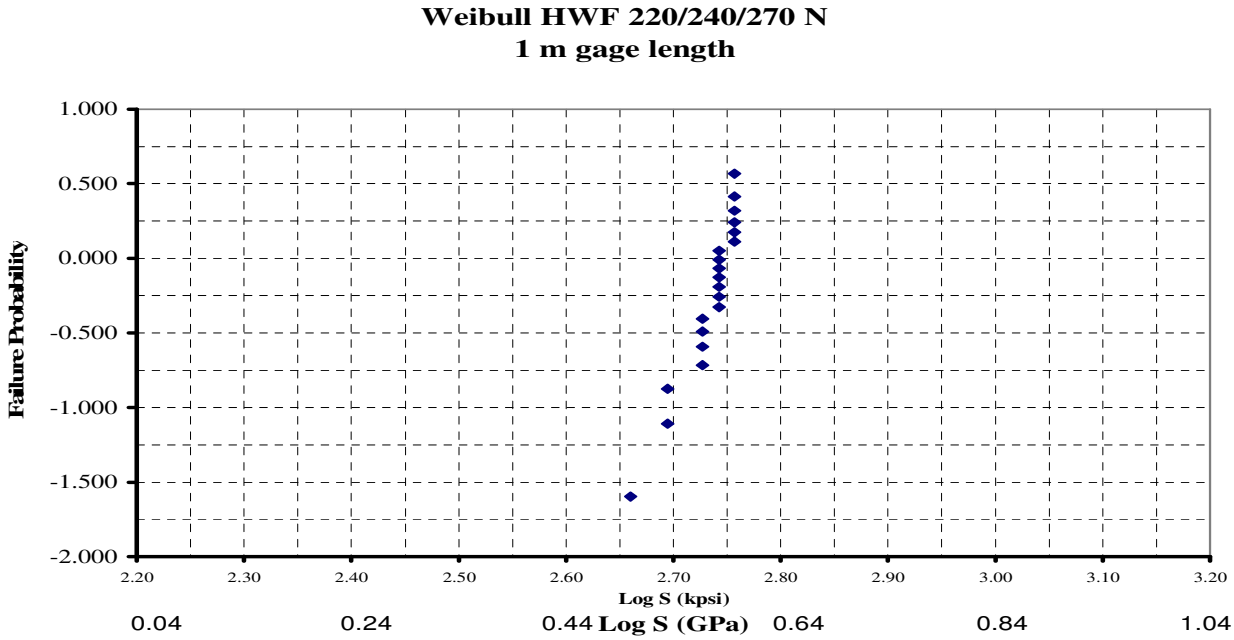

Figure 7: Weibull Plot of 0.48 NA Optran HPCS fiber with ultra-thin nylon jacket

Figure 7 presents a Weibull plot of the new high NA HPCS fiber, but with a very thin nylon jacket. Whereas the earlier graphs were for fibers jacketed with about 135 µm thick Tefzel (® DuPont) this fiber has only about 10 µm thick nylon as its jacket. Not shown here but high NA

Optran HPCS fibers with standard Tefzel jackets had Weibull plots essentially the same as for the standard NA HPCS fibers as shown in Figures 5 and 6.

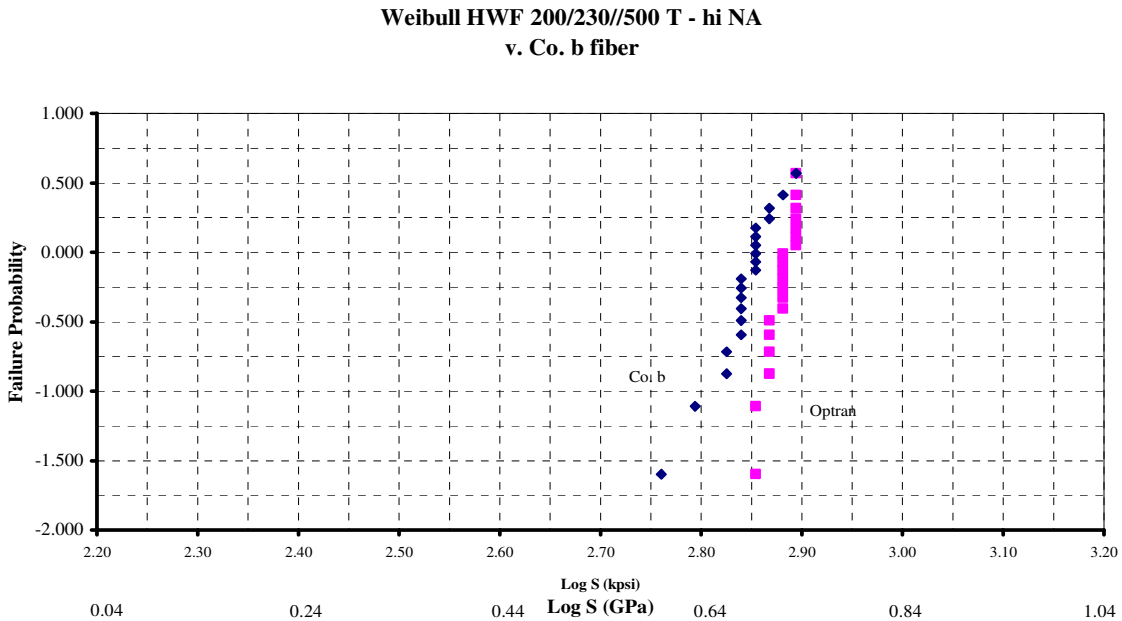

Figure 8: Weibull Plot of Hi NA HPCS fibers with std. thick Tefzel® jacket from Co. b and CeramOptec

A Weibull plot for a competitor's 0.44 NA fiber with the standard 140 µm thick Tefzel jacket is presented in Figure 8, alongside a plot for and Optran Hi NA HPCS fiber of similar construction. Shows at least equivalent strength behavior for the new high NA HPCS fibers as compared to other such fibers now available commercially.

In Figures 9.10 and 11 data representing the time to failure of wound samples of the 0.48 NA HPCS fibers with 20 µm thick nylon jacketing; of the 0.44 NA HPCS fibers with the 140 µm thick Tefzel jacketing, made by Co. b; and of the 0.37 NA HPCS also with the 140 µm thik Tefzel jacketing, made by Co. c, respectively. The 0.48 NA HPCS fiber in Figure 9 corresponds roughly to the fiber whose dynamic strength data were presented in Figure 7 above. The 0.44 NA HPCS of Co. b in Figure 10 corresponds roughly to the fiber whose dynamic strength data were presented in Figure 8. Actual fiber breaks and the average time to failure points for a given stress are plotted on the same graph in Figure 9. For the other two graphs only the time to failure of actual fiber breaks are plotted.

These tests are ongoing with only the short to medium time failures recorded thus far. While the strength for the thin nylon jacketed fibers is lower than for the thick Tefzel jacketed fibers, the Static Fatigue Constant, N_S, is the same or better for the thin nylon fibers (~22) than for the thicker Tefzel fibers (~20 and ~17 respectively). Longer term data may be presented at future symposia.

Finally in the last two figures, Figures 12 and 13, are data for exposure of up to about 6-7 hours of boiling water for samples of the high NA fibers by CeramOptec, Figure 12, and by Co. b, Figure 13. Beyond about a working day, there are problems in how to keep the fibers overnight. Maintaining boiling water for over 12-15 hours is very difficult, thus these tests rarely last longer than a day.

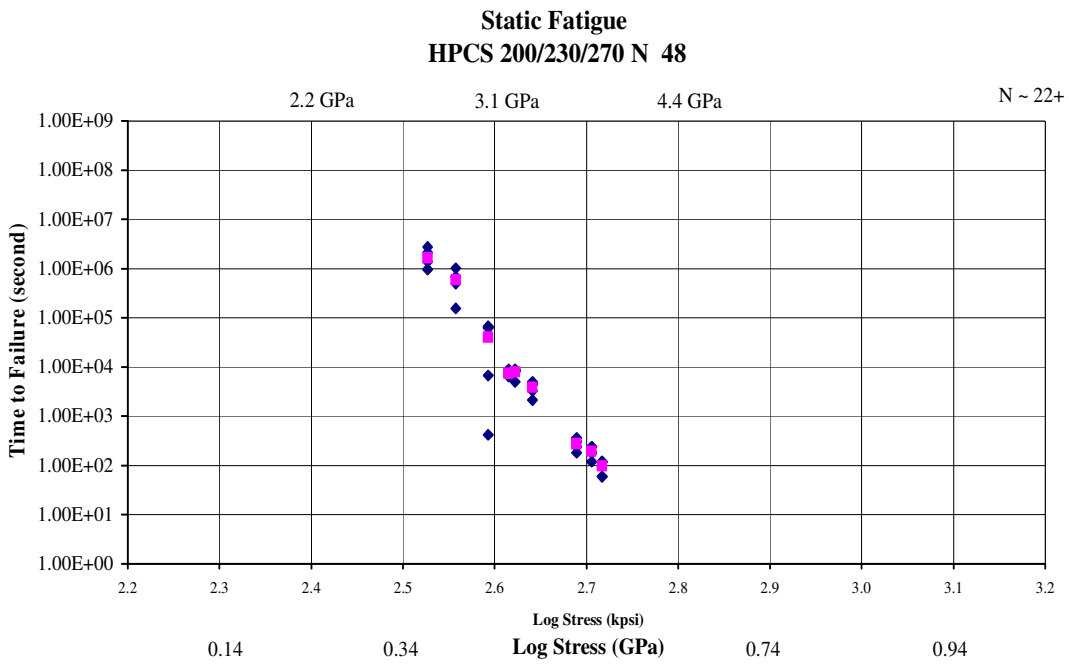

Figure 9: Power law plot of Static Fatigue for HPCS fiber, NA = 0.48

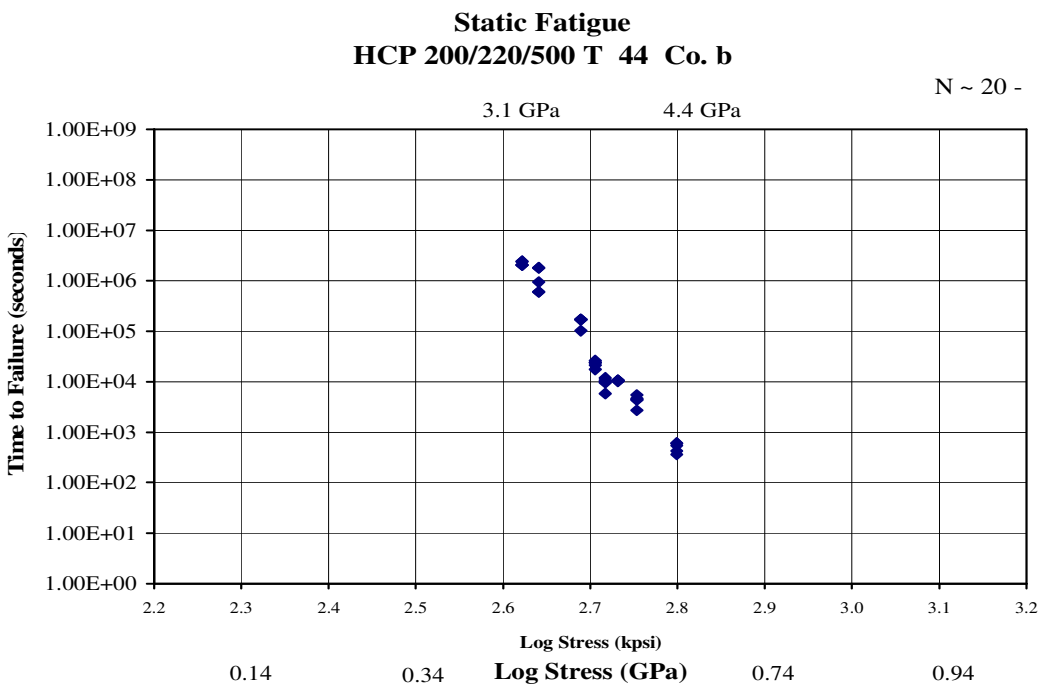

Figure 10: Power law plot of Static Fatigue for Co. b HPCS fiber, NA = 0.44

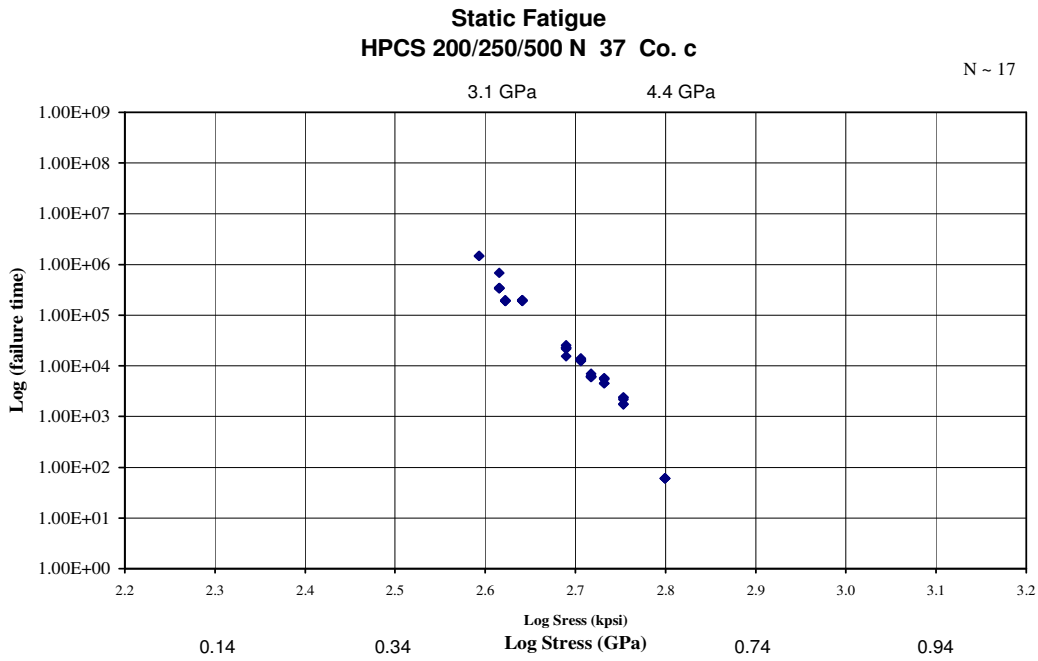

Figure 11: Power law plot of Static Fatigue for Co. c HPCS fiber, NA = 0.37

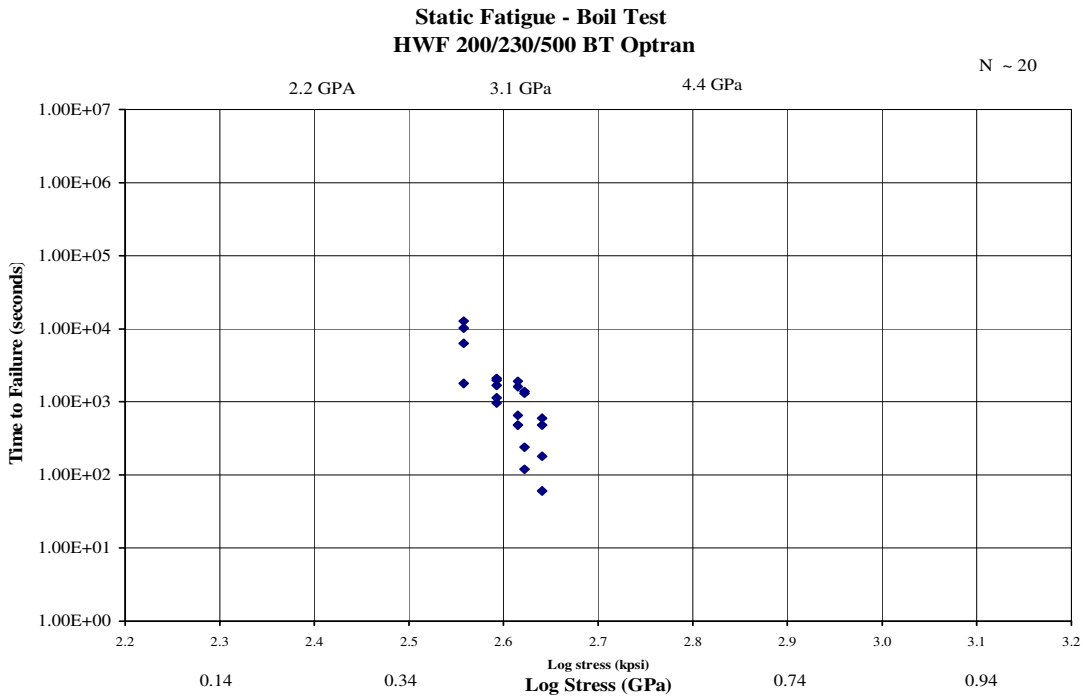

Figure 12: Power law plot of Static Fatigue for HPCS fiber, Boiling Water

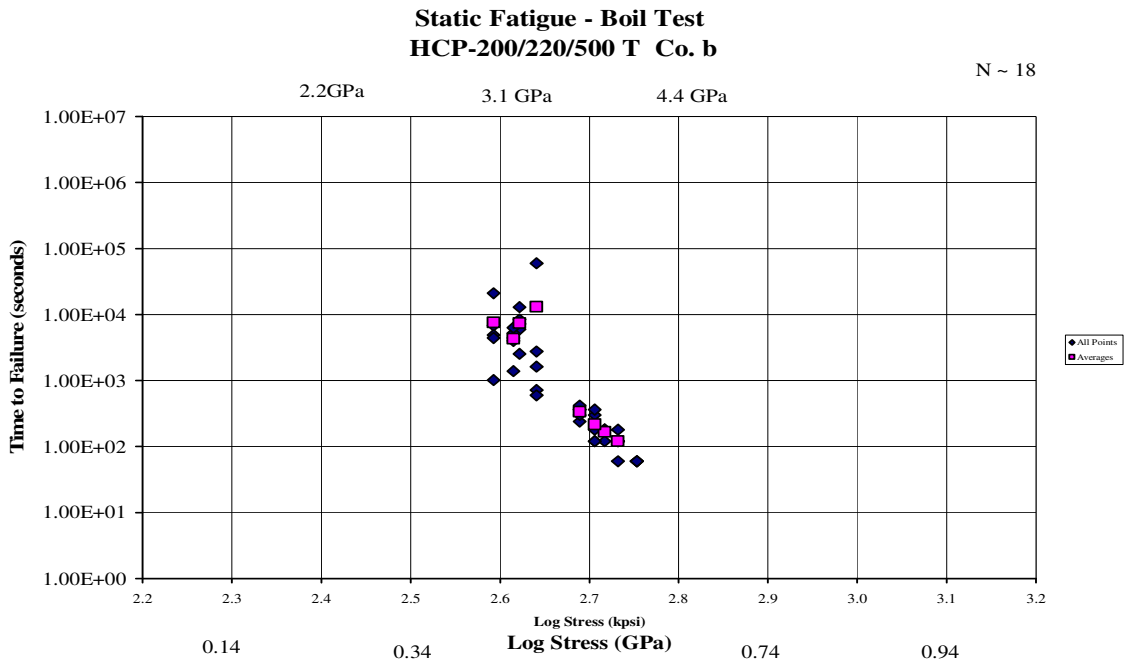

Figure 13: Power law plot of Static Fatigue for Co. b HPCS fiber, Boiling Water

The behavior of both the Optran samples and those of Co. b are consistent with a small drop off in strength and slightly lower Static Fatigue Constant values expected for optical fibers in such a hot moist environment.

4. DISCUSSION

Looking at the spectral data, the first thing to note with reference to these spectra, is that the spectral losses of the high numerical aperture (NA) optical fibers are essentially the same as for optical fibers with normal NAs, having the same chemical materials. Secondly, since the surface area of the acceptance circle is dependent on the square of the numerical aperture value, even small increases in the value lead to much larger acceptance cones.

For most applications, coupling of optical components can and should be improved in a number of situations by the use of high NA, low loss fibers. In the design and functioning of compact laser systems, high NA HPCS fibers can be used for delivery fibers, especially for diode lasers which use bars and arrays to achieve high power, permitting a smaller dimensioned fiber to capture all the laser's power output, possibly without resort to lenses or other optical components. This reduces the size of the package and can improve reliability also by having a simpler, fewer-component system with consequently less critical parameters and less items which could cause the system to go out of specification.

In general, the output from a fiber can be used from near contact to longer distances from the exit of a fiber end. Although a higher NA beam will be more divergent, a smaller fiber diameter will project initially a smaller spot near the fiber end. In applications such as laser marking or ablation this may be critical to get the desired patterns. Laser welding may be aided by having a larger beam with a somewhat diffuse edge. Stronger better welds can result by having thermal distribution

around the seam which diminishes slowly at first from the seam, permitting some adjustment in the material on both sides of the seam to enhance stability.

These represent some of the benefits which become possible in photon processing systems in microelectronics and photonics when low loss, high numerical aperture, optical fibers are available to the designer and end users as is now the case with the more robust 0.48 NA HPCS fiber characterized here.

Furthermore, in many industrial and medical developments, photons are available from sources other than lasers. Coupling photonic energy in many cases using lamps, high brilliance LEDs or other high power LEDs can be a challenge, because the sources often have broad beams and are projected in highly divergent beams from the source. Rather obviously optical fibers with large NAs would be a benefit in capturing the photons and transmitting them to some remote application area, such as inside a patient or to several patients in adjacent stations/rooms/beds.

To summarize, HPCS fibers are shown to be reliable, robust having high dynamic strengths with little change in strength or distribution of flaws after storage at about 0.1-0.2 GPa [10-25 kpsi] for up to, at least, 5 years. Their dynamic strength and fatigue behavior are comparable to all-silica fibers. Weibull mean strengths are above 4.4 GPa [>600 kpsi]. These studies have measured a static fatigue parameter of ~ 22 for the new high NA version, quite comparable to the values seen for regular HPCS fibers. Power capacity approaching 1GW/cm^2 under proper conditions. Their lighter weight can be of some benefit for non-stationary high power laser stations.

A new high NA HPCS with spectral and strength properties similar to the standard NA HPCS fibers has been featured. It is significantly more robust than earlier versions. With the NA= 0.48, it is now possible to provide a larger target for collecting the output from multiple laser sources, e.g. diode laser arrays, and delivering high brightness power for industrial applications as well as to a surgical site, by use of smaller core sizes for the delivery fibers. With optical fibers having NAs as large as 0.53 or 0.55 possible for special cases, they open up more efficient uses of fiber optics and photonics in a wide range of medical applications and treatments, as well as industrial applications, especially high power from diode arrays.

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