The Impact of Hydrogen on Optical Fibers
White Paper

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The exposure of an optical fiber to hydrogen has the potential to change the fiber's performance in several ways. The optical communications industry has been studying these changes for some time and has gained a great deal of knowledge regarding their various causes and effects. This white paper briefly describes some of the different ways that hydrogen can affect optical fibers and illustrates how these effects can play an important role in the overall performance of optical communications systems. Special discussion is given regarding the impact of hydrogen aging on reduced or low water peak fibers, where strict attention needs to be paid in order to ensure stable *long-term* performance.

In the most basic sense, hydrogen aging arises due to the absorption of light by various species in the glass. These species can be either molecular hydrogen (i.e., H_2) or defect sites that have reacted with hydrogen to form various absorbing species. The absorptions may occur at specific wavelengths or over certain wavelength bands depending on the nature of the absorbing species, and are observed as attenuation increases. Some of these absorptions are reversible or transient, due to elimination of the absorbing species through either diffusion (as in the case of H_2) or further reaction of the absorbing species and conversion to a non-absorber. In other cases, the absorption bands may be permanent, resulting in a finite attenuation increase over the remaining service life of the fiber.

The hydrogen that interacts with optical fiber can come from a multitude of sources, including ambient atmospheric hydrogen (either as H-OH or H_2), evolution or dissolution from cable materials (e.g., hydrocarbon polymers, metals), galvanic reaction between dissimilar metals in the cable, general oxidation/corrosion and even the action of microorganisms such as sulfate-reducing bacteria.

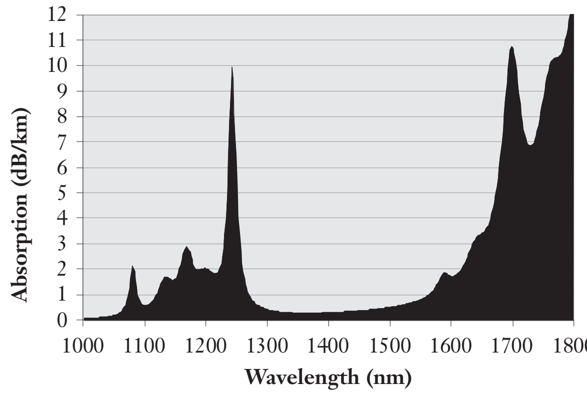
Interstitial Hydrogen

The interstitial hydrogen effect is caused the diffusion of molecular hydrogen (H_2) into the open structure of the glass and does not require reaction of the H_2 with any defect species. The open structure is a result of the ring orientations that form from silica and other metal-based (Ge, etc.) tetrahedra in the glass structure. This openness of the structure on the molecular level is relatively independent of fiber processing, making interstitial hydrogen a potential concern for all fiber types and manufacturing methods (unless hermetically coated).

Figure 1 illustrates an absorption spectrum resulting from molecular hydrogen dissolved within silica optical fiber. Light absorption due to the vibration of unreacted hydrogen has a fundamental peak at 2420 nm, and a first overtone at 1240 nm. Other absorptions of interest are located at approximately 1590 and 1640 nm. The magnitude of the absorptions is dictated by the concentration of hydrogen within the fiber, with the change in attenuation being fully reversible. That is, once the source of hydrogen is removed and ample time has been allowed for hydrogen to diffuse from the fiber, the absorption peaks disappear. The rate of response and recovery is a function of temperature. Interestingly, while the rate of response increases with increasing temperature, the solubility of hydrogen in glass decreases, such that the response will occur more quickly but to a lesser extent at elevated temperatures. The most important component in reducing interstitial hydrogen is eliminating sources of hydrogen through cable materials selection and design.

Illustrative absorption spectrum of molecular hydrogen within an optical fiber. Approximate conditions of 1 atmosphere of hydrogen at room temperature. Created from calculations provided by K. Noguchi, N. Shibata, N. Uesugi and Y. Negishi, "Loss Increase for Optical Fibers Exposed to Hydrogen Atmosphere," J. Lightwave Technol. 3 [2], 236-243 (1985).

Figure 1



Hydrogen Aging Due to Phosphorus

Discovered in the early 1980s, hydrogen aging due to phosphorus was the first type of reactive hydrogen effect observed in optical fiber. It was found in fibers doped with germanium and phosphorous, primarily multimode fibers. Because hydrogen physically breaks and reforms bonds during this type of effect, the resulting increase in attenuation is a permanent change. The wavelengths affected are primarily longer, ranging from approximately 1400 to 1600 nm.

Since this effect was discovered, the amount of phosphorous used in optical fiber manufacturing has been reduced or altogether eliminated in order to mitigate its interaction with hydrogen.

Hydrogen Aging Due to Elevated Temperature

At about the same time as the interaction between hydrogen and phosphorus-doped silica was discovered in multimode fibers, it was determined that some fibers experienced a hydrogen aging effect that was accelerated by heat. This effect primarily occurred in single-mode fibers, and resulted in a permanent change in attenuation. The resulting absorption occurred over nearly the entire wavelength range of interest to optical communications (240 to 1700 nm), with the shorter wavelengths affected to a slightly greater extent. This effect is believed to be related to the reduction of germania, which can occur via interaction with hydrogen.

In terms of quantifying this effect, an exposure to 0.01 atmosphere hydrogen at 100ºC for 14 days could yield an approximate increase in attenuation of 0.01dB/km. At 0.01 atmosphere hydrogen at 45ºC, the time required to observe a 0.01 dB/km increase in attenuation approaches 30 years. While it is important to be aware of the potential for this type of hydrogen aging, it is seldom a problem in the field due to the combination of high temperature and high hydrogen concentration required.

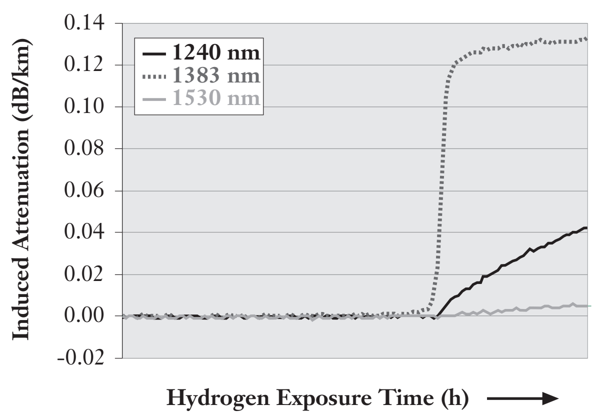
Second-Generation Hydrogen Aging

Second-generation hydrogen aging was first observed in the 1980s, and occurs only in single-mode fibers. While there are a number of affected wavelengths, key absorptions occur at 1383 and 1530 nm. The 1530 nm absorption is transient, and typically occurs to a lesser extent than the permanent 1383 nm absorption. The attenuation increases at both wavelengths occur quite rapidly after a period of initial diffusion. While the attenuation responses typically occur in less than one week when testing at 23ºC and 0.01 atmosphere hydrogen, even trace amounts of hydrogen (e.g., 0.0001 to 0.0002 atmosphere) can cause the attenuation responses to occur to their full extent within the typical service lifetime of an optical cable at room temperature.

In the second-generation case, the attenuation increases are attributed to absorbing species that are formed when hydrogen reacts with existing defect sites in the glass structure. These defect sites may include non-bridging oxygen hole centers or NBOHC (≡Si-O•), E' centers (≡Si•) or additional species. Figure 2 illustrates the behavior of the 1383 and 1530 nm wavelengths, as well as the 1240 nm wavelength which is used to gauge the degree of hydrogen saturation. The figure clearly illustrates the initial diffusion period, as well as the extremely fast kinetic behavior of the 1383 absorption.

Second-generation hydrogen aging as a function of hydrogen exposure time. The 1240 nm wavelength represents the first overtone of unreacted hydrogen and is used to gauge the "saturation" level of the fiber. This particular sample exhibits very little response at 1530 nm, which would occur rapidly (as does 1383 nm) if present in greater magnitude.

Figure 2



Additional Hydrogen Aging Effects

In addition to second-generation hydrogen aging, another type of single-mode aging phenomenon exists whereby defects in the glass structure react with hydrogen to form species that absorb over a relatively wide range of wavelengths. The signature of this effect is a broad peak centered at approximately 1430 nm, and extending from nearly 1350 to 1600 nm. The 1430 nm absorption is attributed to the interaction of hydrogen with germanium-containing defects in the glass.

Implications of Hydrogen Aging

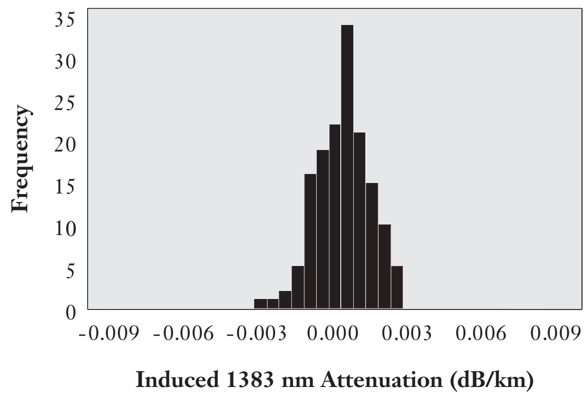
As mentioned previously, the process of hydrogen aging causes light of specific wavelengths to be absorbed, which in turn increases the attenuation of the fiber at those wavelengths. This has obvious practical implications to optical communications systems operating at these wavelengths.

Perhaps of greatest interest is the hydrogen aging behavior of fibers which claim to have a "reduced," "low" or "zero" water peak. Such fibers enable the use of additional E-band channels for applications such as coarse wavelength division multiplexing (CWDM). While the *initial* 1383 nm attenuation of such fibers may indeed be low, some such fibers can still exhibit significant increases in 1383 nm attenuation upon exposure to even trace amounts of hydrogen. These increases can often be on the order of one to several tenths of a dB/km, in some cases nearly doubling the initial attenuation upon aging. In contrast, fibers that meet the ITU-T G.652.C or G.652.D standards are required to have both a low *initial* water peak attenuation and a low attenuation increase due to hydrogen aging. This objective is accomplished by requiring that the average *post-hydrogen aging* 1383 nm attenuation be less than or equal to the specified 1310 nm attenuation.

Corning's SMF-28e® and NexCor™ fibers are fully compliant to the ITU-T G.652.D standard, ensuring stable *long-term* attenuation performance. This is accomplished via Corning's utilization of leading-edge manufacturing technology and processes, combined with the use of rigorous quality architecture. And the proof is certainly in the performance, as evidenced by the data presented in Figure 3.

Water peak hydrogen aging performance of Corning's ITU-T G.652.D fiber. The data represents over 150 unique fiber measurements. Mean performance is 0.0003 dB/km. Fibers tested in accordance with IEC 60793-2-50 Section C.3.1.

Figure 3



The above data clearly shows the resistance of Corning's ITU-T G.652.D fiber to increases in 1383 nm attenuation upon exposure to hydrogen. This industry-leading performance allows Corning's G.652.D product offerings to perform reliably not only in the O-, S-, C- and L-bands, but in the E-band as well, which gives operators a significant increase in channel capacity.

In fact, all Corning® optical fibers are produced to provide extremely low hydrogen aging at the wavelengths of interest to each fiber type, enabling the fibers to perform reliably in their intended applications.

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