PROCEEDINGS, Twenty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 29-31, 2001
SGP-TR-168

Development of Fibers Optic Cables for Permanent Geothermal Wellbore Deployment

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ABSTRACT

The use of fiber optics within geothermal wells has been extremely limited. The high-temperatures and formation of molecular hydrogen within the well have resulted in the early death of fiber optic cables. This paper reveals reasons for hope to extend the life of fibers for many years. Various fibers have been evaluated for degradation when exposed to ambient molecular hydrogen. Two commercially available fibers have been identified as having significant resistance to free hydrogen at 250°C and above.

INTRODUCTION

Sandia, under direction from the DOE, is tasked with the development of fiber optic cable for long term wellbore deployment within high-temperature geothermal wells. The goals of this program are extremely high requiring fiber optic cable to survive a minimum of 4 years at 250°C with < 2°C shift of the DTS (Distributed Temperature Measurement). This tough requirement is needed to make fiber optic wellbore completion the industry standard replacing conventional electronic temperature well logs.

In order to reach these goals, Sandia under took three projects:

1) Working with the fiber industry to develop hydrogen resistant fibers. This work is protected under a cooperative working agreements.

2) Improving the fiber to withstand the wellbore environment.

3) Developing a hydrogen getter to supplement the fiber defenses.

This paper will focus on work to improve the fiber.

THE PROBLEM

The current problems and potential solutions are best explained in terms of the DTS operating principles. The DTS illuminates the glass core of the optical fiber with a laser pulse of 10 nanosecond duration.

As the optical pulse propagates down the fiber, it undergoes scattering even in the absence of impurities and structural defects. The bulk of this scattered radiation occurs at the same wavelength as the incident radiation and is known as Rayleigh scattering. It is caused by the unavoidable density fluctuations frozen into a glassy material. A second and much smaller contribution to the scattered radiation is known as Raman scattering. It is divided into two components, both of which are at a different wavelength from the incident radiation. The so-called Stokes is at a longer wavelength; the so-called anti-Stokes line is at a shorter wavelength. In the latter case, the scattered photon actually has more energy than the incoming photon! Energy is conserved in the two processes, respectively, by giving to or taking from the thermal vibrational energy of the atoms in the glass. Because this vibrational energy is a well-defined function of temperature, the ratio of the signals is also. It is this ratio, in conjunction with the time of flight of an optical pulse, that is used to determine the temperature of the fiber at a given point. It should be noted that most of the scattered light, of any variety or color, leaves the fiber; some of it travels in the forward direction and some of it returns to the source-end of the fiber. It is the last component, termed backscattered radiation, that is of interest here because that is where the data acquisition system can be placed. It is remarkable that such low-level optical power can be used to perform an accurate distributed temperature measurement. The measurement is made possible by the efficient coupling of a high-power pulsed laser into the fiber and signal averaging.

It is important to emphasize that the ratio of the Stokes to anti-Stokes is a well-defined function of

temperature at the point of generation, but the ratio of these two signals can be corrupted by propagation to the data acquisition system. In view of this hazard, we note two forms of degradation can render the measurement inaccurate. One is that the attenuation of the fiber, due to impurities and structural defects, is so severe that the signal at both the Stokes and anti-Stokes wavelengths is too small to be extracted from the noise, even in the presence of signal averaging. The ratio is then essentially meaningless. The second is attenuation that may differ between the two wavelengths, particularly as a function of time. If the difference is static, its effect on the ratio can be calibrated out. If it varies with time *in situ*, then it cannot. Thus, the apparent temperature gradually becomes skewed in time, which is apparently what has happened in certain geothermal wells. As will be discussed, molecular hydrogen diffused into the fiber at high temperature, reacted with the oxygen in the glass to form OH ions having certain characteristic absorption peaks. One of these is centered at 0.95 microns and has a tail encompassing both the Stokes and anti-Stokes component. Since they fall on different positions of this absorption tail, their attenuation will be differ from each other in a time-dependent manner.

Unreacted hydrogen that could exist in the interstices of the glass can also absorb light, but, as our measurements will demonstrate, the product of its reaction with oxygen dominated the loss.

In the following explanation of the problems it is important to understand that the Stokes and anti-Stokes scattering exist at different optical wavelengths. The DTS for the logs reported here (DTS-80, York Instruments, Chandlers Ford UK) uses a 1064 nm wavelength laser. The primary Raman peaks are separated from the laser wavelength by 400 cm^{-1} wavenumbers in 200 cm^{-1} bands [Murata, 1987]. The resulting wavelengths of operation are 1006 to 1026 nm for the anti-Stokes light and 1092 to 1129 nm for the Stokes light. The inherent scattering and absorption losses of the fiber are wavelength dependent. As such, the Stokes and anti-Stokes light incur different amounts of transmission loss for a given length of fiber.

A unique feature of the DTS is the ability to determine the temperature of the fiber at discrete intervals along its entire length. By recording the reflected light as a function of time, the DTS can calculate the origination depth from the time of flight. The length of the laser pulse determines the minimum distance between samples. The York DTS uses a ten nanosecond pulse length resulting in a minimum of one meter between temperature readings.

Test fibers at Beowawe and Dixie Valley saw significant alterations in the temperature measurement as a function of well exposure [Smithpeter, 1999]. Based upon the operating principles, the observed error could be created by dynamic changes in the light loss between the Stokes and anti-stokes wavelengths. That is, if the fiber optical transmission is changing at different rates between the two wavelengths, the difference will skew the calculated temperatures. To confirm this hypothesis, we took optical transmission spectra from a 20 foot section of the failed Beowawe fiber and a new fiber. The relative transmission spectra showed decreased transmission in the Beowawe fiber compared to the new fiber, see Figure 1. Specifically, there was a 2% difference in the transmission loss between the anti-Stokes and Stokes wavelengths. When translated from the 20 foot length measured to the 1000 foot length of the Beowawe fiber, there is factor of two difference in losses between the two wavelengths. This difference would account for the temperatures errors observed over the life of the fiber.

While looking for cause of the transmission losses we noticed the relative transmission spectrum, shown in Fig. 1, contains strong absorption peaks at 1.4 and 2.2 microns. Both of these peaks correlate with known

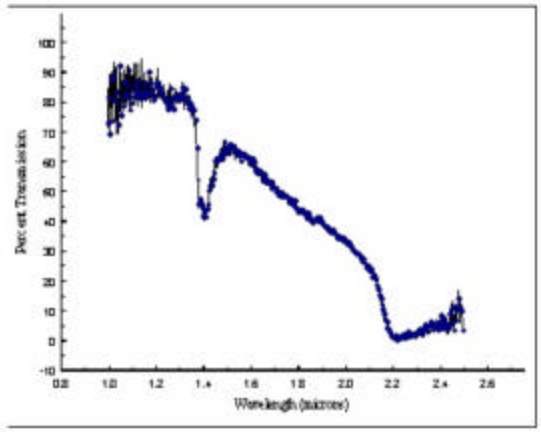


Figure 1. Light loss of 20 ft of fiber removed from a well at Beowawe NV. The light losses at 1.4 and 2.2 are typical of hydroxyl degradation.

absorption peaks of hydroxide (OH) in silica glass [Murata, 1987]. Past research in OH contamination of telecommunication fibers [Lemaire, 1993] found the contamination mechanism is free hydrogen diffusing into the core and reacting with oxygen trapped in the glass.

WHERE IS THE HYDROXYL COMING FROM?

The most likely hydroxyl creation factors come from exposing the fibers to water or free hydrogen. Water can be found as a normal process of humidity found in the air around the fibers or placed on the fibers as a process of fiber installation. Early fibers were installed within the protective stainless steel tubing using jets of water! Naturally, using water for fiber installation cannot be tolerated. However, water alone was not solely responsible for fiber failure in the wellbore. Fiber installed without water and dried with nitrogen also showed degradation in time.

It is commonly known and will be shown that free hydrogen can penetrate the fiber and form hydroxyls inside the fiber core. Once this hydrogen has formed a hydroxyl in the fiber, the damage is permanent and accumulative. So where does the hydrogen come from?

Free hydrogen is a function of three processes:

1) Wellbore fluids contain some small amount of free hydrogen that can diffuse through the steel tubing.
2) Wellbore oxidation of steel casing (including stainless steel protecting the fibers) creates free hydrogen
3) Oils inside new stainless steel tubing actually 'crack' and free hydrogen in the process

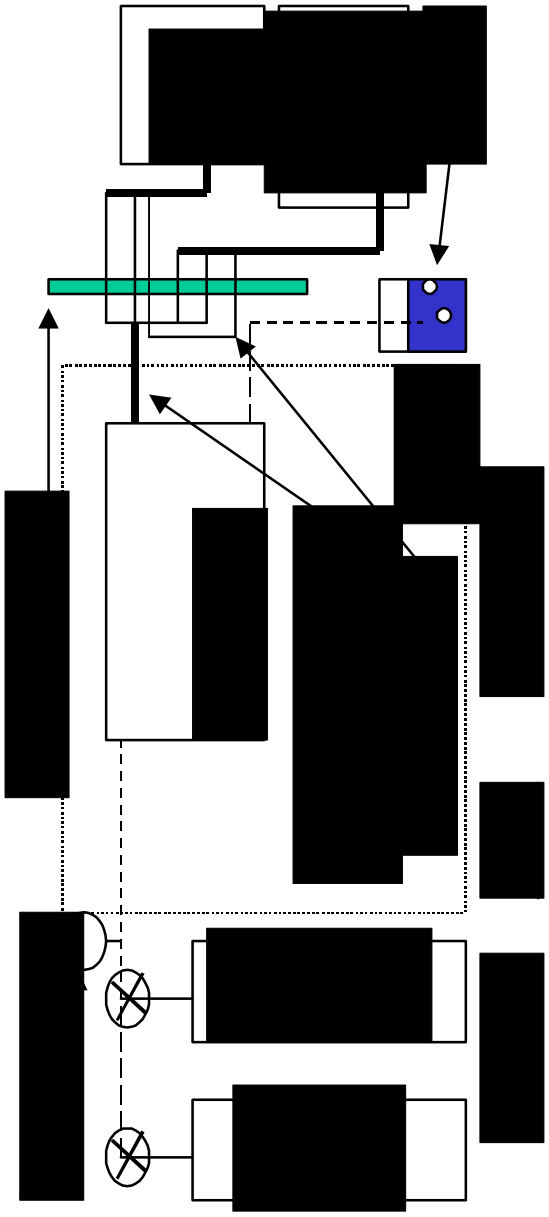
Item 3 is surprising. Gas samples where taken from new stainless steel (316, I.D. 0.25 inch) tubing after heating the tubing to 250C. An analyst of the captured gas sample found 0.39% H_2. Also, there was a reduction of O_2 of 4% possible due to the creation of H_2O which was lost when the gas sample cooled.

This creation of free hydrogen might explain why some early fiber deployments within geothermal wells showed fibers degrading very quickly while the new replacement fiber might perform better. If the stainless steel tube was being reused then the older (seasoned) tubing would have had the initial oils already removed by the wellbore exposure. There is a known record tracking the repeated use of tubing.

Cleaning the oils from the tubing is important, however, there is nothing that can be done about the naturally occurring hydrogen within the wellbore. So a new improved fiber or process of protecting the fiber must be developed.

Before discussing fiber improvements, a description of the fiber test configuration is given.

Figure 2. *Below is the basic test configuration for H2, Ar, or water exposure. Here we are testing 2 fibers in 5%h2 forming gas.*



LABORATORY TEST SETUP

A special test configuration had to be built for conducting these tests. The test configuration is shown in Figure 2. This system can test up to 6 fibers at one time. All 6 fibers will see the exact same environment within the autoclave and will see the same broadband light source. To insure the light source is NOT changing over time, a calibration fiber is used. This calibration fiber does not enter the autoclave but instead, simply connects the lamp to the spectrum analyzer.

The fiber bundle from the light source to the patch panel was never disconnected once testing was

started. This greatly reduced the chance of connector induced error.

A number of reliability concerns were addressed as can be seen in our normal testing procedures.

Normal Testing Procedures

1. The autoclave and matching hardware is cleaned and then baked at 250°C for 24 hrs to remove any cleaning materials.

2. The test fiber is wound on a copper wire fixture (not shown in Figure 2) and suspended inside the autoclave.

3. The fiber is wound by technicians using photographic gloves to insure that finger-prints are not introduced into the test.

4. Once the system is in place, room temperature spectrum readings are recorded. Not shown in Figure 2 is the temperature probe located inside the autoclave.

5. In the case of pressured gas testing, the autoclave is purged with 10 volumes of argon gas prior to heating. The autoclave is then brought to temperature.

6. Once at temperature, spectrum readings were periodically taken.

To insure the level of test gas is not depleted inside of the autoclave a bubbler was used to monitor a small amount of gas flow.

CHOOSING FIBERS FOR TESTING

Clearly, to meet the objective of <2°C drift over four years at 250°C is difficult. Normally, the diffusion constant, D, of a material is Arrhenius in character:

$$D(T) = D_o \exp(-E/RT),$$

where T is the absolute temperature, D_o is a constant, E is an activation energy in kcal/mole, and R is the ideal gas constant (1.987 cal/deg K-mole).

Assuming zero concentration of H_2 everywhere within the fiber at time = 0, an equilibrium concentration at the fiber's outer surface, and no chemical reactions that would deplete the diffusing hydrogen, the time, $\mathbf{T}_{95}$, it takes to reach 95% at the center of the fiber is:

$$\mathbf{T}_{95} = .6a^2/D(T),$$

where "a" is the fiber radius. For a standard communications fiber with a 125 µm diameter, this time is about 50 minutes at 200°C. This type of estimation is simplified by ignoring any polymer coating of reasonable thickness, as a result of the extremely rapid diffusion through it. [Lemaire, 1993] It should be noted that the full solution of the diffusion equation giving the concentration at any point in the fiber, at any time, is contained in the book by Crank.

Buffer materials as carbon, gold, silver, aluminum, or other buffers extend the diffusion time. However, none tend the diffusion time to years at temperatures seen in geothermal wells. This work evaluated different fibers dopings.

Three fibers were tested. These fibers compare types of optical fibers not buffer material.

Fiber 1 is a common communication fiber similar to the same fibers used on the DTS. It is a graded-index fiber, doped with germanium to raise the refractive index of the core and with phosphorus for viscosity control. Both of these elements are known to create defect centers which promote the formation of OH under diffusion of hydrogen [Stone, 1987]. In fact this fiber has been used in failed wellbore deployments with teflon, polymide, and/or carbon buffers.

Fiber 2 is also a graded-index fiber without the normal phosphorus doping.

Fiber 3 is a step-index fiber containing a low-OH, pure-silica core and a fluorinated. low-OH silica cladding. This combination forms a waveguide because fluorine, unlike most impurities, lowers the refractive index of silica. This fiber was chosen for several reasons. First, it contains neither germanium nor phosphorus. Second, the fluorine in the cladding was expected to be helpful because it is known to suppress OH formation [Wehr, 1985]. Third, the low-OH character of the core was produced by adding chlorine to it. Since chlorine lies directly under fluorine in the periodic table, we speculated that it might have a similar effect on suppressing OH formation. A potential disadvantage of this fiber, however, is a bandwidth lower than that of the graded-index fiber. A lower bandwidth results in lower spatial resolution of the temperature measurements.

All three fibers are muti-mode (50 micron core) with polyimide-buffers. Initial testing was performed using equal 50 ft lengths of fiber. All three fibers are commercially available.

TEST DATA RESULTS

Temperature only test:
The first test involved temperature only. The fibers were exposure to normally dry Albuquerque air at one atmosphere. Testing continued up to 300°C without any fiber measured degradation. The testing went in stages up to 300°C in the test matrix below.

Matrix for temperature only test
100C for 24 hrs. This first 24 hour test gave us a chance to check for operational problems, none were found.
150C for 64 hrs.
200C for 48 hrs.
250C for 100 hrs.
300C over night.

Temperature and pressure test:
To insure that the fiber spectrums would not change under gas pressure, a test using argon gas was run. The test fibers were exposed to 1500 psi argon at 250°C for 24 hrs. Again, there was no measured change in the test fibers.

These null results gave us confidence that the experiments involving hydrogen would not be corrupted by these extraneous factors.

Fiber Exposure to H2:

While the fibers were at 250°C in 1500 psi of 100% argon gas, the argon gas was exchanged for hydrogen forming gas consisting of 5% H2 and 95% Ar. The common polyimide-buffered fiber started showing OH degradation almost immediately. Figure 3 shows the measured change over the initial 8.5 hrs of exposure.

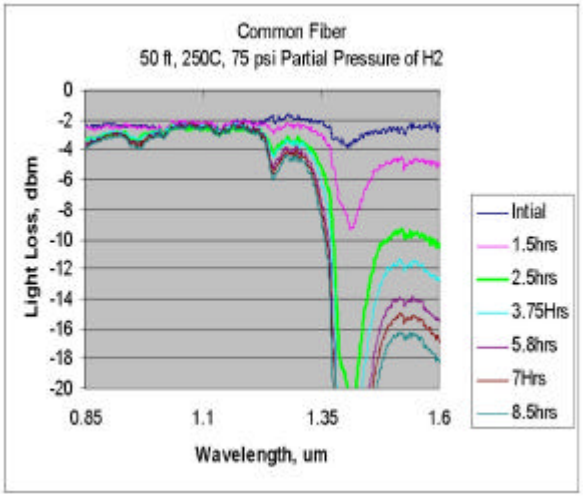


Figure 3. This polyimide-buffered fiber experienced no light loss when tested to 300°C in air. However, following exposure to a H2 partial pressure of 75 psi, the fiber reacts quickly to the creation of OH light loss bands.

Figure 4 shows the measured light loss between 850 and 1600 nm. The OH peaks can be clearly seen in the common fiber. The common fiber is a fiber similar to those tested within geothermal wells.

Keep in mind that the primary Raman peaks are separated from the laser wavelength by 400 cm^{-1} wavenumbers in 200 cm^{-1} bands. The resulting wavelengths for calculated DTS temperature depend on the ratio of the Stokes wavelenghts at 1006 to 1026 nm for the anti-Stokes and 1092 to 1129 nm for the Stokes. Looking closely at Figure 4, the DTS measurement ratio falls between the two peaks at 950 and 1250 nm. This may explain why some degraded DTS fiber starting reading too low while others started reading too high. The creation of large OH losses corrupts the assumption that the dynamic losses corrected for in the DTS ratio measurement are the same for both Stokes wavelenghts.

Also of interest was a loss toward the lower wavelenths. This is more easily seen in a follow test using a longer fiber section to see more detail.

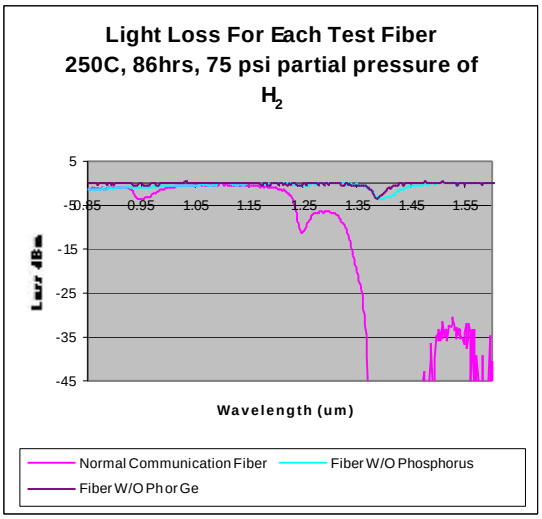


Figure 4. Here are test results from all three fibers. It is clear that the removal of phosphorus is significantly reducing the creation of OH. OH creates light losses at 1.25 and 1.4 micrometer.

FOLLOW ON 500 ft HYDROGEN TEST

To further validate data from the first hydrogen test, a second test was conducted using the phosphorus, germanium free fiber. However, before conducting this test, 200ft of this fiber was used with a DTS to measure temperature. The system provided encouraging temperature measurements requiring only a change in calibration from the normal low temperature fiber.

This second test used 500 ft of the phosphorus free

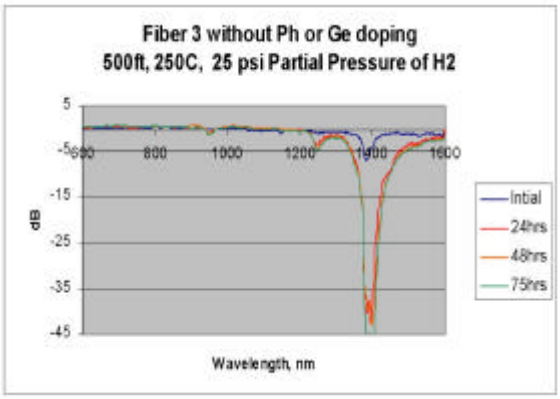


Figure 5. Here the phosphorus free fiber under test is 500 ft long. This allows more detail to be seen.

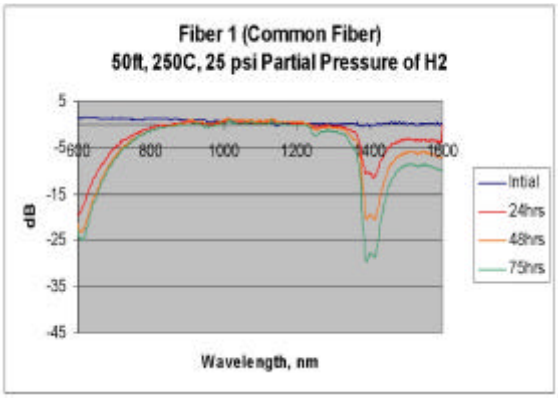


Figure 6. Here a 50 ft common fiber is tested with the fiber in figure 5 to help validate the test. When comparing fibers 5 and 6 keep in mine that the loss in dB is proportional to length.

fiber. In order to insure that the test was representative of the first test, a 50 ft section of the common fiber was also placed in the autoclave. Results of these tests can be seen in Figures 5 and 6. Another change in the test was to reduce the partial pressure from 75 to 25 psi. The change in partial pressure did not result in a change in fiber degradation.

Fiber 3 is slower to build OH losses. Fiber 3 is ten times longer than the control fiber and light loss is cumulative per unit length. Also, this test looked at the loss at 600 nm. There is a significant loss appearing below 600 nm in the common fiber but not the low OH fiber. This is an unexplained benefit to the low OH fiber.

The Stokes and anti-Stokes wavelengths continue to be flat in our 500 ft test. Thus the DTS response should be unaffected.

RELATIVE TO GEOTHERMAL WELLS

This testing was designed to be a gross over test to quickly exploit weaknesses in test fibers. In the well, fibers are installed inside steel tubing protecting them from the wellbore pressures. The hydrogen partial pressures are well below 1 psi inside the tubing. However, there are no typical geothermal wells and there is little known about free hydrogen at depth inside a geothermal well.

To gain a better understanding of this problem, both a low OH fiber and a common fiber will be deployed within a well. The common fiber will be used as a hydrogen monitor while the low OH fiber will be used to conduct a life study. The magnitude response seen by the common fiber used in this test will help researchers develop a scale to better identify the potential life expectancy of the new DTS fiber.

DISCUSSION

Hydrogen has been identified as a major reason for optical fibers failing within the geothermal wellbore. The hydrogen comes from a number of elements, one is the stainless steel tubing used to house the fiber.

To protect the fiber, the stainless steel tubing must be cleaned of machine oils prior to fiber installation. However, this is not enough to prevent fiber degradation. Fibers created without the normal phosphorus doping have been shown to be highly resistant to OH creation even at elevated temperatures as high as 250°C.

Since a carbon buffer does offer some protection to the fiber from the ravages of ambient hydrogen, coating the step-index fiber with carbon will further improve its performance. We recommend that this be done. We also suggest that the creation of a graded-index fiber consisting of a fluorinated cladding and a graded fluorine-doped core may be the optimum solution, particularly if such a fiber is coated with carbon. As stated earlier, fluorine is known to inhibit OH formation and there will be more of it in such a fiber than in any tested. In addition, it would have the same high bandwidth as existing graded-index fibers.

The use of the new fibers will increase the life expectancy of permanently installed fiber optic cables within the geothermal well. Additional wellbore testing is being planned.

ACKNOWLEDGMENTS

Sandia is a multiprogram DOE laboratory, operated by a subsidiary of Lockheed Martin Corp. With main facilities in Albuquerque, NM and Livermore, CA, Sandia has major research and development responsibilities in national security, energy, and environmental technologies and economic competitiveness.

REFERENCES

J. Crank, The Mathematics of Diffusion, Oxford University Press, London, Ch. 5, 1975

S. Grobwig, E. Hurtig, K. Kuhn, “Fibre optic temperature sensing: A new tool for temperature measurements in boreholes.” Geophysics, 61, 1065-1067, July-August 1996

P. Lemaire, "Hydrogen induced losses and their effects on optical fiber reliability", In: Fiber Optics Reliability and Testing. Ed. Dilip Paul. SPIE, 1993, 80-104.

C. Smithpeter, R. Normann, J. Krumhansl, D. Benoit, S. Thompson (1999), “Evaluation of a Distributed Fiber-Optic Temperature Sensor for Logging Wellbore Temperature”, proc. twenty-fourth workshop on geothermal reservoir engineering, Stanford Ca, Jan 25-27

J. Stone, "Interactions of Hydrogen and Deuterium with Silica Optical Fibers: A Review", Journal of Lightwave Technology, Vol. LT-5, No. 5, May 1987, 712 - 733.

H. Wehr, et al., "Transmission Loss Behavior PVCD Fibres in H_2 Atmosphere", Electronics Letters, Vol. 21, No. 9, 12 Sept. 1985, 853-854.