RECENT DEVELOPMENTS IN FIBER OPTIC SENSOR TECHNOLOGY FOR HIGH TEMPERATURE WELL MONITORING

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Abstract

New developments in fiber optic sensor technology for high temperature well monitoring have been driven by their use in thermal recovery wells in the Canadian oilsands industry. These developments have resolved hydrogen-induced optical failure of fiber optic systems deployed in steam-assisted gravity drainage (SAGD) wells operating up to 300°C. This same hydrogen failure was likewise experienced in deploying fiber optic sensors in geothermal wells at similar temperatures. High temperature upgrade of a suite of downhole optical sensors is enabled through refinement of high temperature, hydrogen-tolerant optical sensing fibers and cables. This paper will review hydrogen effects on optical systems operating in high temperature, hydrogen-rich well environments, and mitigation of these effects through use of pure silica optical fibers. Field results for optical distributed temperature sensors and point pressure sensors operating on these fibers in high temperature SAGD wells validate the use of these sensors in these environments, and demonstrate reliability and good correlation to downhole thermal references. These results, along with design features and operating aspects for these systems will be discussed to show the technology now well-positioned for use in high temperature geothermal well monitoring.

Introduction

Downhole monitoring of geothermal well temperature, pressure and fluid flow is essential to effectively stimulate the reservoir and augment operations for maintaining temperature and production rate to maximize energy extraction. High quality data in terms of reliability and accuracy becomes critical for improved reservoir management through better insight into reservoir evolution, temperature decline, and validation and updating of reservoir models. Fiber optic distributed temperature sensors (DTS), in which temperature is measured along the entire length of a sensing fiber, has long been attractive as a geothermal well logging tool to provide a full wellbore temperature profile in real time to monitor trends in the well over its operational lifetime. A permanently installed DTS sensing fiber encased in small diameter stainless steel armored tubing provides a simple yet elegant sensing architecture over conventional logging tools periodically run in the well. While presenting a more cost-effective logging solution over time, a single permanent tool promises step-improvement in accuracy and repeatability over conventional methods that are prone to variability in calibration.

Despite these advantages, early work by Smithpeter et al(1) in deploying such DTS systems in geothermal production wells at the Beowawe and Dixie Valley fields in Nevada were challenged by the high temperature well environment. These systems experienced rapid hydrogen-induced fiber attenuation when operating in the high temperature/hydrogen-rich well environment, leading to measurement error and premature failure. These hydrogen-induced failures are common to fiber optic sensors operating in high temperature well environments. To address this problem, most oil and gas fiber optic sensing systems today, rated upwards to 175°C or so, use hermetic fiber coatings or cable materials to block or slow hydrogen diffusion to mitigate hydrogen effects. An effective hydrogen mitigation strategy is critical for success in any downhole fiber optic sensing system, and serves as the basis for the design of most oil and gas sensing cables.

Hydrogen Effects in Fiber Optic Sensors

Based on quartz optical fibers, fiber optic sensors have long been viewed as an upgrade technology for high temperature logging applications. Conventional tools such as thermocouples, while proven at these elevated well temperatures, are not practical for installing the necessary number of sensors to give a meaningful spatial representation across the entire wellbore. In recent years however, the hydrogen problem has reemerged when deploying extensions of oil and gas fiber optic sensing systems in SAGD where they have experienced significant hydrogen-induced failure. While these systems survive mechanically through use of high temperature polymer fiber coatings up to 300°C, they are prone to hydrogen diffusion as hermetic materials available in the supply chain that are compatible with oil and gas optical sensing cables are ineffective at these regimes, becoming porous to hydrogen diffusion above 200°C.

Hydrogen is ubiquitous in any well environment due to formation chemistry, and the liberation of hydrogen the product of galvanic reaction between well fluids and steel completion parts. Hydrogen diffusion in optical fiber manifests into both transient and permanent attenuation in which the magnitude of latter is dominant and highly dependent on the glass composition of the optical fiber itself. Transient losses are reversible, caused by absorption due to dissolved hydrogen in the glass. Once hydrogen is removed, the fiber returns to its original clarity. In contrast, permanent losses are irreversible, caused by chemical reactions of hydrogen with glass precursor defects that form light absorbing species (e.g. hydroxyl ion).

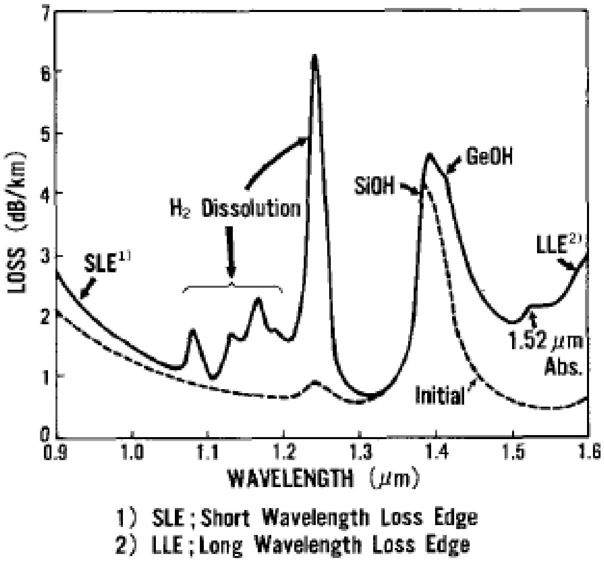


Figure 1. Typical Hydrogen-Induced Fiber Attenuation In Silica Optical Fiber
Source: Iino et al (Reference 2)

Hydrogen loss growth is dependent first on hydrogen diffusion rate, a function of temperature, in which initial transient loss is observed, its magnitude governed by the hydrogen solubility in the glass, which quickly achieves equilibrium as a function of temperature and hydrogen partial pressure. From there growth in permanent losses begins to take over, in which loss growth is relatively complex and difficult to predict. A typical loss spectrum (2) is shown in Figure 1, in which transient losses, a function of hydrogen solubility, with characteristic monotonic loss growth at hydrogen absorption lines with a principal line at 1240nm in the near-infrared wavelength range of interest. Transient loss is uniform across different fiber types, as the solubility of hydrogen in the glass is independent of fiber type, and achieves equilibrium once hydrogen diffusion reaches saturation.

Chemical reactions that drive permanent losses are more complex, a function of defect type, their concentration, and the activation energy of bonding and valence specific to each reaction. The type of defect and population is dependent upon the glass composition, and subtleties of the fiber manufacturing process. The magnitude of permanent hydrogen loss has been found to be directly dependent upon the amount of common refractive-index modifying dopants such as GeO2 and P2O5 used in conventional telecom fibers. This can be seen in Figure 2 that shows growth in attenuation (pure hydrogen at 185°C) for a set of fibers with various dopant profiles.

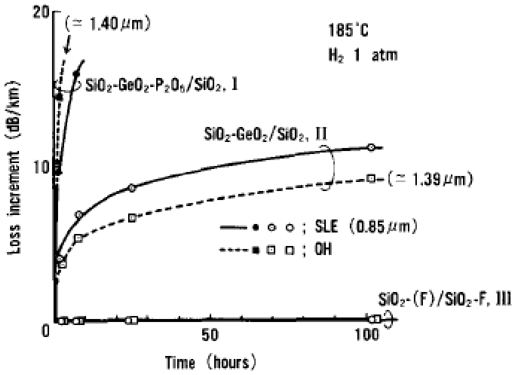


Figure 2. Loss Increase a Function of Time for Different Fiber Types
Source: Iino et al (Reference 2)

Of the three types, pure silica core with fluorinated cladding show superior response with no discernable loss increase in this test. The absence of dopants in the core practically eliminates all precursor defects, with only Si diamagnetic centers contributing to hydroxyl formation, with absorption at 1385nm, the primary permanent loss effect common in these fibers. Furthermore, fluorinated cladding materials have been shown to not adversely affect hydrogen performance of these fibers.

Such pure silica core fibers present a resolution to hydrogen aging and induced attenuation effects, to operate effectively in high temperature hydrogen environments in which permanent losses, if any, are minimized and while still subject to transient hydrogen loss, is minimal at elevated temperature and typical hydrogen partial pressure seen in downhole applications.

Hydrogen-Tolerant Fiber for High Temperature Wells

High temperature, hydrogen tolerant fibers based on pure silica core fibers present a solution to the hydrogen problem in the SAGD sector for sensor operating to 300°C. Typical permanent loss contribution of these fibers is isolated to hydroxyl formation with absorption at 1385nm. Sensor systems operating at the1550nm "telecom" or shorter wavelengths centered around 1064nm, are both out of this absorption band and avoid any effects due to hydroxyl loss growth. Both single mode and multi-mode hydrogen tolerant fibers of this class have been commercially introduced, to operate all sensor types. Figure 3 shows hydrogen loss increase for commercial polyimide coated pure silica core single mode and multi-mode fibers with a control telecom-type fiber for reference. The fiber was tested to saturation over 300-hours exposure at 220°C to 1,200psi pure hydrogen. As seen in the data, both pure silica core fibers show negligible permanent hydrogen loss except the increase at the 1385nm hydroxyl line for the multi-mode fiber typical for these fibers. This data is consistent and further verified with more extensive fiber manufacturer hydrogen test data.

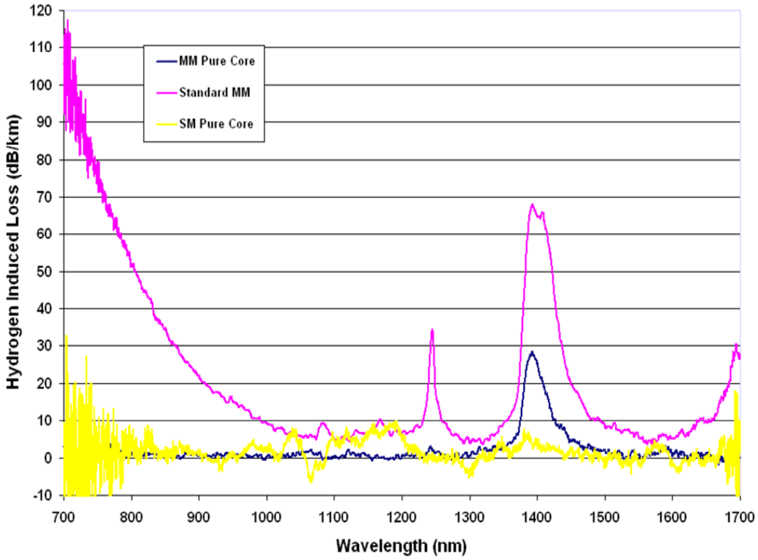


Figure 3. Hydrogen Induced Spectral Attenuation 300-hours 220°C 1200psi H_2

All-metal construction, high temperature cables have been developed to deploy, seal and protect the fiber from well fluids and rigors of installation. These cables feature a design excess fiber length evenly distributed within the cable to bias thermal expansion mismatch between the metal cable and glass optical fiber and subsequent strain during heating. Cable form factor is the same ¼" alloy armor as electrical or hydraulic control lines, and therefore compatible with conventional well installation equipment and procedures.

High Temperature Fiber Optic Sensors Systems

Raman type DTS instruments have been in the commercial stream over 30-years. These systems are based on Raman scatter effects of high intensity light launched into an optical sensing fiber, in which interaction between light and glass, part of the light energy is transferred, and subsequent loss of energy increases the wavelength of light (Stokes-shift), while the transferred energy can be donated to excited state atoms to cause decreased wavelength (Anti-Stokes shift). The amount of energy donated, and relative intensity of Anti-Stokes shifted light, is related to the amount of atoms in an excited state, a function of temperature. Such nonlinear shifted light can be collected and guided by the fiber to be received and analyzed. In these systems, light pulses are launched into a sensing fiber and the return time and intensity of backscattered signals recorded to calculate temperature at specific locations all along the fiber to yield a fully distributed temperature sensor. Such Raman DTS systems have emerged in the oil and gas industry as a powerful monitoring tool for downhole applications. Since commercial introduction of fiber optic sensors in the launch offshore sector, Shell and others have reported over 1200 permanent installations in which Raman DTS is the prevalent sensor technology offered by leading oilfield services firms.

Conventional Raman DTS instruments measure slight changes in the ratio of Stokes/Anti-Stokes intensity, which are separated in wavelength approximately 200nm apart in typical near-infrared systems. Prior to installation, the sensing fiber or cable must be calibrated for each individual sensing fiber as this coefficient, and intrinsic optical attenuation at these wavelengths will vary among different sensing fibers. Once installed, successful operation of these sensors requires isolating the fiber from hydrogen, as even small amounts of hydrogen diffused into a sensing fiber creates measurement error in which wavelength-dependent hydrogen absorption creates differential fiber attenuation (DFA) between that of the intrinsic calibrated fiber and the fiber under hydrogenated condition, and furthermore will affect the Stokes/Anti-Stokes lines differently as the wavelength separation between them is significant. DTS measurement error due to hydrogen-induced DFA is shown in the figure below that plots DTS measurement performance operating on a conventional telecommunications-grade optical fiber held at steady temperature but exposed to hydrogen. Here the DTS measurement is corrupted almost immediately upon hydrogen diffusion and subsequent DFA causing offset of the ratio of backscatter signal intensity.

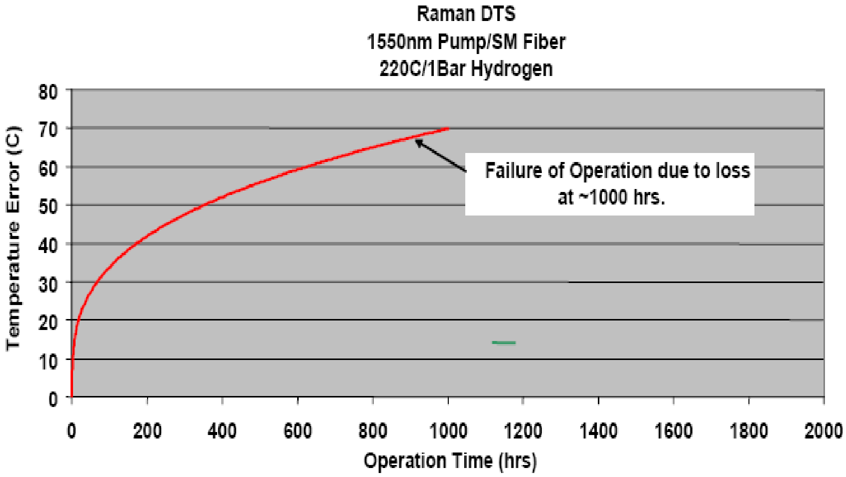


Figure 4. Hydrogen-Induced Measurement Error

To address this problem, DTS suppliers have developed compensation methods through dual- or partial-return downhole sensing configurations and measurement protocols, which are now commonly offered as a standard feature in most DTS interrogator instruments. In a dual-ended or partial return sensing configuration, the fiber is installed into the well with fiber in a turnaround loop or sub at the end of the well, where the fiber returns partially or all the way back to surface. With these sensing configurations, it is possible to re-calibrate DTS measurements to compensate for DFA by implementing a measurement protocol and compensation algorithm. As shown in the Figure 5 below, this particular architecture has two variations, one where the sensing cable has access to both ends at the surface, and the other where the sensing cable has a "turn-around" at the bottom, and the cable travels only a portion of the way back up the well. The strategy in both cases relies on the fact that two positions of the cable (separated by a distance L) are exposed to an identical temperature. If the cable length between the two sensing points experiences a differential loss due to hydrogen diffusion into the glass or possibly from mechanical bending, there will be a temperature difference between the two points. This temperature difference is then used to compensate the particular length of fiber between the two points and correct for the temperature difference. This process is applied over the entire length of the fiber section that has overlapping temperature points and a complete picture is then stitched together to correct the measured temperature along the entire section of cable that has duplicate points. The fully dual-ended system, where the cable is interrogated from each end, has the ability to compensate the entire cable from top to bottom.

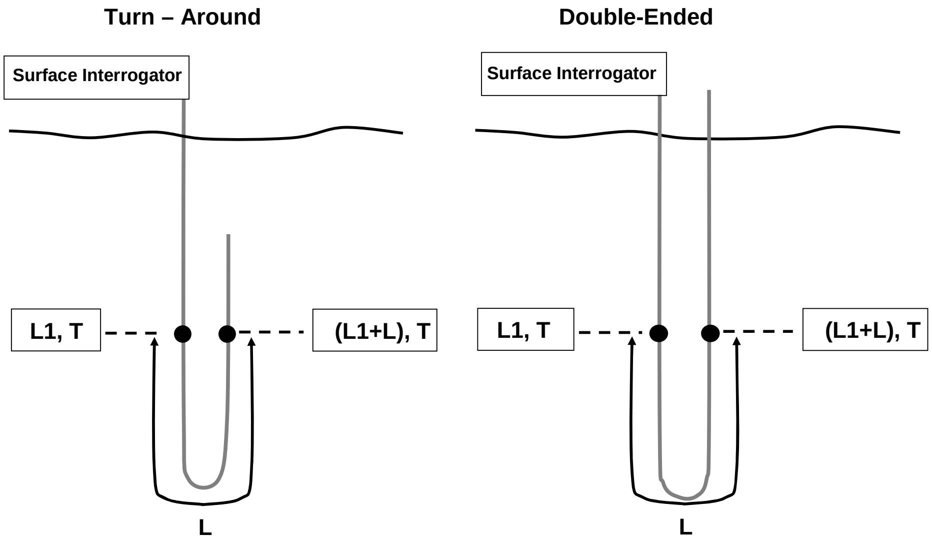


Figure 5. Dual and Partial Return DFA Compensation Configurations

High Temperature DTS Field Results

Optical sensors have a strong track record of reliability in the conventional oil and gas sector where maximum operating temperature up to 185°C allow use of hermetic sensing cables to deal effectively with hydrogen. Upgrade of these systems for use in SAGD and other applications at higher temperature requires the system to tolerate hydrogen rather than prevent its diffusion. With Raman DTS systems, this has been accomplished through the combination of new hydrogen tolerant, pure silica core sensing fibers, and dual-ended compensation. Laboratory and field results in operating SAGD wells show little to no permanent hydrogen-induced attenuation, with transient induced hydrogen, although minimum at these high temperatures, effectively compensated through dual-ended architectures. Over 20-month field results were recently published by Kaura et al.(3) for a DTS system installation in a JACOS well that continues to operate with good correlation to downhole thermo-couple references as shown in the 12-month published(4) data in Figure 6 below.

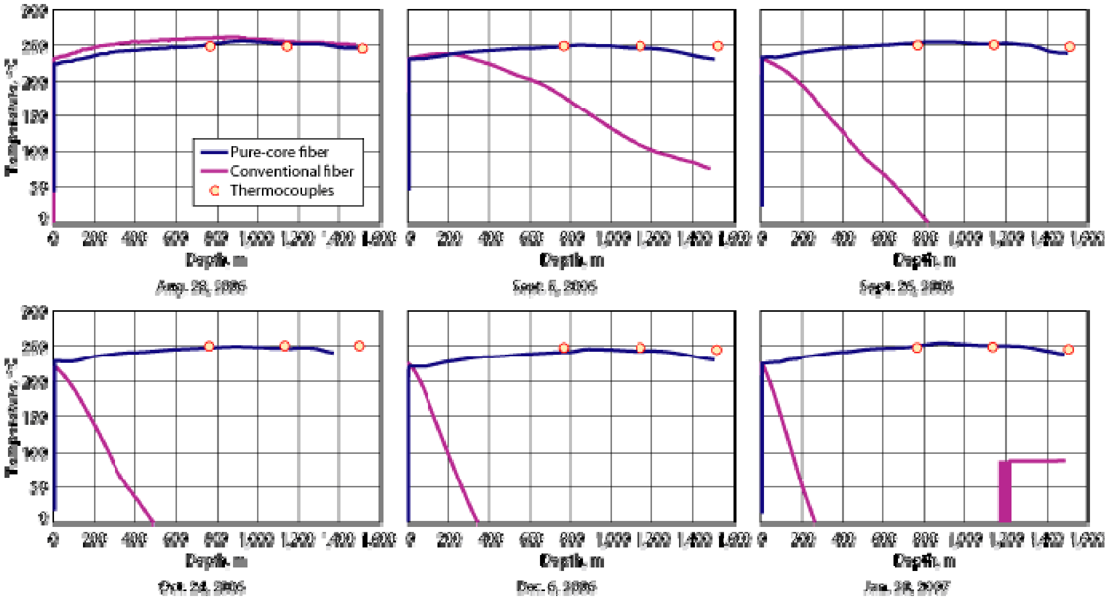
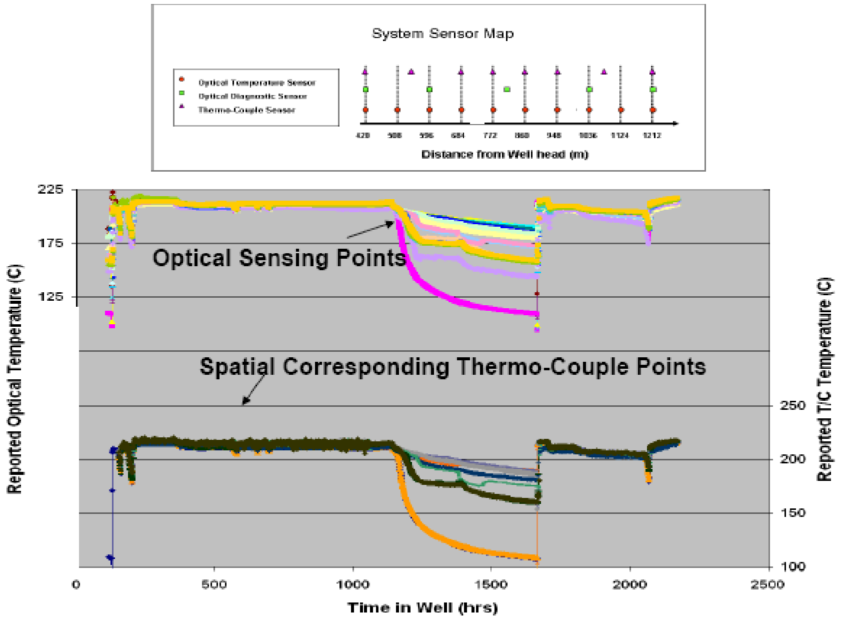


Figure 6. Published DTS Field Data- JACOS SAGD Well (Reference J Kaura et al. World Oil June 2008)

Here the system includes three thermo-couple references, the new pure silica core sensing fiber, and a conventional sensing fiber as a control. Just one week exposure, the adverse effect of hydrogen on reported temperature of the control fiber can be seen, until signal is lost at the far distal end of the control fiber within one month. This is the typical failure mode of Raman DTS operating on these fibers in SAGD, which have now been resolved as demonstrated in the pure silica core fiber results.

High Temperature Fiber Bragg Grating Sensors

An alternate hydrogen strategy is through use of frequency-encoded rather than intensity based systems that are impervious to DFA hydrogen measurement errors. Brillouin OTDR and fiber Bragg grating sensors operating on pure silica or other hydrogen tolerant fibers have been investigated, with the latter configured in multi-point sensor arrays demonstrating superior measurement performance in SAGD wells. Fiber Bragg grating arrays (FBGA) in which commercial systems incorporate over 40 discrete sensors in a single sensing fiber, offer the advantage of greater power, update rate, and measurement resolution over Raman DTS. Such arrays are available from some manufacturers leveraging production methods that “imprint” the sensors in the fiber in a continuous process as a practical means of creating arrays with out splices for high mechanical reliability. First trial FBGA systems were installed in a pilot SAGD injection well at Nexen’s Long Lake facility in fall 2007. Field performance data for this system shown in Figure 7 below, was reported at a Petroleum Technology Alliance Canada (PTAC) technical information session in Calgary in March 2008.



PTAC Technology Information Session March 5, 2008

Figure 7. Fiber Bragg Grating Thermal Monitoring Field Data- Nexen Long Lake SAGD Pilot Injector Well (source: LxDATA)

According to the manufacturer, LxDATA, this system continues to operate with better than 95% installed optical power budget, delivering ±1.7°C absolute accuracy (3σ) measurement performance compared to collocated thermo-couple references (8 each) evenly distributed over the heated horizontal well section (1200m) with an average operating temperature of 220°C. Since the trial system, over 20 well installations in a mix of SAGD producer and gas lift completions have been completed with similar measurement results in wells operating up to 280°C. Recently, extension of the FBGA technology has been used to introduce point pressure gauges on the same fiber and sensing platform as presented in a recent PTAC session in 2009.

Aspects in High Temperature Geothermal Wells

Successful demonstration of hydrogen-tolerant fiber optic sensors in the SAGD sector present a solution to the hydrogen failures experienced in early deployment such sensors in geothermal wells. Major system components including surface interrogation instruments, surface cabling systems, and downhole sensing fibers and cables are transferable for use in geothermal wells up to 300°C. Anticipated EGS wells however depart from SAGD in vertical well depth, up to 10,000ft versus 500ft or so before “turning” horizontal in SAGD, and could be uncased compared to SAGD cemented liner completions. Sensing cable installation in the well using conventional coiled tubing deployment methods used in SAGD should also be easily transferable, as the vertical geothermal well configuration is more receptive of these methods. The long vertical uncased well however presents a strain and potential dynamic environment acting on the sensing fiber cable that would need to be addressed in the cable design. Cable designs to impart a deign amount of fiber stiction and other supporting features are envisioned for upcoming EGS demonstrations.

Conclusions

Refinement of high temperature optical sensors in the thermal recovery sector of oil and gas positions the technology to provide a set of high temperature logging tools for geothermal well monitoring. Specifically, use of new hydrogen tolerant pure silica core fibers and dual-ended sensing fiber configuration and measurement protocol has resolved hydrogen failures for operating Raman DTS systems in high temperature, hydrogen-rich well environments above 200°C. An alternative approach uses frequency-encoded fiber Bragg grating technology that is not affected by hydrogen-induced measurement errors of which intensity based systems are prone. Multi-point grating arrays provide distributed temperature sensing architecture on a single sensing fiber. The fiber Bragg grating platform is also extended to provide point pressure gauges operating on the same sensing fiber and surface data acquisition system as the thermal monitoring system. Both the Raman DTS and fiber Bragg grating array technology have been installed in numerous SAGD wells with excellent correlation to collocated downhole thermocouple references, operating for over 10,000 hours at continuous temperatures to 280°C. These systems are rated to 300°C operating temperature which can address the bulk of anticipated geothermal wells, in which EGS trial systems are slated for demonstration at these temperatures and super-critical well temperatures up to 375°C. High temperature cables and downhole completions hardware compatible with conventional installation methods and equipment available from the oil and gas industry, hold promise for reliable deployment of sensing fibers in geothermal wells. New sensor interrogation equipment can probe the deployed fiber and bring forward an extended set of measurements, such as acoustic and strain, to realize the potential of fiber optics as a downhole sensor platform for future EGS systems.

References

1. Smithpeter C., Normann R., Krumhansl J., Benoit D., and Thompson S., 1999, “Evaluation of a Distribute Fiber-Optic Temperature Sensor for Logging Wellbore Temperature at the Beowawe and Dixie Valley Geothermal Fields”, Proceedings24th Workshop on Geothermal Reservoir Engineering, Stanford University, SGP-TR-162
2. Iino A., Kuwabara M., Kokura K., 1990, “Mechanisms of Hydrogen-Induced Losses in Silica-Based Optical Fibers”, Journal of Lightwave Tech., Vol. 8, No. 11, pp 1675-1679
3. Kaura J., Sierra J., 2008, “ Successful Field Application In Continuous DTS Monitoring Under Harsh Environment of SAGD Wells Using Improved Optical Fiber Technology”, SPE/PS/CHOA-117206
4. Kaura J., Sierra J., 2008, “High Temperature Fibers Provide Continuous DTS Data in Harsh SAGD Environment”, World Oil Magazine, June 2008