**'Corning's Hermetically Coated Erbium-Doped Specialty Fibers'**

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***Corning Erbium Doped Specialty Fiber, manufactured by Corning Incorporated is hermetically coated, providing a significant advantage with respect to mechanical reliability and optical attenuation related to hydrogen exposure.***

## Introduction:

Erbium-doped fiber amplifiers (EDFA's) were invented more than 15 years ago and have seen widespread use in telecommunications systems for nearly a decade. Erbium is an optically active element that provides emission in the 1.5-1.6 μm band when it is activated, or pumped, at an energy level that is greater than that corresponding to this emission band. Practical pump bands correspond to 800, 980, and 1480 nm semiconductor laser diodes. Today, EDFA's are commonly pumped at 980 nm and 1480 nm. EDF coils are typically pumped at 980 nm to achieve optimal noise figure and 1480 nm to obtain maximum power conversion efficiency in the amplifier.

Though many host glasses for Er-amplification have been investigated in the past decade, virtually all commercially available Er-gain fibers are high-silica fibers. The core glass compositions are typically based on the ternary oxide system consisting of Al-Ge-Si, and the clad glass of the optical fiber is typically silica. Silica fibers enable high reliability fusion splices to other silica fibers, and are also relatively resistant to environmental factors such as ambient water. However, even silica-based fibers are not entirely immune to environmental conditions. Within an amplifier, lengths (typically 5-50 m) of EDF are coiled to small diameters so that the amplifier itself may occupy a small volume. A clear trend in the optical amplifier industry is toward miniaturization. As a result, the deployment of EDF is pushing toward coil diameters as small as 15 mm. Coiling optical fiber in these conditions increases the stress applied to the fiber and enhances a phenomena known as fatigue. It is well known that ambient water in the region of a crack existing at the surface of the fiber enhances fatigue, or crack propagation. Furthermore, fibers that are exposed to hydrogen are susceptible to the formation of hydroxyl units (OH) in the glass that lead to attenuation (passive loss) in the short wavelength region of the Er-gain band. Additionally, Er-gain efficiency can be impacted by the presence of OH units in the glass, since there can be transfer of energy from the Er $^4I_{13/2}$ level to -OH bonds in the glass network, rather than useful emission at 1.5 um. Moreover, it is not uncommon for EDF coils to be maintained at elevated temperatures (40-70$^o$C) within advanced amplifiers, in order to maintain a constant level of gain as the ambient temperature fluctuates. At elevated temperatures, hydrogen diffusion and stress-corrosion (fatigue) are enhanced. For this reason, it is of great value to protect the fiber from ambient effects. Corning EDF Specialty Fiber is hermetically coated, and therefore provides a significant advantage with respect to mechanical and optical attenuation related to hydrogen exposure.

**The Value of Corning EDF Specialty Fiber:**

Bellcore requirements for EDFA's (e.g. GR-1313-CORE) indicate that the device must be able to function over the following temperature and humidity ranges.

| | Minimum | Maximum |
|---|---|---|
| Temperature ($^oC$) | -10 | 70 |
| Humidity (%RH) | 0 | 90 |

Additionally, Bellcore requirements indicate the need for the EDF to be protected against hydrogen levels as high as 1% of the ambient atmosphere, since these levels can be generated by charging batteries in the environment of the EDFA.

Corning's solution to protection of the EDF involves the application of an amorphous carbon coating on the fiber, rather than requiring that the EDFA be hermetically sealed in a costly package. Corning Incorporated has successfully implemented hermetic fiber in long-haul, undersea applications since 1992.[1] This same hermetic coating is applied to the EDF glass surface immediately after the fiber draw and prior to the application of the protective polymer coating. The hermetic layer is typically on the order of 50 nm in thickness and consists of disordered graphitic platelets or ribbons. Due to the nature of the coating, it is necessary to ensure a minimum thickness so that hydrogen or water ingress is prevented. A number of techniques have been used to verify the hermetic nature of the coating. These techniques include on-draw optical detection and a non-contact electrical resistance technique. Other, off-line characterization methods include an electrical contact device, electron-microscopy, Raman spectroscopy, as well as accelerated or routine environmental testing.

Corning's hermetic coating has a dramatic impact on the reliability of optical fiber. Studies at Corning Incorporated have shown that our hermetically coated fiber has no measurable hydrogen induced loss after 375 days under 11 atm (100% $H_2$) pressure at $85^oC$. Moreover, the application of the hermetic layer has been shown to reduce the number of flaws near the proof stress level compared to standard single-mode fiber. Hence, 10's of km's of fibers can be proof-tested at stress levels as high as 200 kpsi with few failures.[2,3] Some users find that it is easier to break hermetically coated fiber during manual handling. This can be easily avoided and will be discussed further in the next section.

In the deployment of EDF in today's high-end, compact optical amplifiers, perhaps the most important reliability consideration is the fatigue of the fiber. Fatigue is a phenomenon where surface flaws grow over time in the presence of stress and moisture.[4,5] Fatigue results in the degradation of fiber strength over time, and if extensive enough can result in premature fiber failure. Consequently one must put limits on the stress to which the fiber is exposed during its lifetime. The most basic mechanical design model for 25 to 40 year life is:

$$\sigma_a \leq \chi\sigma_p \qquad (1)$$

where $\sigma_a$ is the sum of all applied stresses, $\sigma_p$ is the proof stress, and $\chi$ is a factor that accounts for the effects of fatigue. For standard silica-clad fiber, $\chi$ is 0.2. That is to say, standard silica-clad fiber can be loaded to $1/5^{th}$ of the proof stress level for 25 to 40 years without failing.[6] Note that this model is conservative for short-length applications (meters) as it assumes that a failure-related flaw is likely to be present near the proof stress level.[α]

The application of the hermetic layer effectively removes one of the key ingredients for fatigue; namely, water. Without moisture, fatigue cannot take place. Corning uses $\chi$=0.8 for hermetic fiber. The reason $\chi$ is not 1 is precautionary, since it is sometimes difficult to have precise control of applied stresses. Typically, EDF is deployed in round or oval coils. Assuming the simplest case, the total stress for Eq. (1) would be the wind tension plus the coil-induced bending stress. The wind stress is simply the wind tension divided by the cross-sectional area. The coil-induced bending stress ($\sigma_{coil}$) is related to the bend radius of the coil by[7]:

$$\sigma_{coil} = E_o[1 + 2.3(r/R)]r/R \qquad (2)$$

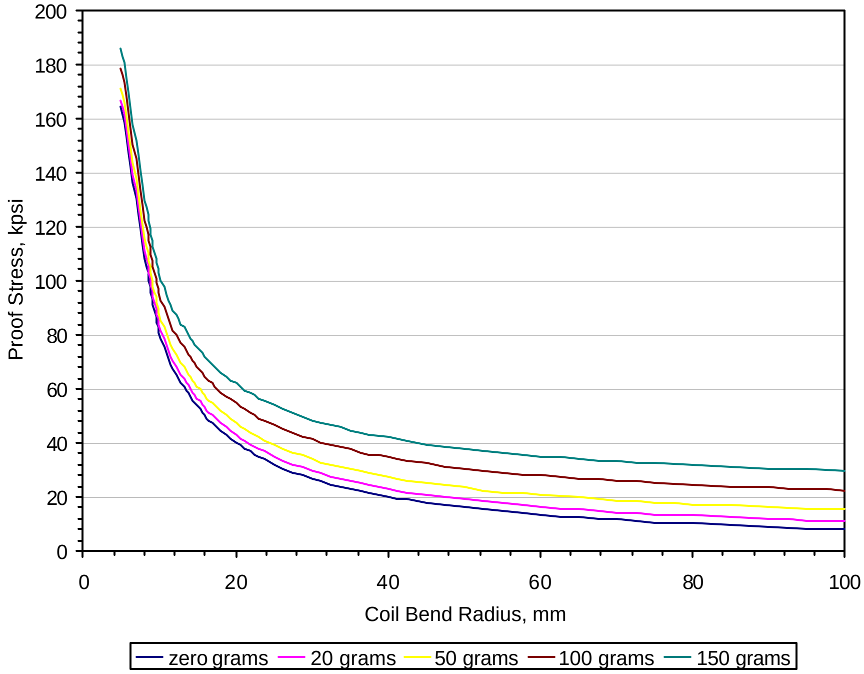
where $E_o$ is Young's modulus at zero stress, r is the radius of the fiber, and R is the radius of the coiled fiber. Thus, one can state the reliability equation for coiled hermetic EDF as,

$$F/A + E_o[1 + 2.3(r/R)]r/R \leq \chi\sigma_p \qquad (3)$$

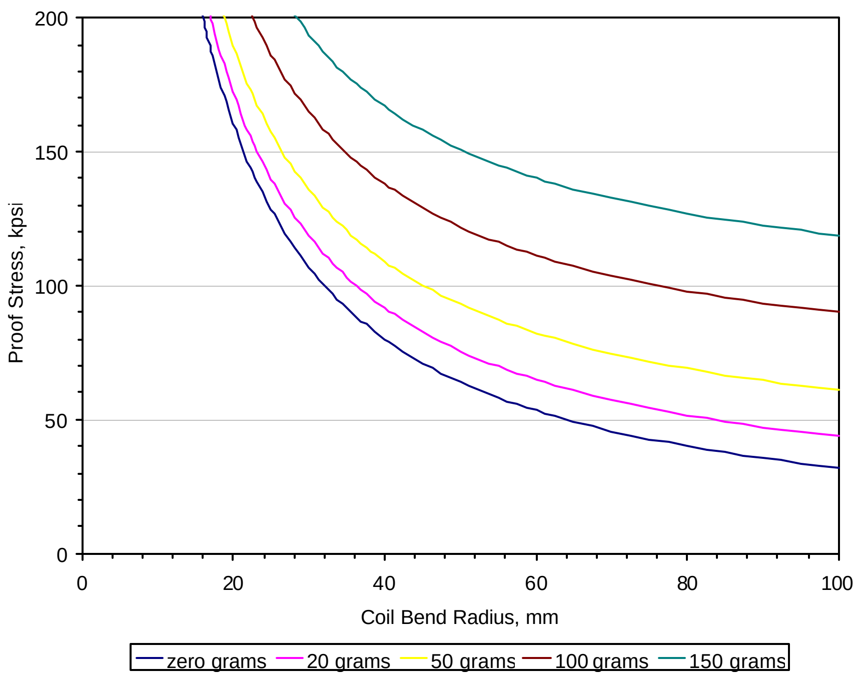
The following figures show the allowable bend radius for various proof stress levels, as a function of winding tension for 125 μm diameter fiber. Both the hermetic ($\chi$=0.8) and non-hermetic ($\chi$=0.2) cases are shown, and the advantage of hermetically coated fiber is clearly significant. Consider the condition of a 20 mm bend radius and zero wind tension, it can be seen that hermetically coated fiber need only be proof-tested to 40 kpsi, whereas the non-hermetic fiber should be proof-tested to nearly 200 kpsi.

[α] Corning has a mature failure probability model for those applications where only meters of fiber are deployed. One should design around the proof stress level for applications on the order of 100's of meters and longer.

Proof Stress as a Function of Coil Bend Radii for Various Wind Tensions: Hermetic Fiber




Proof Stress as a Function of Coil Bend Radii for Various Wind Tensions: Non-Hermetic Fiber



**Recommendations for Handling and Splicing of Hermetically Coated EDF:**

Though hermetically coated fiber requires different handling considerations when compared to non-hermetic fiber, these procedures are relatively simple. First, Corning's hermetically coated fiber appears black because of the amorphous carbon layer. As with any fiber, proper mechanical removal of the polymer coating, i.e. stripping, is necessary in order to minimize surface abrasion. If mechanical stripping tools such as Miller Mechanical Strippers are used, then it is advisable to use a larger hole size, e.g. 165 μm versus 127-130 μm. A new tool should be conditioned to remove burrs by performing routine stripping for several minutes before proceeding to normal use. Also, in order to minimize breakage, it is recommended that no more than 30-35 mm of the coating be removed in a single strip. Longer lengths can create high bending stresses. Though Miller strippers are commonly used in industry, other stripping tools are recommended by Corning, such as thermal strippers that heat the protective acrylate coating, allowing it to expand from the hermetic coating for easier removal. These tools should also have a larger orifice when applied to the fiber, i.e. on the order of 150-165 μm. Still another option that Corning favors for hermetic fiber is the use of a stripper like the Luminos Industries soft-contact acrylate stripper, which uses polymer blades instead of harder metals that can damage the surface of the glass.

When splicing hermetically coated fiber, it is recommended that a pre-heat or pre-fuse step is part of the splicing process. During this process the carbon coating is oxidized or "burned-off", thus leaving approximately 1.0-1.5 mm at the end of the fiber uncoated. It is recommended that the electrodes are cleaned regularly. Note that most splicer manufacturers recommend a maintenance schedule for electrode cleaning that is sufficient to prevent build-up on the electrodes before there is a degradation of splice quality anyway. If the end-user of the fiber has the need to reconstitute the hermetic coating in the region of the splice, there are techniques which have been successfully developed.[8]

Splicing recipes for Corning Specialty Fibers to our Er-doped fibers are available upon request, and are tailored for commonly used commercial splicers.

**Conclusions**:

Corning's hermetically coated Er-doped fiber provides end-users with a unique product that is well suited to high-reliability, compact optical amplifier designs. The hermetic coating provides a protective layer which is impermeable to molecular water or hydrogen that may be present within the environment of the amplifier. The hermetic coating prevents the ingress of hydrogen into the optically active region of the fiber and water from reaching flaws that are susceptible to slow-crack growth. Thus, the presence of the hermetic coating enables one to bend the fiber more tightly than non-hermetic fiber. This allows more freedom to reduce package size without worry of post-installation fatigue failures. Our mechanical reliability models can be adapted to almost any manufacturing or in-service scenario. Perceived differences in acrylate coating removal from hermetic fiber, or with fusion splicing, are easily addressed using Corning's recommended handling techniques for Corning Er-doped specialty fiber.

## References:

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