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EVALUATION OF A DISTRIBUTED FIBER-OPTIC TEMPERATURE SENSOR FOR LOGGING WELLBORE TEMPERATURE AT THE BEOWAWE AND DIXIE VALLEY GEOTHERMAL FIELDS

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ABSTRACT

A distributed temperature sensor (DTS) system, utilizing Raman backscattering to measure temperatures of optical fiber, has recently been installed in production wells at the Beowawe and Dixie Valley, NV, geothermal fields. The system has the potential to reduce the cost and complexity of acquiring temperature logs. However, the optical transmission of the initial fibers installed at Beowawe degraded over several months, resulting in temperature errors. Optical transmission spectra of the failed fibers indicate hydroxide contamination via hydrogen diffusion as a possible failure mechanism. Additional fibers with coatings designed to resist hydrogen diffusion were installed and have maintained their optical transmission over several months in the 340-360 °F Beowawe wells.

The same fibers installed in a 470 °F Dixie Valley well rapidly failed. Possible methods to prevent fiber degradation include encasing the fiber in metallic buffer layer that resists hydrogen diffusion. Additional methods to correct temperature errors include using additional optical sources to measure fiber losses at the operating wavelengths. Although the DTS system is expected to have one degree F accuracy, we have observed an average accuracy of five degrees. The fiber connections appear to be the uncertainty source. Using connectors with greater stability should restore accuracy.

INTRODUCTION

With the implementation of cold water injection and maximized production from geothermal wells, it is desirable to monitor the well temperature, and thereby the reservoir, for cooling trends. The importance of temperature monitoring for injection well placement is indicated by the trends previously reported [1] at the Beowawe, NV, geothermal field. Traditionally, monitoring well temperature has involved traversing the well bore with a thermocouple encased in a logging tool. It is difficult to monitor the subtle trends in well over several years with conventional tools due to variability in the calibration between tools, and possibly variation in one tool over time. Some wells require a high temperature electrical cable, which adds to the cost of logging. There is also a risk of losing the tool in the wellbore with each traverse.

The distributed temperature sensor (DTS) is a relatively new technology with the potential to solve many of the current problems in monitoring well temperature. The sensing element is a fiber optic cable that can be permanently installed in the well. Because the fiber is permanently installed, the same DTS installation can provide accurate and highly repeatable temperature measurements over many years. The fiber is run down the well in small diameter stainless steel tubing that can be integrated into scale inhibition or pressure monitoring systems [2]. Distributing the cost of installing the fiber over many years can reduce the cost of temperature logging. Integrating the fiber into scale inhibition systems minimizes the risk of fouling the wellbore.

Although the DTS system has the potential to improve well temperature logging, and has been successful in other industries, there have been problems implementing the system in the harsh environment of a geothermal well. In the initial installation at the Beowawe geothermal field, the well operator has observed large temperature changes over several months and variations of several degrees in logs taken a few minutes apart. Comparison of the DTS logs to conventional temperature logs shows the DTS logs are erroneous. This paper describes our understanding of the DTS operating principles, assessment of the problems, and current work to correct the problems.

PRINCIPLE OF DTS OPERATION

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 nano-second duration. As the laser light travels through the fiber, small defects in the glass scatter a portion of the light moving through the fiber. The light scattered back toward the laser, termed backscatter, is detected by the DTS as a function of time. The majority of the backscatter is at the same optical wavelength (color) as the laser and is referred to as Rayleigh scatter. A small portion of the backscattered light will be shifted in optical wavelength from the laser. Although there are several phenomena that shift the wavelength, the DTS uses light shifted in wavelength by Raman scattering to sense temperature.

Raman scattering refers to an in-elastic collision of the light with the atoms in the glass fiber. Raman differs from Rayleigh scattering in that energy is transferred between the light and the atoms. In the majority of Raman scattering, the laser light loses part of its energy to the atom before moving on. The loss of energy increases the wavelength of the laser light in a process known as a Stokes shift. The energy gained by the atom promotes the energy level of its electrons to an excited state. If the electrons of the atom happen to be in an excited state at the time of the collision, the atom can donate its electron energy to the scattered photon. The added energy decreases the wavelength of the scattered light in a process known as an anti-Stokes shift. As the temperature of the atoms increase, more of the electrons are in an excited state and more of the anti-Stokes scattering occurs. Hence, the anti-Stokes light is temperature dependent.

Conceptually, the DTS could monitor the fiber temperature by detecting only the anti-Stokes Raman scattering. In reality some of the laser light is lost to bending, environment stresses, and other unpredictable localized losses in the fiber. As a result, a decrease in the detected anti-Stokes scattering could either be a new loss in the fiber or a temperature decrease. To compensate for dynamic losses, the DTS normalizes the anti-Stokes signal with the Stokes signal. Both the Stokes and Anti-Stokes light will incur the dynamic loss, such as a bend, however only the anti-Stokes will decrease due to dropping temperature. The ratio of anti-Stokes to Stokes cancels the dynamic losses, leaving the temperature changes.

It is important to understand that the Stokes and anti-Stokes scattering exist at different optical wavelengths. The DTS used for this study (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 [3]. The corresponding 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. The problems described in the following sections are dependent on the difference in losses between the two wavelengths.

The Raman scatter returning from the fiber is detected by a photodetector. To provide temperature data, the digitized voltage from the photodetector must be calibrated to a reference temperature. Because the Raman scattering is dependent on the glass defect density, which varies between individual fibers, each fiber must be calibrated separately. The DTS ratio of anti-Stokes to Stokes Raman scattering includes three calibration coefficients that relate the detected intensity to absolute temperature. One factor determines the sensitivity, the second is a constant offset, and the third corrects for the difference in losses at the Stokes versus anti-Stokes wavelengths. In the recent installation of fibers at the Dixie Valley field, a thermocouple installed at the bottom of the fiber tubing and temperatures from a conventional logging tool at the surface and middle of the fiber were the reference temperatures. The calibration coefficients were varied until the DTS temperature matched the references at the three depths.

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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 nano-second pulse length resulting in a minimum of one meter between temperature readings.

INITIAL FIBER FAILURES

As described in ref. [1], the initial installation of fibers at the Beowawe field began to produce erroneous temperatures soon after installation. The error could be corrected by adjusting the calibration coefficients, however doing so requires the fiber be recalibrated to known temperatures. In addition, the errors continue to accumulate over time, requiring recalibration for every reading. The cost and complexity of recalibrating reduces the benefits of the DTS system.

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. 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 a 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 absorption peaks of hydroxide (-OH) in silica glass [3]. Past research in OH contamination of telecommunication fibers [4] found the contamination mechanism is free hydrogen diffusing into the core and reacting with oxygen trapped in the glass.

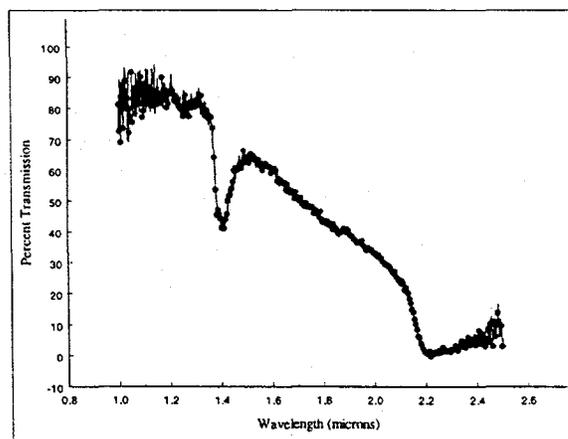


Fig. 1: Transmittance of light through the degraded polyamide fiber relative to new polyamide fiber.

NEW BEOWAWE FIBERS

All optical fibers are coated with a buffer layer to protect them from their environment. The initial fibers installed at Beowawe were coated with a layer of polyamide that is commonly rated for high temperature environments. To correct the apparent problem with hydroxide contamination, fibers with carbon coatings in combination with polyamide or Teflon were installed in the Beowawe wells. The carbon coatings have been developed to resist similar hydroxide contamination via hydrogen diffusion in deep-sea fiber optic cable [4]. In addition to the carbon fibers, an enhanced polyamide fiber was installed. Table 1 lists the second generation of fibers installed in the Beowawe wells.

Well	Fiber Coating	Date Installed
Ginn 1	Enhanced Polyamide	3/98
Ginn 2	Polyamide/Carbon	12/96
77-13	Teflon/Carbon	8/97

Table 1. Fiber optics currently installed in the wells at the Beowawe, NV, field.

To monitor the condition of the new fibers, we have measured their optical transmission in the wells using an optical time-domain reflectometer (OTDR). An OTDR uses the same operating principle as the DTS (inject a pulse of light into the fiber and measured the amount of backscattered returned as a function of time) except, it uses the Rayleigh scattering rather than the Raman. OTDR is commonly used to measure the transmission losses of telecommunication fiber optic cables. Unfortunately the OTDR measures the transmission losses at 850 and 1300 nm, which are the dominant telecommunication wavelengths and not the DTS wavelengths. However, the OTDR wavelengths do

surround the DTS operating wavelengths and the proximity of 1300 nm to the 1380 nm hydroxide absorption peak is a good indicator of hydroxide contamination. Figure 2 shows the OTDR traces from the Polyamide/Carbon fiber in Ginn2 over a seven month period.

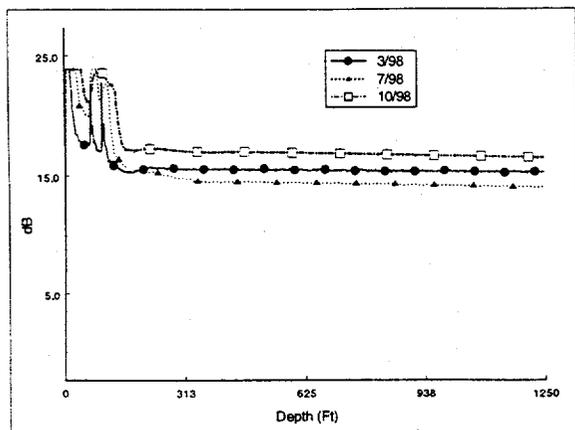


Fig. 2: OTDR traces from the carbon/polyamide coated fiber installed in the Ginn2 well, Beowawe Field.

The slope of the traces in Figure 2 is constant, indicating that the fiber losses have not changed. Because the loss values match the manufacturer specification for new fiber, it appears the transmission has not changed since the fiber was installed in December of 1996. The offset between the traces in Figure 2 indicates changes in the transmission of the fiber interconnects and the peaks are reflections from the connections. The other fibers in the Beowawe wells have also maintained their transmission properties.

The DTS logs from the new fibers have been within five degrees of the expected temperatures from conventional logs since they were installed. The DTS accuracy is limited to five degrees, rather than the expected one degree, by variance that shifts the temperature log between repeated acquisitions. This variance is discussed in a following section.

DIXIE VALLEY INSTALLATION

Based on the success of the new fibers in the 340-360 °F Beowawe wells, polyamide/carbon and enhanced polyamide fibers were installed in a 470 °F production well at the Dixie Valley, NV, field. These fibers were installed in two configurations: the enhanced polyamide was single ended and carbon/polyamide was double-ended. Single-ended refers to a length of fiber starting at the surface, running down the well and ending at the bottom. The

double-ended configuration is a single length of fiber that starts at the surface, runs down the well, loops at the bottom, and runs back to the surface. The details of the installation can be found in ref. [2.] All of the previous Beowawe installations were single-ended.

A double-ended installation allows the DTS to acquire scattering data from both ends of the fiber. The purpose of taking data from both ends of the fiber is to cancel the transmission difference between the Stokes and anti-Stokes. The double-ended operation is best explained in terms of an example. Consider a fiber at constant temperature along its entire length. The Stokes and anti-Stokes traces from the fiber would appear very similar to the traces of Figure 2 when plotted on logarithmic scale (constant slope) except for the different slope between them. The difference in slope relates to the difference in inherent loss per unit length between the Stokes and anti-Stokes wavelengths. When the ratio is taken to calculate the temperature, the result will not be constant as expected. Instead, the temperature will be increasing or decreasing with a slope equal to the difference in slope between the Stokes and anti-Stokes traces. The ratio of the data from the other end of the fiber will have an identical slope, *except*, it will be reversed in regards to depth. The DTS takes a geometric mean of the two ratios resulting in a flat line and constant temperature. For the single ended fiber, the DTS uses the differential loss calibration (DLC) factor to scale the slope of the ratio back to a flat line in this example.

A double-ended fiber was included in the Dixie Valley installation to see if the technique could correct for changes in the fiber transmission and improve the accuracy observed in the single ended fibers at the Beowawe field. Unfortunately, the fibers began to fail soon after they were installed in the 74-7 well at Dixie Valley. Figure 3 shows the temperatures logs produced by the DTS after installation on 7/9/98. The log on 7/10/98 does match a conventional log taken on the same day. The logs in the next two months show the correct profile but have unacceptable errors. By 10/14/98 the DTS does not receive enough scattering from the fiber to produce a profile. The accuracy of the double-ended fiber was ± 1 °F in the July log but degraded to the ± 5 °F in the following months.

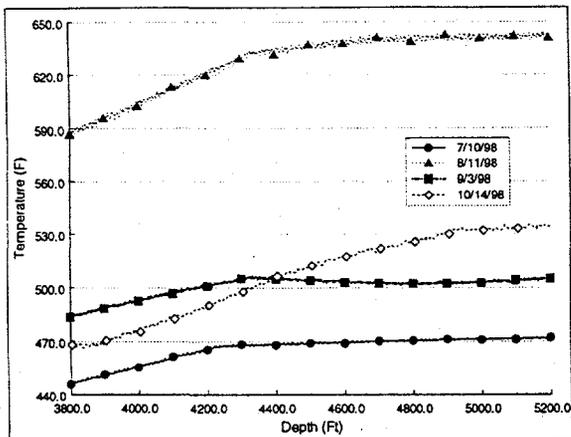


Fig. 3: DTS temperature logs over time from a failing fiber in the 74-7 well, Dixie Valley field

The degradation of optical transmission in the Dixie Valley fibers was monitored with OTDR measurements. Figure 4 shows the 1300 nm traces from the double-ended fiber one day and three months after installation. Apparently, the changes in the optical transmission began at installation and were accelerated between 4000 ft and the loop at 5000 ft. The change at 4000 ft corresponds with the flash point of the flowing well. By 10/14/98 no 1300 nm light was returned from depths greater 4000 ft and 850 nm light reached only 5500 ft.

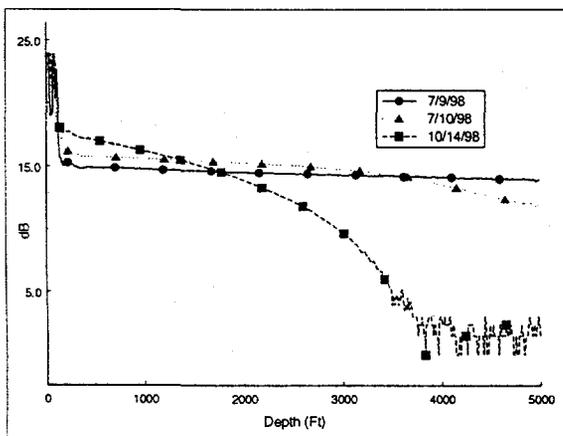


Fig. 4: 1300 nm OTDR trace of failing fiber in 74-7 well, Dixie Valley field.

Although the increase in light loss was non-linear versus increasing depth, the losses at 1300 nm appear to increase at a rate five times greater than 850 nm. The greater increase and the proximity of 1300 nm to the 1380 nm hydroxide absorption peak suggests hydroxide contamination, via hydrogen diffusion, was again the cause of the DTS error.

DTS ACCURACY

Although the temperature logs from the current Beowawe fibers are stable, we have observed variations up to $\pm 5^\circ\text{F}$ around the expected water temperature below the flash point. A typical series of sequential logs is provided in Figure 5 where the second log is shifted from the first by three degrees. Ideally, these logs would have $\pm 1^\circ\text{F}$ accuracy or better to follow the subtle trends shown in ref. [1]. Similar uncertainties are seen between logs taken months apart.

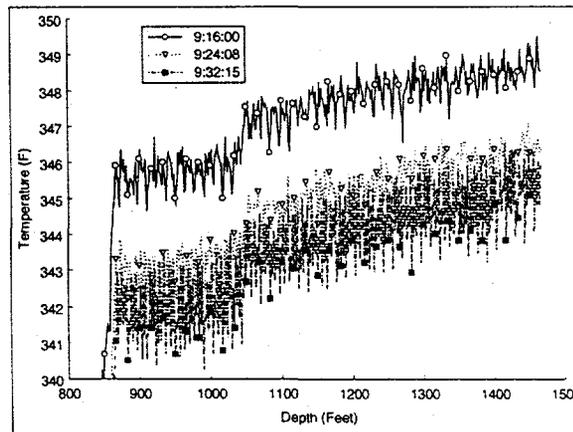


Fig. 5: Sequential DTS temperature logs from the Teflon coated fiber in the Ginn2 well, Beowawe field. The start time for each log is shown in the legend.

The well owner has monitored the water temperature below the flash point with conventional logging tools in the recent past. The conventional tool shows little temperature variation above its own noise level. Hence, the DTS temperature shifts are an artifact and limit the DTS accuracy to $\pm 5^\circ\text{F}$. However, Figure 6 illustrates that the DTS can produce 0.1°F repeatability in a fiber optic reference coil, contained in the DTS, for the same logs shown in Figure 5. Similar repeatability had been seen in fiber deployed into a gas well [5.]

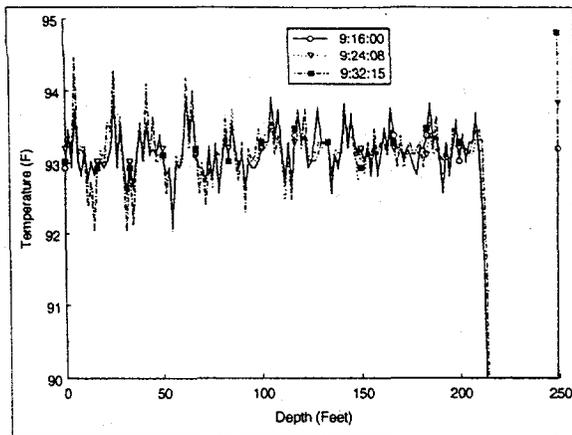


Fig. 6: Sequential temperature logs of the DTS reference coil for the same logs shown in Fig. 5.

Figure 7 shows the difference between the first and second trace of Figure 5. Between 0 and 200 feet is the DTS fiber reference coil, which never shows a variation greater than 0.5 degrees. A patch fiber runs from the DTS at 200 ft to the wellhead at 370 ft. There is a 1 degree negative offset in the patch cable. The step change in temperature at the wellhead creates large differences. The difference remains a constant 2 degrees in the well even though the temperature is increasing between the wellhead and water level. Because the variability makes discrete changes in amplitude and those change are correlated with the fiber connections, it appears the fiber interconnects are the uncertainty source.

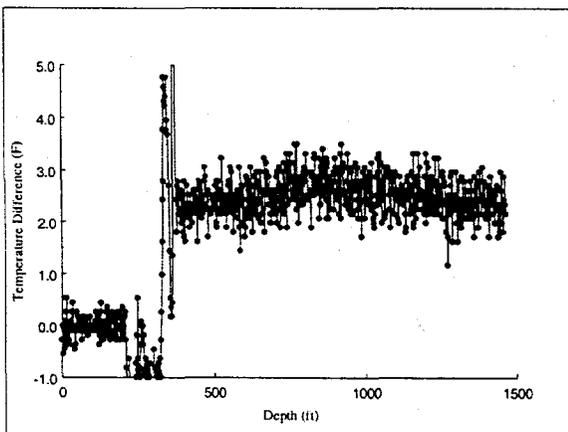


Figure 7. The Temperature difference between the first and second traces of Fig. 4.

Before the double fiber failed in the Dixie Valley, it provided +/- 1 degree accuracy in repeated logs. The single-ended fiber had +/- 1 degree on the same day. From these limited results, it appears the double-ended technique could restore the DTS to the ideal levels.

DISCUSSION

There are two problems to solve before the DTS will be a viable alternative to conventional logging techniques: hydrogen diffusion into the fiber and poor repeatability.

At this time, it appears the problem of hydrogen diffusion has been solved in the Beowawe wells with carbon and enhanced polyamide buffers. However, these same fibers began to degrade within a day of installation in a Dixie Valley well of greater temperature and length. The double-ended correction was unable to cope with the magnitude of the changes. The cause of the failure appears to be accelerated hydrogen diffusion into the fiber. Diffusion of hydrogen into the stainless steel tubing and the carbon coating is exponentially dependent on temperature. In addition, the loss of light is exponentially dependent on length of the fiber. Hence, the fiber resistance to hydrogen must be increased to operate in wells of greater temperature and length than the Beowawe wells.

An additional buffer layer is needed around the fiber to resist hydrogen diffusion. At this time there are several possible methods under review. One possibility is a thin (1-10 μm) coating of silver on the fiber or interior of the stainless steel tubing. We estimate the silver coating could lengthen the hydrogen diffusion time by a factor of 100 to 1000 times its current rate. Another possibility is continuously flushing the stainless steel tubing with nitrogen to evacuate the hydrogen.

Although the above methods will deter the hydrogen diffusion, it is unlikely the diffusion will be stopped. To reduce the sensitivity of the DTS to the hydrogen and hydroxide contamination, the laser wavelength can be moved away from the absorption peaks. A likely replacement is an 850 nm diode laser. To compensate for any remaining changes in the optical transmission it may be possible to include additional laser sources at the anti-Stokes and Stokes wavelengths. These lasers will measure the losses at both wavelengths using the OTDR technique. The measured loss values can then be used to maintain the temperature calibration even as the fiber transmission changes.

Figure 7 indicates the accuracy problem is related to the fiber connectors. The cause of the variation could be a time varying misalignment of the fiber cores at the connections. In particular, the higher order modes that propagate at the periphery of the fiber optic are

lost for core misalignments on order of microns. Just like the transmission losses, the number of modes are wavelength dependent. The anti-Stokes scattering contains approximately 17% more modes than the Stokes scattering. Hence any misalignment has a greater affect on the anti-Stokes scattering and varies the calculated temperature.

To reduce the uncertainty of the DTS logs, all connections that can be permanent will be fusion spliced and a connector with greater stability will be used in the necessary connections. Currently the system uses the E1200 quick connector type. Switching to the threaded FC type should improve the stability. If improving the connector does not meet the accuracy goals, using double-ended fibers may correct the remaining variation.

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