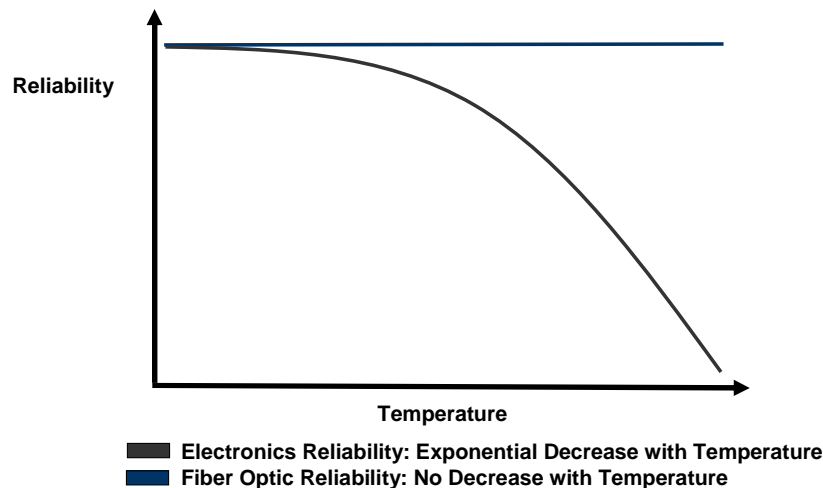




Fiber Optic Monitoring: Challenges and Solutions in High Temperature Steam Flood Environments

Introduction

Fiber optic sensor technology was first introduced to the oil and gas industry as a high reliability option over electronics in the higher temperature segment of the market, leveraging the reliability model of a quartz optical fiber based passive downhole sensing section (no moving parts) connected to a surface interrogation instrument.



Today a range of fiber optic sensor products are used throughout the oil and gas industry, with distributed temperature sensors (DTS) by far the most prevalent optical sensors currently in use. Since their commercial introduction roughly 10 years ago, fiber optic sensors have enjoyed an impressive record of success delivering critical downhole data, reliably, primarily in the offshore sector- the first to adopt the technology, as well as playing an increasing role in the onshore secondary recovery arena. Of course there have been some failures, typical with any new technology, but overall fiber optics has lived up to expectations and proven suitable in these intended applications. Unfortunately, this is not the case in attempts to apply DTS products in the unconventional thermal recovery sector, where the technology has under-performed in terms of reliability and quality of data. Simply put, these systems, designed for use in conventional wells, with an upper temperature rating of 185°C, are ill-suited for the more challenging +200°C and higher temperature environment typical in thermal recovery operations.

This paper will review these shortcomings and refute some of the attempted design modifications to the standard DTS platform to resolve the problem. This discussion will lead to abandonment of legacy DTS technology in high temperature wells, with a more robust distributed thermal monitoring solution realized in fiber Bragg grating array (FBGA) technology. This technology, pioneered by LxSix Photonics, has

demonstrated suitable reliability and performance required in preliminary SAGD field operation at continuous temperatures in excess of 200°C.

Limitations of Current Raman DTS Technology

When high energy laser pulses are launched and travel in an optical fiber, part of their energy is scattered due to inelastic interaction with the lattice structure and molecules of the glass, producing both wavelength up-shifted light (Stokes) and down-shifted light (Anti-Stokes). The intensity of these lines, the product of so-called nonlinear effects, is in some cases temperature sensitive, and as a consequence can be used to measure temperature. This phenomenon is used to configure a fully distributed temperature sensor (DTS) system in which the optical fiber itself is the sensing element.

In a typical DTS system, light pulses are launched into a sensing fiber and the return time and intensity of the backscattered signals recorded to compute the temperature at specific locations all along the fiber. Commercial DTS systems exploit either one of two nonlinear effects, namely Raman and Brillouin. Raman systems are the most common and used broadly for thermal measurements due to insensitivity of the scattered lines to strain, whereas Brillouin systems are used to monitor both strain and temperature. The cross-sensitivity inherent with Brillouin, and difficulty in discriminating temperature from strain in the dynamic downhole well environment has led to predominance of Raman systems in oil and gas.

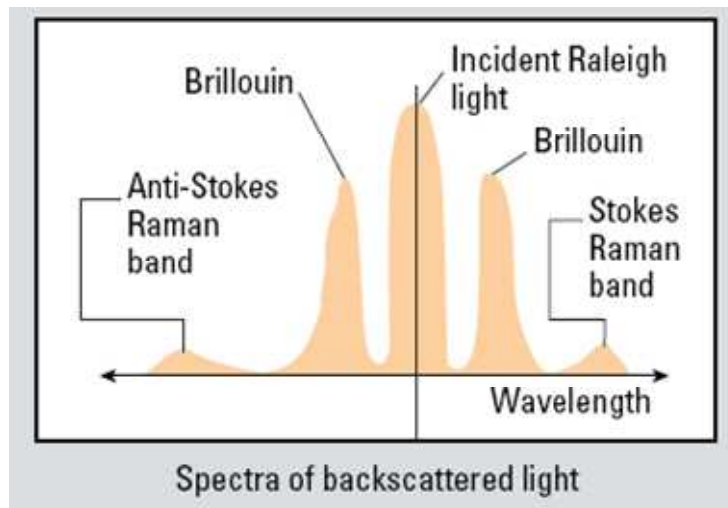


Figure Courtesy Sensa

Nonlinear Effect	Light Interaction	Relative Position	Temp Sensitivity	Strain Sensitivity
Rayleigh	Molecular Scatter	Incident	Weak	Weak
Raman	Molecular Vibration	26THz Separation	Strong (A-S) Intensity	Weak
Brillouin	Lattice Acoustic	22GHz Separation	Strong Frequency	Strong Frequency

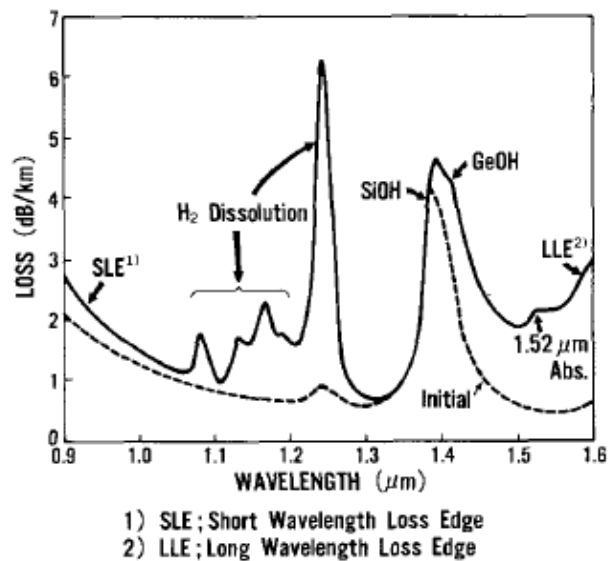
Raman DTS systems however are faced with several challenges when applied in oil and gas wells. The main challenge in deploying Raman technology becomes one of received signal power. Even with use of high-power pump lasers, the excited temperature-encoded Raman lines are quite weak, with thermal information extracted via measuring very small incremental power differences between the Stokes/Anti-Stokes lines. The low intensity signals lead to a limited dynamic range which minimizes system reach and presents performance tradeoffs in resolution and scale factor. Furthermore, the ability to measure such small power differences and extract useful temperature information requires massive data stacks to

average, leading to long processing time between measurements, one-hour or more is typical, and added instrument complexity and cost.

The Hydrogen Problem

Despite these challenges, refinement made to DTS instruments coupled with suitable protective cable design and careful attention to installation details, Raman DTS has emerged as a powerful monitoring tool in oil and gas, albeit with limitations. A key design consideration for these systems in oil and gas is the requirement to prevent any hydrogen from permeating into the sensing fiber and interfering with and corrupting the measurement.

Any optical system deployed downhole in oil and gas wells must deal with hydrogen which is present in the well chemical environment, as well as the product of galvanic reaction between well fluids and steel completion parts in the well. Hydrogen diffusion into optical fibers manifests into both transient and permanent attenuation i.e. signal loss. Transient losses are reversible, caused by absorption due to dissolved hydrogen in the glass. Take away the hydrogen and 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).



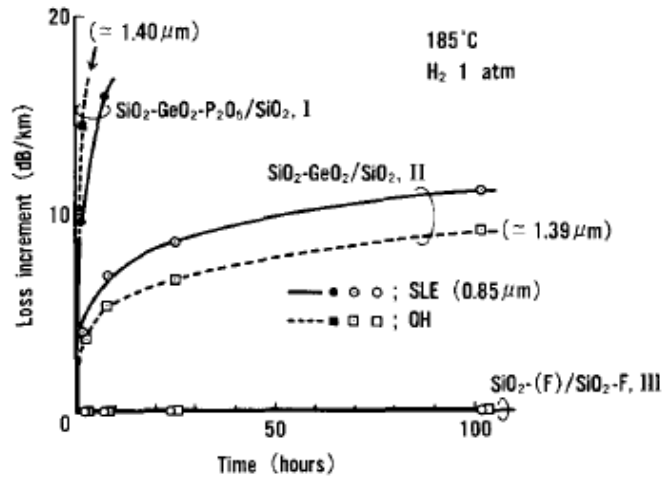
Source: lino et al., Journ Lightw. Tech, Vol. 8. No.11, 1990 .

In both cases, loss growth is dependent first on hydrogen diffusion rate, a function of temperature and hydrogen concentration, in which initial transient loss is observed, its magnitude governed by the hydrogen solubility in the glass, which quickly achieves a saturation and loss equilibrium point 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- even among the same fibers from the same manufacturer.

Transient loss is strictly a function of hydrogen solubility, with characteristic monotonic loss growth at hydrogen absorption lines which appear as peaks at 1.08, 1.17, 1.24, 1.59, and 1.63 μm within the wavelength range of interest (a good reference for hydrogen induced losses in optical fiber is the lino et al. paper referenced in the appendix). As a result, transient losses are 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. Conversely, the 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 specific population and type of defect is dependent

upon the glass composition, and subtleties of the fiber manufacturing process. As a consequence, permanent losses manifest radically different for different fibers, even among fibers of the same type from the same manufacturer, with complex polytonic peak growth that is difficult to model and predict.

Compositionally, the sensitivity and magnitude of permanent hydrogen loss has been found to be directly dependent upon the amount of common refractive-index modifying dopants such as GeO_2 and P_2O_5 that are used in conventional telecom fibers. This can be seen in the graphic below that shows growth in attenuation (pure hydrogen at 185°C) for a set of fibers with various dopant profiles, ranging from pure silica, to binary Ge and tertiary Ge-P doping.



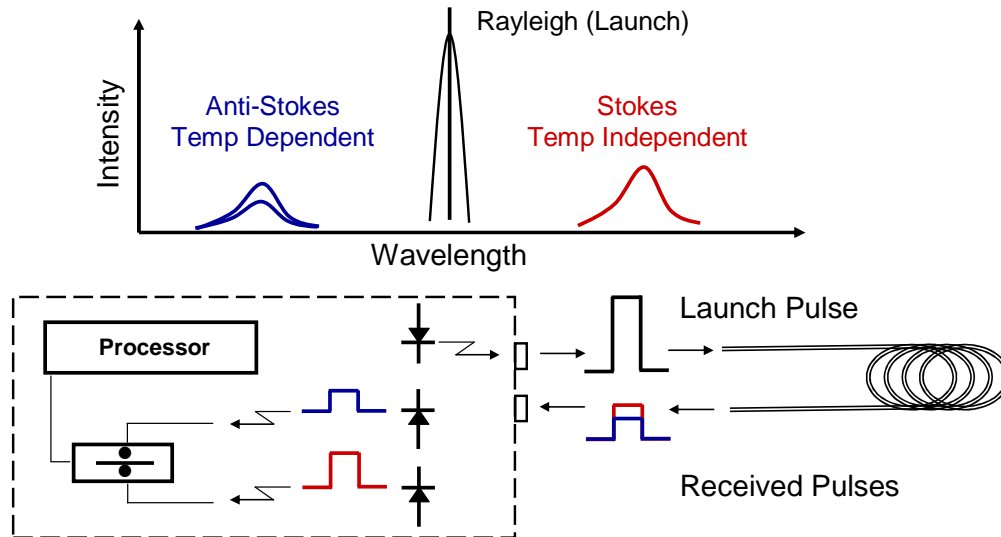
Source: Iino et al., Journ Lightw. Tech, Vol. 8, No.11, 1990

Of the three types, $\text{SiO}_2\text{-GeO}_2\text{-P}_2\text{O}_5$ core fibers are the most sensitive to hydrogen primarily due to P-associated centers induced by P_2O_5 and higher valency that combine with Ge to form weaker bonds that compete with Si-O lattice bonds. This leads to a greater mix and concentration of precursor defects, and subsequent complex polytonic peak growth, with significant short and long wavelength loss edge. Telecom-grade step-index single mode fibers typically have a lower dopant level and use $\text{SiO}_2\text{-GeO}_2$ core materials. Pure silica core single mode fibers were originally developed and have long been used in undersea telecommunication cables specifically for their insensitivity to permanent hydrogen losses. The absence of dopants in the core practically eliminates all precursor defects, with only Si diamagnetic centers contributing to hydroxyl formation the primary permanent loss effect typically seen in some of these fibers. Pure silica core fibers are used in some downhole oil and gas cables to exploit this performance. The table below lists the three common fiber types used in oil and gas sensing, and their relative hydrogen sensitivity and effects.

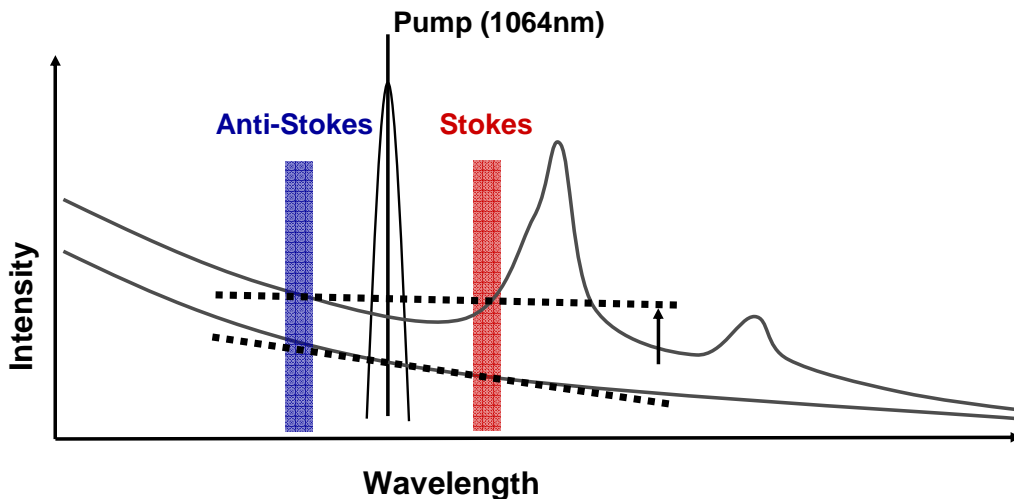
Fiber Type	Core/Cladding Composition	Transient Response	Permanent Response	Permanent Loss Spectrum
Graded-Index Multimode	$\text{SiO}_2\text{-GeO}_2\text{-P}_2\text{O}_5/\text{SiO}_2$	Same	Highly Sensitive	Polytonic; Short and Long Wavelength Edge
Single Mode	$\text{SiO}_2\text{-GeO}_2/\text{SiO}_2$		Sensitive	Polytonic; Short and Long Wavelength Edge
Pure Silica SM	$\text{SiO}_2/\text{SiO}_2\text{-F}$		Low Sensitivity	Hydroxyl; Short Wavelength Edge

Hydrogen Effect on Raman DTS Performance

Even trace amounts of hydrogen diffused into a DTS sensing fiber creates significant measurement error with Raman systems, compromising the quality and reliability of the data. As discussed previously, Raman DTS temperature measurement is accomplished by measuring small incremental changes in the ratio of power between the received Raman backscattered Stokes/Anti-Stokes lines.



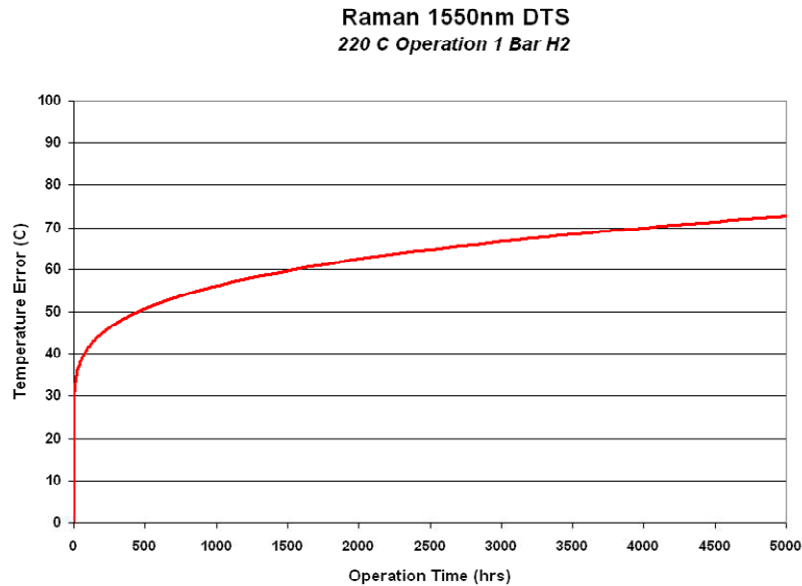
Introducing hydrogen into the sensing fiber leads to wavelength-dependent hydrogen absorption that alters the fiber attenuation in which the Raman backscattered signal will “see” a different attenuation rate depending on the hydrogen environment as depicted below for a typical fiber spectrum with varying levels of hydrogen. Here the received power ratio between the lines, in a steady thermal environment, is offset due to a changing spectral attenuation due to hydrogen.



As a consequence, the instrument cannot discriminate between temperature- or hydrogen-induced received power changes between Raman lines, leading to significant measurement error. Such errors as much as 50 to 70C offset of reference thermocouples are not uncommon with Raman DTS systems

operating in SAGD wells. Furthermore, the most common fiber used in Raman DTS today is graded-index multimode fiber- the most reactive among fibers to hydrogen and subsequent to permanent loss growth.

The figure below illustrates the speed and magnitude of hydrogen errors in Raman systems. Here a 1550nm pump Raman system operating on 1km of standard telecom single mode fiber is exposed to 1bar hydrogen at 220°C. Within a few hours, hydrogen diffuses into the fiber causing initial transient loss and associated measurement offset. After 200 hours or so, permanent losses take over with a steady decline in measurement offset until the system is non-operational due to loss of signal around 1,000 hours. This behavior- initial measurement error and then catastrophic system failure, is the common mode for legacy Raman DTS systems deployed in SAGD wells.



Hermetic Coatings the Only Proven Solution for Raman DTS

The only solution proven successful for applying Raman DTS technology in oil and gas is to prevent hydrogen ingress into the fiber by employing hermetic coatings, applied to the fiber or protective cable sheathing, to block hydrogen from diffusing into the fiber. Commercially available materials include amorphous and diamond-like carbon coatings applied directly to the glass fiber, and a range of metals of varying thicknesses used in protective armored cable construction. This sets the practical upper temperature limit for Raman systems between 120°C and 185°C, the peak operating temperature for available hermetic materials before they degrade and become porous, allowing hydrogen to permeate quickly into the fiber. While effective for the broad spectrum of wells in conventional oil and gas production, these sensing cables are not fit for use in higher temperature SAGD conditions. Operating in SAGD wells where typical temperatures are in excess of 200°C, these cables become prone to hydrogen ingress and suffer the subsequent effects on system performance and reliability- the consequence seen in the poor performance of legacy DTS systems deployed in SAGD wells.

A number of legacy DTS suppliers have either discontinued offering the product in the SAGD sector, or have pursued design solutions including purging/venting of the cable, instrumentation upgrades and modeling of hydrogen effects, or use of more resilient fibers in combination with these. While there is

merit to these approaches, they are successful only in either delaying eventual hydrogen effects, or reducing the magnitude of measurement error.

In the past year, new DTS systems have been introduced that operate on pure silica core fibers- both single mode and multimode. These fibers use index-depressed fluorinated glass cladding waveguide design, eliminating hydrogen sensitive dopants in the core, thereby less susceptible if at all to permanent hydrogen losses. However despite the promise of greater operational lifetime than legacy technology, pure silica core fiber is still subject to transient hydrogen loss and associated differential loss measurement error inherent in a Raman system. It is important to recognize the potential to monitor and model hydrogen using these fibers, as transient loss growth is quasi-monotonic and therefore somewhat predictable. Use of novel interrogation routines and multi-wavelength instrumentation are among the techniques being pursued to correct the reported data by monitoring hydrogen loss changes in the fiber and applying compensation algorithms.

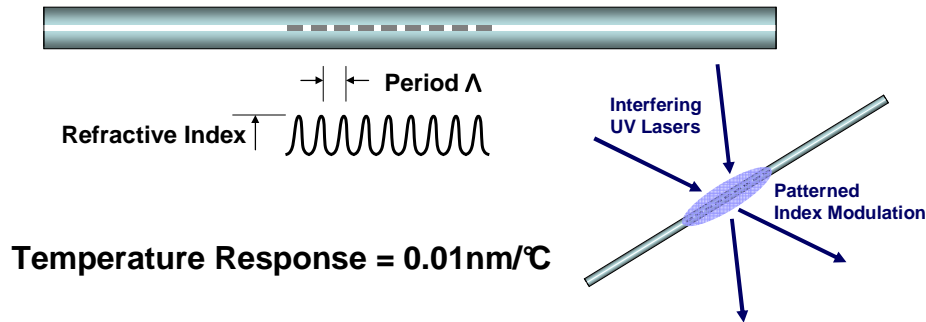
There are significant challenges to success in applying these techniques in a dynamic well environment, and to date there have been no reports to substantiate the effectiveness of these techniques. Furthermore, even if these challenges can be overcome, there are inherent performance limitations when operating Raman systems on pure silica core fiber. The predominant fiber used in legacy systems is graded-index multimode fiber by virtue of its Raman scattering cross-section- a measure of the amount of Raman excited light and the ability of the waveguide to capture this light to be transmitted to the receive end. The high dopant level of this fiber promotes its Raman scatter cross-section, but also its susceptibility to permanent hydrogen losses. Pure silica core fiber, by eliminating these dopants, reduces its hydrogen sensitivity and in parallel, its Raman scatter cross-section to the detriment of measurement performance. Already a power-starved system, the reduced intensity of backscatter signals when operating on these fibers makes resolution even more challenging, reducing it significantly even with extended averaging time.

Recently, pure silica core multimode fiber has been introduced as a means to improve the capture of Raman backscatter signals compared to their single mode counterpart. The move to multimode fiber might address the resolution shortcomings of the single mode approach; however it comes with a tradeoff in Raman scatter cross-section and more importantly, in absolute accuracy. The nominally 50 μ m step-index multimode fiber transmits thousands of discrete modes- preferred paths of light propagating in a fiber. As discrete paths that interact in slightly different trajectories through the fiber medium, each mode will have slightly different propagation speed and loss. Light launched into the fiber tends to excite all modes, and from there they exchange power due to mechanical bending and other physical perturbations, both static and dynamic acting along the fiber. This precludes the ability to accurately factory-calibrate a Raman DTS system, as measurement accuracy is made by averaging loss across all modes at the Stokes/Anti-Stokes wavelengths. Absolute accuracy thus requires exact simulation of the deployed fiber configuration during factory calibration, replicating all mechanical, vibrational, and thermal effects acting on the fiber which is impossible. This sets the limit for absolute accuracy uncertainty of 2 to 3 $^{\circ}$ C at best from factory to field installation with out further downhole referencing.

Fiber Bragg Grating Array Technology: Proven Upgrade Path for High Temperature

Fiber Bragg grating (FBG) technology on the other hand is not subject to the error modes of Raman technology, and provides a solution for systems operating above 200 $^{\circ}$ C in that it can tolerate significant levels of hydrogen. FBGs are tiny mirrors formed in single mode fibers through holographic exposure to high intensity laser radiation to create a patterned refractive index modulation in the fiber core. Light propagating in the fiber passes through the grating undisturbed except light at a distinct wavelength that is strongly reflected, this wavelength prescribed by the period and index “depth” of the modulation. FBG

is a mature technology developed by the optical communications industry, with millions of devices in continuous operation today in the global telecom network.



FBGs are intrinsically sensitive passive optical sensor elements, with well characterized, linear *frequency* response to temperature. As a frequency-encoded sensor, temperature measurement is not affected or corrupted by spectral attenuation changes in the fiber that corrupt intensity modulated Raman DTS technology. Furthermore, typical FBG sensors enjoy a much larger dynamic range, up to 30dB- much greater than Raman systems. The greater signal-to-noise ratio allows for better signal fidelity and fast measurement response (Hz). More importantly relative to hydrogen, the greater power budget of an FBG system, coupled with the use of more hydrogen insensitive single mode fibers, promotes an extended operational life- years compared to days at temperatures above 200°C. As a consequence, FBG technology provides a true upgrade path to address SAGD and even higher temperature CSS environments.

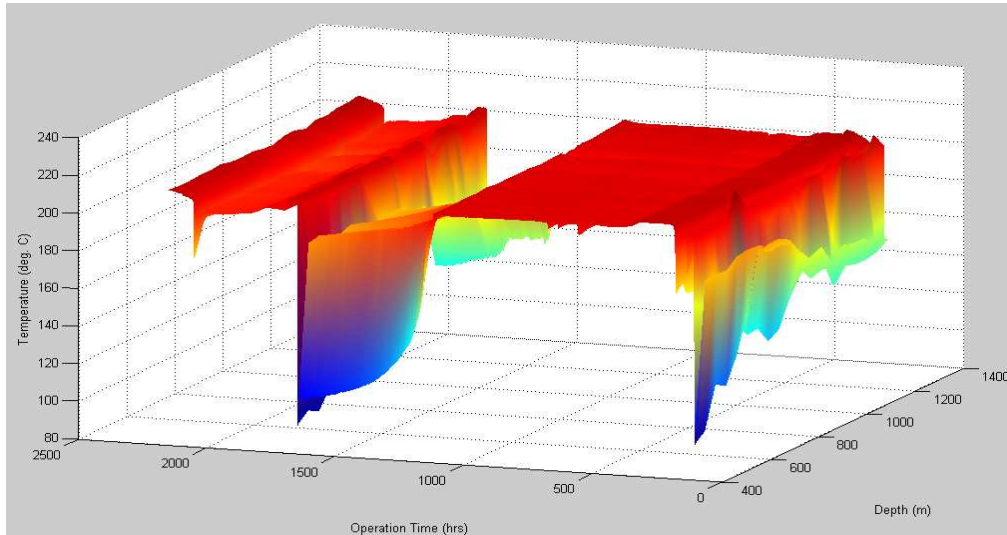
LxSix has pioneered the development of high reliability FBG arrays in which FBGs are formed in a continual process along a length of fiber. Rather than splicing together FBGs to form an array, the LxSix process enables virtually any number of FBG sensors to be selectively placed and distributed along the fiber without manually handling of the fiber that degrade its inherent strength. This leads to an array manufacturing platform with unprecedented levels of flexibility and reliability. Recognizing the limitations of legacy DTS in serving the burgeoning SAGD sector, LxSix developed LxIQ™ thermal monitoring system to leverage the benefits of FBG array sensing technology specifically to meet the demands of SAGD. Extensive laboratory testing of LxIQ™, over 10,000 hours at high temperature 300°C in pure hydrogen, gave confidence to test a trial system in an operating SAGD well, in which an injector well was chosen to test in a more rigorous temperature environment.

Field Trial Results

The LxSix FBG array platform allows for placement of proprietary diagnostic grating sensors in tandem with the thermal sensors to investigate the actual well environment and track cable degradation and aging. This enables real-time holistic monitoring of the system along to better understand and determine failure modes and rate both short and long term performance of the system. The trial system included 60 thermal sensors with these diagnostic sensors, as well as 8 collocated thermocouple references to assess system measurement performance.

The system was installed and commissioned in late November 2007. The downhole sensing section was integrated into a 38mm instrumentation string and installed in the well using conventional coiled-tubing injection equipment and procedures without encountering any problems or delays. Since startup all 60

optical sensors are fully operational with good step response coincident with well operations, and meeting or exceeding expectations in measurement performance and lifetime. Raw data for the first 2,000 hours of operation is shown in the graph below.



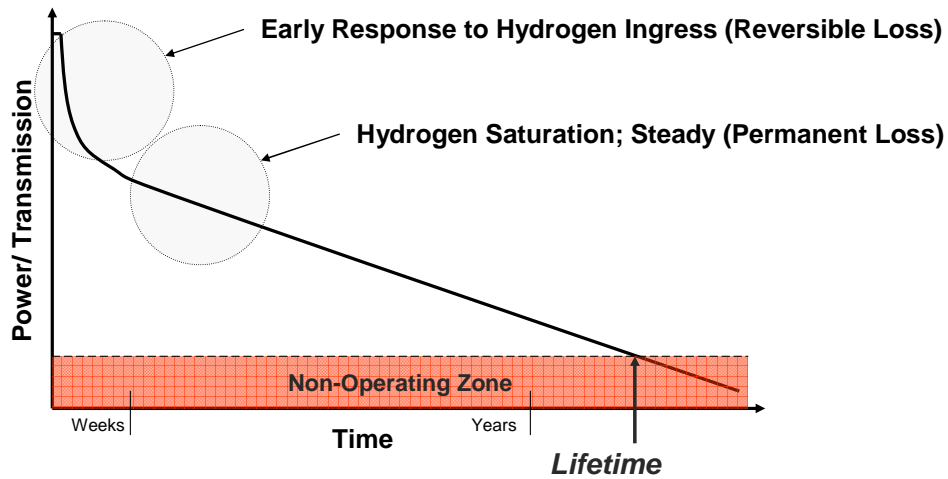
A comprehensive data analysis was performed at 2,000 hours, comparing raw data of thermal measurements between collocated optical sensors and reference thermocouples. Results of this analysis, listed in the table below are encouraging.

Parameter	Performance
Accuracy	$\pm 2.7^{\circ}\text{C}$ (3σ)
Resolution	$0.17^{\circ}\text{C}/\sqrt{\text{Hz}}$
Lifetime (at specification)	+10 Years

The system has been operational at temperature for over 3,000 hours; well beyond the point where legacy fiber optic systems typically fail. Hydrogen and its effect on the optical sensing cable has been observed, although minor, with less than 1% loss of system operating power. No degradation of system measurement performance in terms of accuracy and resolution has been observed since startup.

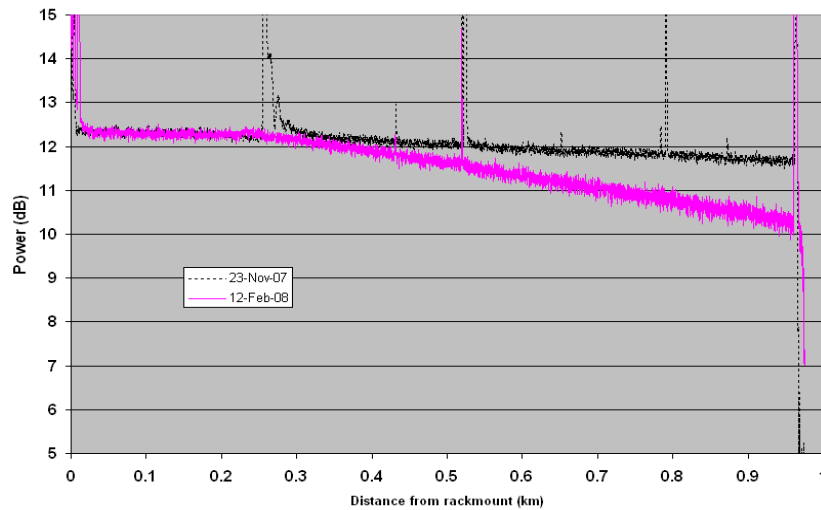
Preliminary Reliability Assessment

Hydrogen-induced attenuation in sensing fibers is the dominant source of failure in applying fiber optic systems in SAGD wells. Failure will be modeled as the time required for the hydrogen effects to create enough loss so that the reported optical temperature data is out of specification. By monitoring the loss growth using the installed diagnostic tools an exponential decay model can be used to extrapolate the operating lifetime of the system. The figure below shows the predicted aging model established through extensive laboratory testing, in which the system exhibits serial bimodal behavior. Here the system will experience an almost immediate loss of signal upon hydrogen ingress due to transient loss, and then upon saturation, will see a slow steady decline as permanent losses take over.



In the trial system, diagnostic sensors in the sensing strings and diagnostic cable are accurately characterizing the downhole environment and its effect on the optical system. Optical transmission data clearly shows evidence of hydrogen, and its effect on the optical system has been closely monitored with system response following the predicted reliability model. The chart below plots system attenuation from startup to 2,000 hours. As expected, after initial hydrogen permeation and step response, fiber transmission appears to have reached a slow asymptotic linear decay regime, from which a lifetime expectation can be projected.

OTDR trace, initial vs 2 000 hr



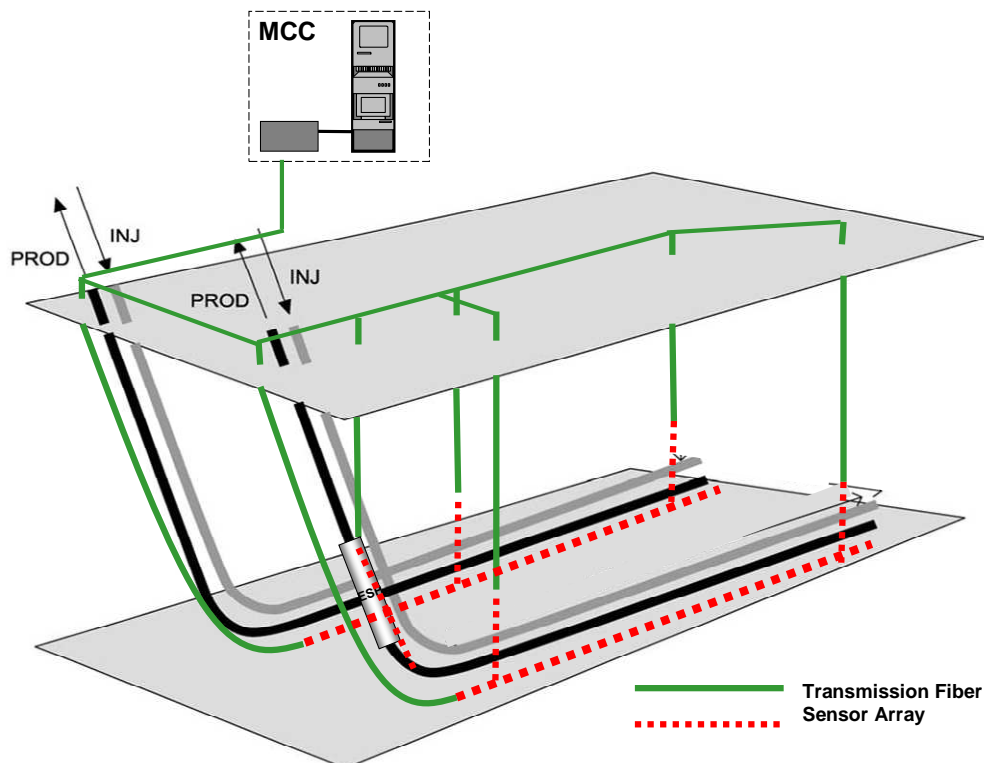
The sensing cable appears to be in the linear decay zone, with preliminary lifetime expectation extrapolated from this slope trending 17 years which will be confirmed with more data over time. A more detailed report on LxIQ™ system reliability is available upon request.

LxIQ™ Features and Benefits

The ability of FBG array-based LxIQ™ to operate effectively and reliably in the aggressive SAGD environment alone separates it from other distributed temperature sensing products. The ability to realize this important distributed sensing architecture, with performance on par with thermocouples, positions LxIQ™ as the choice thermal monitoring solution for SAGD operators going forward.

There are other features and benefits of LxIQ™ worth mentioning. The sensing fiber configuration is single-ended, which simplifies installation and well completion details over dual-ended systems. As a frequency-encoded technology with high dynamic range, thermal measurement does not involve massive amounts of data to average as in competing technology. The system measurement is therefore fast and easily multiplexed. The standard LxKey™ MCC cabinet is easily upgraded to monitor up to 16 sensing strings, in which an update of all strings can easily be completed within minutes compared to hours with competing DTS systems. Furthermore, the LxSix FBG array platform allows for selective placement of FBG sensors even centimeters apart. This allows for “clustering” of sensors for higher spatial resolution sensing strings, ideal for steam chamber monitoring in vertical observation wells, as well as special “zoom” type cables to diagnose problem wells for closer characterization in critical areas (e.g. ESP).

These features combine to create a thermal monitoring solution that goes beyond distributed sensing architecture to a more powerful pad-level architecture, one that integrates into one central interrogation and processing unit, a full suite of horizontal/vertical/specialist sensing strings to deliver a real-time, pad-level representation of the thermal environment. This creates new possibilities in advanced imaging, reservoir modeling, and ultimate process optimization.



Summary

Optical sensor technology is a useful tool and used globally in the conventional oil and gas sector. Optical distributed temperature sensing has long been pursued as a tool to augment SAGD bitumen production, however reliability problems due to the extreme temperature and hydrogen conditions have rendered fiber optic products unsuitable. These systems cannot tolerate even trace amounts of hydrogen in the fiber to operate effectively, and use hydrogen blocking hermetic coatings to prevent hydrogen diffusion into sensing fibers. These coatings are rated to 185°C, and become porous and thus ineffective at typical SAGD operating temperature. Deploying these systems in SAGD wells where they are not fit for purpose, results in significant measurement error, and then eventual catastrophic system failure. A number of design attempts to resolve this problem have only delayed time to failure or reduced the magnitude of error. Recently new fibers and interrogation systems have been introduced that promise to extend their operating life in SAGD, however these systems are still subject to transient hydrogen effects that are difficult to compensate and deliver high quality data required in many SAGD applications. No published data has been reported to substantiate the effectiveness of these compensation techniques.

In contrast, LxSix has introduced LxIQ™, a thermal monitoring system based on FBG array technology that operates effectively in hydrogen by virtue of its frequency-encoded temperature measurement that is not affected by the unavoidable attenuation growth in the sensing fiber due to hydrogen. After extensive laboratory tests, the system has been successfully field tested in a live SAGD injector well. The system has been fully operational for over 3,000 hours- well beyond the failure point of legacy systems. Diagnostic sensors in tandem with the thermal gauges have been monitoring hydrogen and its aging effect on the sensing cable. After 3,000 hours, the system maintains over 99% factory performance (less than 1% loss of power) with no degradation in measurement performance as verified against collocated downhole thermocouple references. The system is following a predicted reliability model with lifetime trending in excess of 17 years under the trial well conditions.

This level of performance and reliability positions LxIQ to transcend thermocouple and legacy fiber optic systems as the thermal monitoring solution going forward in SAGD. LxSix's unique capability to selectively position sensors along the fiber allows for a range of application-specific sensing strings. Coupled with the ease of multiplexing these strings, this new sensing platform will herald a next generation of cost-effective, pad-level thermal monitoring to realize the promise of fiber optic sensing, and unleash new possibilities in SAGD reservoir monitoring and process optimization.

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