Systems Approach to Thermal Asset Monitoring using Advanced Distributed Temperature Sensing (DTS) Technology.

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ABSTRACT

Distributed Fiber Optic Sensing is a powerful technology with wide spread use in the oil & gas industry. This paper will review system considerations with the latest Raman technology, Hydrogen tolerant optical fibers and fiber deployment.

Keywords: *Distributed Fiber Optic Sensing, Distributed Monitoring Systems, Rayleigh, Brillouin, Raman, Distributed Temperature Sensing, DTS, Hydrogen induced attenuation, steam drive, heavy oil, tar sands*

1. INTRODUCTION

Raman based Distributed Temperature Sensing (DTS) was invented in the early 1980's, and was first deployed in the Oil & Gas industry in the 1990's. DTS is today widely used in conventional oil wells with great track record. Successful applications range from monitoring of water injection, gas lift, well integrity, flow modeling to thermal asset monitoring.

Steam drive oil wells with high temperatures and Hydrogen in the well is one of the more challenging applications. Early deployments in Hydrogen rich hot wells experienced fiber failures due to increased optical attenuation (fiber darkening). Recent success stories [1] show that Hydrogen darkening for properly designed systems is a thing of the past.

Fiber darkening occur in telecommunication grade fibers when Hydrogen react with dopants, and this was one of the early and painful learning's the oil & gas industry experienced. The industry today understands the issues and can provide system solutions meeting the needs for hot and Hydrogen rich wells.

Most new technologies have a technology introduction cycle, where application specific challenges are discovered and overcome.

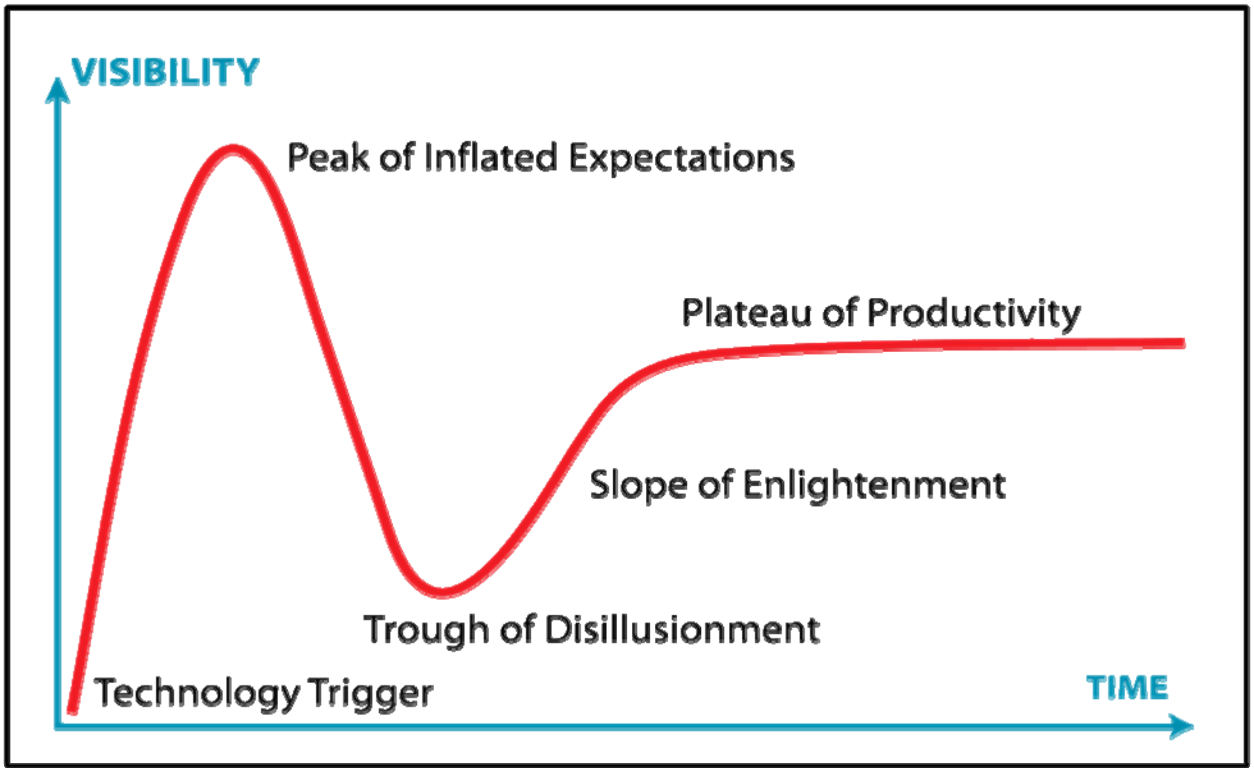

Figure 1.1. Technology Introduction Cycle.

We have today, in the area of thermal asset monitoring using DTS, climbed up the Slope of Enlightenment and are moving to the Plateau of Productivity.

This paper will review DTS Technology, optical fibers and deployment from a system perspective to move us further up towards the Plateau of Productivity.

2. BRIEF TECHNOLOGY INTRODUCTION

The majority of Distributed Monitoring Systems are based on the Optical Time Domain Reflectometry (OTDR) principle. A very short light pulse is launched into an optical fiber and the pulse interacts with the fused silica in the optical fiber as it propagates down the fiber. This interaction will cause light to scatter back along the full length of the optical fiber. The backscattered light will consist of 3 different components, Rayleigh, Brillouin and Raman backscattered light, figure 2.1.

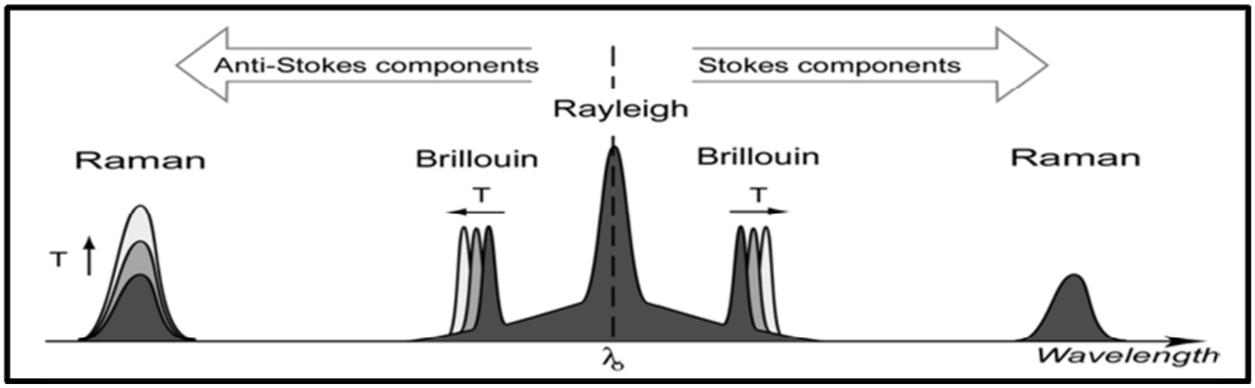

Figure. 2.1. Backscattered Rayleigh, Brillouin and Raman light in optical fibers.

The Rayleigh component is scattered back at the same wavelength as the launched pulse whereas both the Brillouin and Raman components are shifted in wavelength.

- Rayleigh scattering is proportional to the optical loss in the fiber.
- Brillouin wavelength shift is a function of temperature and strain.
- Raman component intensity is a function of temperature.

The location along the fiber can be determined by measuring the time of flight between the transmitted pulse and the reflected light. Well designed systems use these effects to measure various parameters in a wide range of applications. This paper will focus on Raman based Distributed Temperature Sensing (DTS).

3. DISTRIBUTED TEMPERATUR SENSING BASED ON RAMAN SCATTERING

Raman scattering converts a small fraction of the power from the launched light pulse into frequency shifted Stokes and anti-Stokes components due to vibrational modes of fused silica [2].

The temperature can be calculated as a function of the ratio between the anti-Stokes and Stokes intensity. Raman based Distributed Temperature Sensing (DTS) is the most common Distributed Monitoring System, with widespread adoption across oil & gas, power, fire detection and other industrial applications.

The system performance ranges from basic single ended short range systems to high end multi wavelength long range systems. System performance is normally a trade-off between temperature resolution, measurement time and fiber length.

Deployed DTS systems can be divided in three categories: Single ended single wavelength systems, double ended single wavelength systems and single ended multi wavelength systems.

3.1 Single Ended Single Wavelength DTS Systems

The classical way to measure distributed temperature using Raman scattering is to send a single pulse at wavelength λ_0 down the optical fiber and measure backscattered Raman Stokes (λ_s) and anti-Stokes (λ_{as}) components as a function of time. Time of flight will allow a calculation of the location, and the temperature can be calculated as a function of the ratio between the intensity of the anti-Stokes and Stokes components at any given location. Figure 3.1. below show a single ended system.

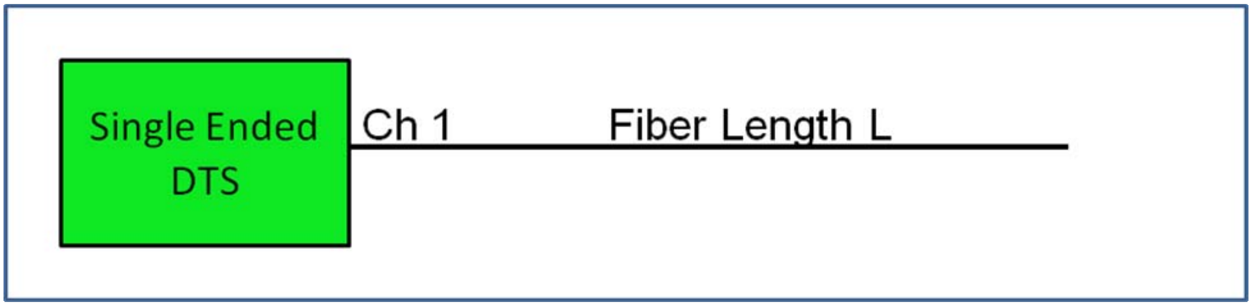

Fig. 3.1. Single ended DTS system.

Fiber attenuation due to absorption and Rayleigh scattering introduce wavelength dependent attenuation [2]. The peak wavelengths of the Stokes and anti-Stokes components are separated by 13[THz] from the transmitted pulse. A system operating at λ_0 = 1550[nm] produces Stokes wavelength λ_s at 1650[nm] and anti-stokes wavelength λ_{as} at 1450[nm]. This difference in wavelength dependent optical attenuation ($\Delta\alpha$) between the Stokes and anti-Stokes wavelengths must be compensated for. This is often added to the fundamental Raman equation below where the impact of differential attenuation Δα is corrected for over distance z.

$$R(T) = \frac{I_{AS}}{I_S} = \left(\frac{\lambda_s}{\lambda_{as}}\right)^4 \cdot \exp\left(-\frac{hc\upsilon'}{kT}\right) \cdot \exp(-\Delta\alpha z)$$

The underlying fundamental assumption for accurate temperature measurements with a single wavelength DTS system is a constant differential attenuation Δα.

This assumption is not valid in many applications. Examples of situations where the differential loss Δα varies are cabling induced bends, radiation induced attenuation or Hydrogen induced attenuation to name a few.

Advantages of a classical single ended system are the simple deployment and long reach in applications where the differential attenuation between Stokes and anti-Stokes components remain constant.

Disadvantage of a classical single wavelength DTS system is that it will experience significant measurement errors due to wavelength dependent dynamic attenuation when e.g. the fiber is exposed to Hydrogen. The total increase in optical attenuation in many fibers may be in the order of 10's of dB/km, and may exceed the dynamic range of the system.

3.2 Double Ended Single Wavelength DTS Systems

The impact of varying differential attenuation Δα can be mitigated using single wavelength DTS systems with double ended fiber deployments. Figure 3.2 below show a double ended system.

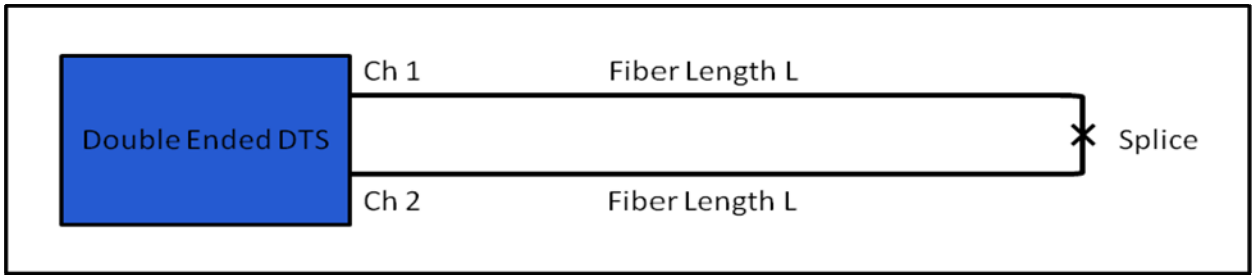

Figure. 3.2. Double ended DTS System

A fiber is deployed in a loop configuration and a full temperature trace is taken from channel 1 to channel 2 for a total fiber length of 2L. A second full temperature trace is taken from channel 2 giving two temperature points at every point along the sensing fiber. Using this information, the differential attenuation factor Δα can be calculated at every location along the optical fiber [3]. This distributed differential attenuation factor Δα(z) can then be used to calculate a corrected temperature trace.

There are several issues to be aware of and to consider when considering using a double ended system [3].

1. Using twice the fiber length requires twice the optical budget on the DTS instrument. This often limits double ended system performance while reducing any margin in the optical budget.
2. Interrogating sensing fibers from two directions require twice the optical connections and drives system complexity.
3. Twice the fiber is exposed to the environment so Hydrogen induced attenuation will create twice the attenuation increase in a loop when compared to a single ended system.
4. The noise increases exponentially with distance and this noise term show up in the distributed differential attenuation factor over distance Δα(z) and temperature trace.

Numbers 1 and 2 increase the total system cost while adding deployment complexity. Number 3 reduces the service life of the system. Number 4 impacts the quality of the data, which in turn makes the interpretation of temperature data more difficult. In many installations, it is impractical or even impossible to deploy double ended systems.

The advantage of a double ended system is the ability to correct for dynamic differential attenuation changes. The disadvantages are cost, complexity, system performance and data quality.

3.3 Single Ended Multi Wavelength DTS Systems

A new single ended multi-laser technology [4] has been introduced. It solves all the issues with a double ended system, while providing all the benefits of a single ended system. The system use multiple lasers and will by design be tolerant to wavelength dependent attenuation. Careful selection of the laser wavelengths will provide signal paths with equal amount of round-trip attenuation for the launched light and backscattered Stokes and anti-Stokes components thus eliminating the effect of distributed differential attenuation $\Delta\alpha(z)$. The performance of a multi wavelength system will be illustrated in figures 3.3.- 3.4. Figure 3.3 below shows OTDR data for 4 different optical fibers at room temperature.

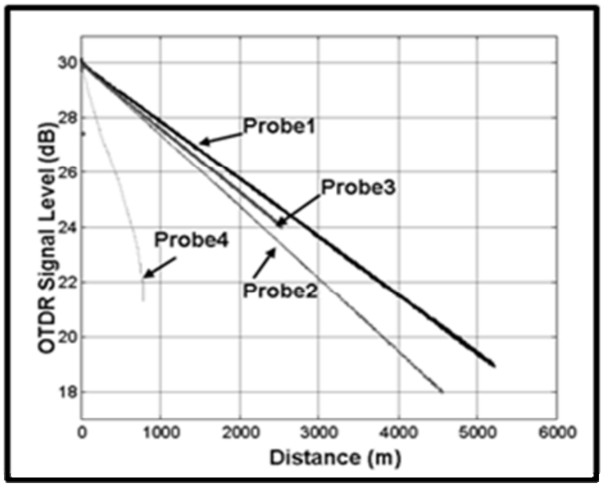

Fig 3.3. OTDR traces.

Fiber probes 1-3 are pristine fibers on shipping spools while the 4th fiber probe is recovered from a steam drive well in Canada. The 4th fiber was retrieved for failure analysis after the operator came to the conclusion that a single wavelength single ended system could not measure any useful temperature data due to Hydrogen induced attenuation. The results in fibers 1-3 show expected linear optical attenuation values while the 4th fiber shows high non-linear attenuation.

Figure 3.4(a) show DTS data measured with a classical single wavelength DTS, and figure 3.4(b) show the same DTS data with a multi-wavelength DTS.

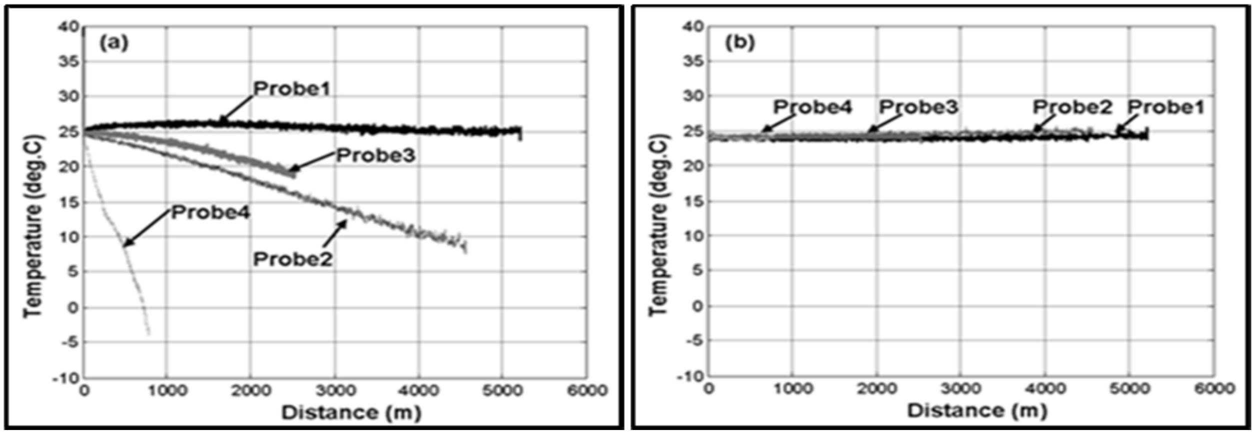

Fig 3.4. Single ended single wavelength DTS data(a) and multi wavelength DTS data(b).

When the fibers are interrogated using a classical single ended DTS, fibers 1-3 show a largely linear behavior (fig. 3.4a). The slope in the measurement for fibers 1-3 can be calibrated out by varying the differential attenuation Δα assuming the temperature is known at some point along the fiber. Each of the fibers must be individually calibrated for accurate measurements, but non-linear contributions cannot be calibrated out as can be seen on fiber probe 1 (fig.3.4a). The 4th fiber shows a large non-linear temperature error due to the Hydrogen induced attenuation. In steam drive wells, the distributed differential attenuation would vary with time, temperature and Hydrogen exposure making any calibration attempts inaccurate for single ended single wavelength systems.

The same fibers were interrogated using a single ended multi wavelength PerfectVision™ (fig. 3.4b). The measured temperature data for all fiber probes, regardless of the difference in distributed differential attenuation, agrees well with the room temperature. The system is by design immune to changes in differential attenuation. Dynamic time varying changes in differential attenuation Δα(z) in the fiber probe are automatically cancelled out. This clearly shows the capability of the multi wavelength technology to overcome dynamic non-linear distributed differential attenuation variations [4].

Challenges for single wavelength Raman based systems include sensitivity to distributed dynamic differential attenuation changes due to Hydrogen. The sensitivity to dynamic differential attenuation effects can to some extent be mitigated using double ended systems and pure silica core type fibers. Double ended systems are challenged in performance, complexity, deployment and operational cost.

Advantages of the latest generation multi-wavelength Raman technology [4,6] eliminate the sensitivity to dynamic differential attenuation effects while providing the simplicity of single ended systems. When combined with the latest generation Pure Silica Core Hydrogen tolerant fibers, multi-wavelength systems provide greatly extended service life at reduced total cost of ownership.

4. OPTICAL FIBERS

Fiber darkening, or Hydrogen induced optical attenuation, is caused when Hydrogen react with defect sites in optical fibers [5]. The permanent Hydrogen induced attenuation varies with fiber chemical composition, Hydrogen concentration, temperature and exposure time. The induced optical fiber attenuation is therefore likely to be non-uniform along the length of the optical fiber as down-hole conditions vary along the well bore.

Several options to mitigate Hydrogen induced attenuation exist. Fixed cables can be manufactured with a Hydrogen scavenging gel in the cable. The Hydrogen scavenging gel can be viewed as a sponge soaking up the Hydrogen. At some point in time, the sponge will be saturated if there is enough Hydrogen present. Hydrogen scavenging gel is used in applications below 150[ºC] as the gel break down at elevated temperatures and release Hydrogen.

The next level of Hydrogen defense is Carbon coatings. Hydrogen caused attenuation increases in early sub-marine communication cables, and this resulted in the development of carbon coatings. Carbon coatings mitigate Hydrogen permeation in optical fibers up to 150[°C] and some high quality Carbon coatings can be used to higher temperatures for short periods of time, see figure 4.1. below.

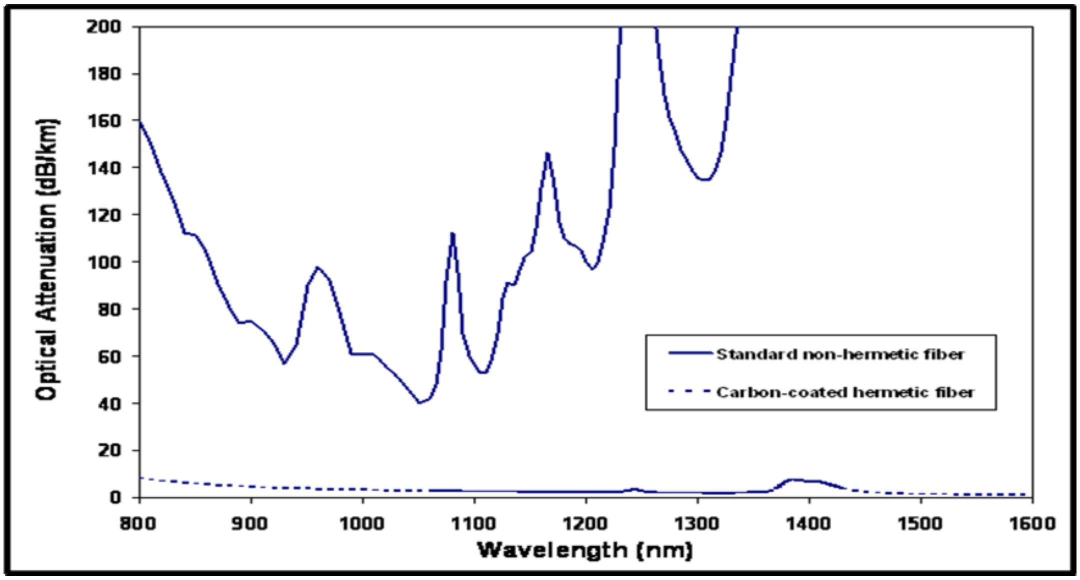

Figure 4.1. Optical Spectra of a standard MM50/125 fiber compared to a carbon-coated hermetic fiber after test at 200[^{o}C] and 1500[psi] of H_2 for 17 hours. Courtesy Verrillon.

Steam drive heavy oil wells operate at elevated temperatures up to 300[°C]. Carbon coatings are not effective against Hydrogen at these temperatures and Hydrogen scavenging gels cannot be used as they break down.

The next level of Hydrogen mitigation is Pure Silica Core (PSC) optical fibers. Dopants and chemicals, the cause of permanent Hydrogen induced attenuation, are neutralized from the optical fiber core.

Free Hydrogen will still induce wavelength dependent attenuation in Pure Silica Core optical fibers, see figure 4.2 below. Hydrogen induced attenuation due to free Hydrogen show up at different wavelengths [5].

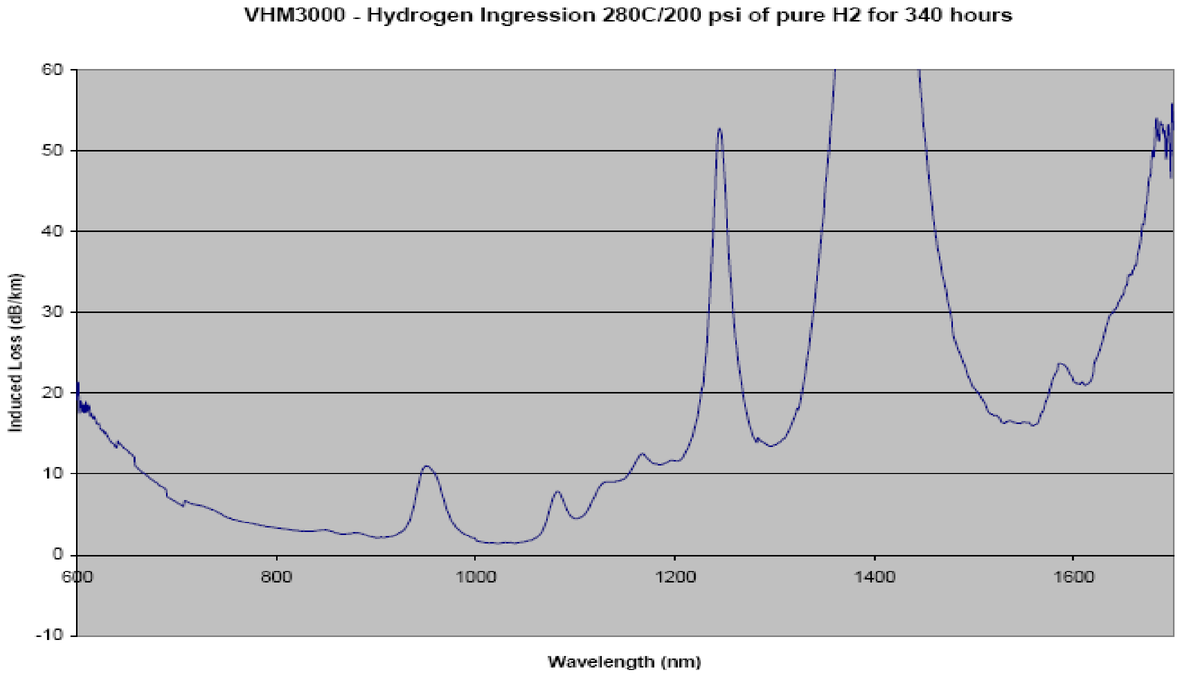

Figure 4.2. Pure Silica Core optical fiber after 340 hours of Hydrogen exposure at 280[ºC] with a Hydrogen pressure of 200[psi]. Courtesy Verrillon

Optical fibers can be engineered to show low loss at certain wavelengths. The fiber in figure 4.2. is a good example where the lower wavelengths show low attenuation in certain bands as a result a focused engineering effort.

5. DEPLOYMENT

Fiber deployment is a key aspect of a DTS system for thermal asset monitoring. The two most common ways to deploy optical fiber in thermal assets are to pump a fiber into a pre-installed conduit or to deploy a fixed cable. The conduit or fixed cable may be part of a coiled tubing assembly that is pushed into the thermal well.

5.1 Pumped Fiber Deployments

Optical fibers can be pumped into conduits. A pre-deployed conduit of a suitable size is connected to a pumping unit that will pump fluid in the conduit. A fiber or a cable is then deployed in the fluid, and friction between the fluid and the fiber/cable pulls the fiber/cable into the conduit.

It is common to use double ended systems in oil & gas applications like down-hole sensing. Two conduits, or stainless steel tubes, are deployed along the tubing (or coiled tubing) and these tubes are then connected at the distant end using a Turn-Around-Sub (TAS). Single ended system with a check valve has been used in some applications.

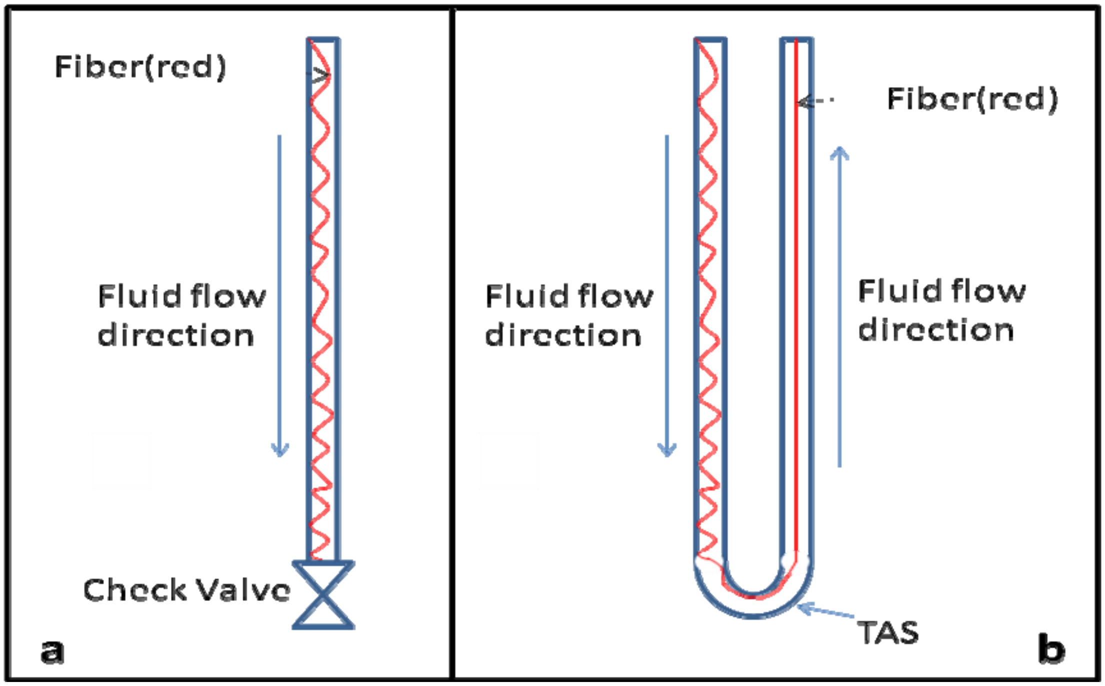

Figure 5.1. Single ended and double ended pumping configurations.

The most common size tubing is a ¼" capillary line or chemical injection line. A liquid flow is produced within the ¼" metal tube using a high pressure pumping unit. The viscosity of the fluid develops a drag force along the surface of the fiber, and this drag force will move the fiber in the direction of the flow. In some cases a pig or a chute is used to add pull to the distant end of the cable, see figure 5.2.

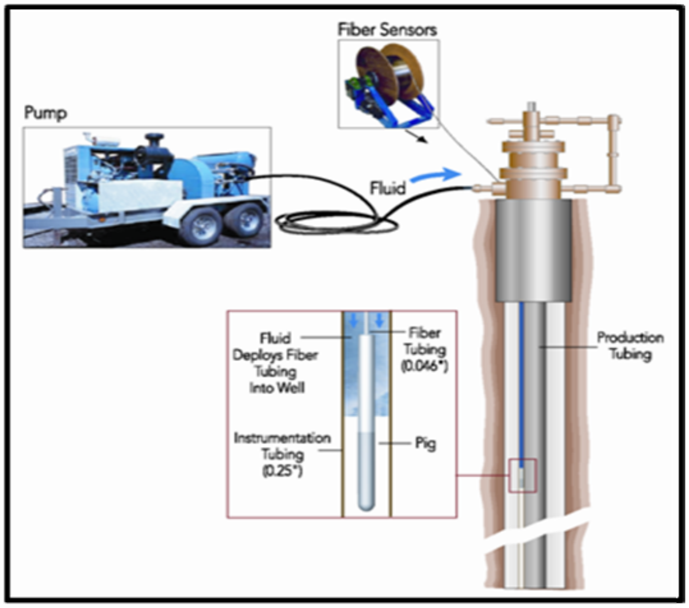

Figure 5.2. Pumping setup for fiber and cable pumping.

The pressure required to pump a bare fiber into a ¼" control line may be as high as 10,000[psi]. Surface friction along the inner surface of the conduit will create turbulence at the boundary and the fluid velocity is slower at the edges and fastest in the center of the conduit.

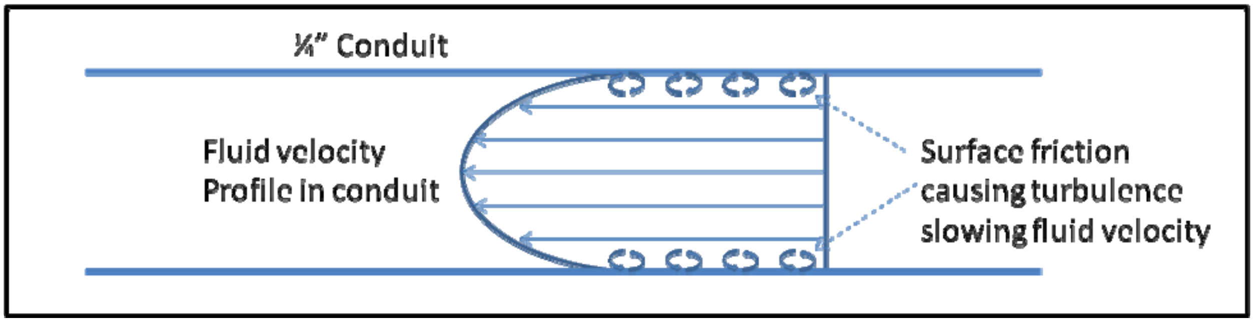

Figure 5.3. Fluid flow velocity profile in conduit.

The fluid profile tends to center the fiber due to the higher velocity and keep it from dragging on the inner wall of the conduit. Friction points between the conduit and fiber may cause mechanical damage and should be avoided. Similarly, the inner surface of the conduit and any transitions between conduits must be smooth, de-greased and de-burred.

Several of the challenges with pumped systems tend to occur as the fiber reaches the turn-around-sub. One is the un-known fiber overstuff, or Excess Fiber Length (EFL), of the pumped fiber as the fiber length in the downward path often differs from the fiber length in the upward path. The fiber in the downward path buckle as the fluid push more fiber down the conduit as the friction at the turn-around-sub limits the fiber speed around the turn-around-sub. If the conduit is part of a 1 ¼" coiled tubing string, then the TAS, given its size limitations will add considerable friction due to the capstan effect. The optical fiber, as it is dragged around the TAS, may suffer mechanical damage to the coating due to the capstan effect and sharp edges where the TAS is mechanically connected to the conduits. The fiber in the return path is normally pulled straight by the fluid drag as there is little friction in the return path.

The straight fiber in the return path may however be a reliability concern. Thermal expansion of the conduit material as the well is put under steam may cause the fiber to exceed the recommended fiber strain range for reliable long-term operation. This may cause a fiber break and a multi-wavelength DTS system would then be required to accurately read a hydrogen damaged broken fiber.

Fiber is sometimes pumped after the well has been put on steam to minimize the impact of thermal expansion. The disadvantage of this approach is that the early thermal behavior of the well cannot be monitored as the fiber is not deployed until the well has been heated up.

Another challenge with pumped systems is the fact that pumping fluid under high pressure may penetrate the coating and cause fiber degradation over time. This could be chemical degradation of the optical fiber or coating degradation exposing the fiber cladding (bare glass) accelerating surface crack growth.

One advantage with pumped fiber is the ability to replace a fiber in a conduit. If a fiber degrades, a crew can pump out the existing fiber and pump in a replacement fiber. This operation can be done without pulling the completion. The risk with pumped systems is that the fiber may get stuck in the well and a full double ended system cannot be achieved.

5.2 Fixed Cable Deployments

The fundamental cable part in a fixed cable is the Fiber In Metal Tube (FIMT). The FIMT is manufactured in a controlled environment and the fiber EFL is well known and controlled. The fiber is never exposed to chemicals or mechanical damage during the manufacturing process.

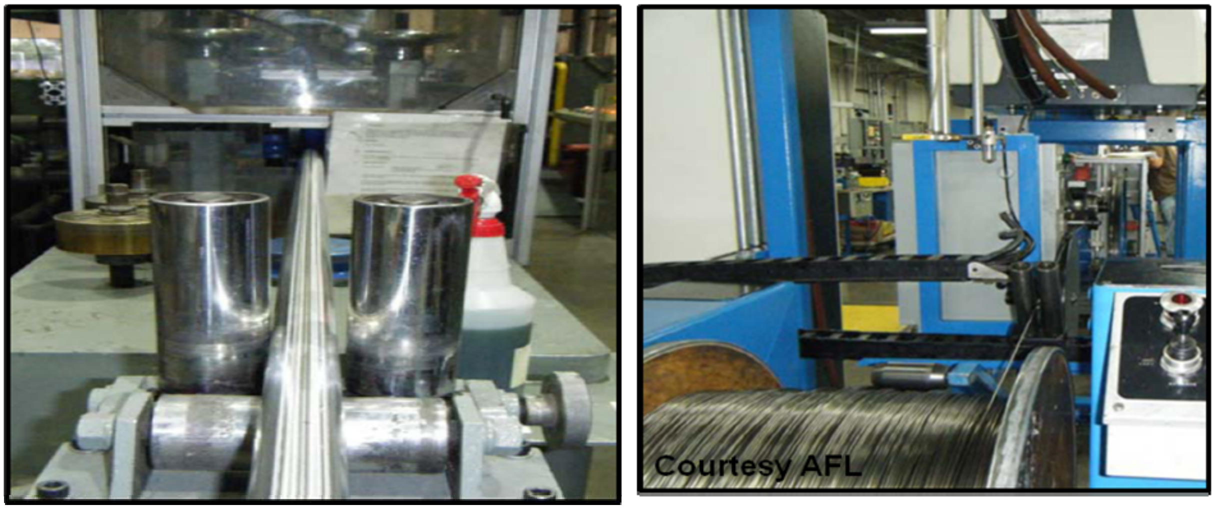

Figure 5.4. FIMT Manufacturing equipment. Courtesy AFL.

A Fiber In Metal Tube (FIMT) cable for e.g. 300[ºC] operation should be manufactured with sufficient EFL to accommodate the mismatch in Thermal Coefficient of Expansion (TCE) between the fused silica fiber and the metal tube. The metal tube size must have an ID large enough to house the optical fiber without causing any additional attenuation as the FIMT contracts and expands during the heavy oil production cycle.

The FIMT can be incorporated into the coiled tubing for deployment or additional mechanical protection can be added to the cable so it can be clamped to a tubing string. In some cases additional tube layers build the cable OD up to ¼” to allow the use of standard clamps. The steel tube(s) around the optical fiber will protect against high pressure fluids and mechanical abuse during deployment and cable service life.

To replace a fixed cable is more time and labor intensive than re-pumping a fiber. The well must be taken off steam and the completion or coiled tubing must be pulled. However, the likelihood of fiber damage is significantly lower in a fixed cable given the mechanical and chemical protection.

6. SYSTEM DESIGN CONSIDERATIONS

A system block diagram and a system optical power budget must be among the first items done for any fiber optic sensing system. Items like well depth (fiber length), surface transit cable length, junction boxes housing optical splices, connectors and any other items that may cause optical loss must be identified. All the items causing optical loss must be identified in the block diagram and entered into a system optical power budget. The system optical power budget should show the available optical budget of the DTS unit, the expected optical losses in the system as installed, power margin to mitigate Hydrogen induced fiber attenuation and any aging of components and/or DTS unit.

The required power margin for Hydrogen mitigation over the service life of the monitoring system is often the hardest item to estimate. This requires fiber test data and knowledge of the DTS system operating wavelength band. Required fiber test data is fiber attenuation over wavelength, with the fiber exposed to down-hole temperatures and Hydrogen pressure (fig. 4.2.).

The most common DTS systems are single wavelength systems operating at 1064[nm] +/- 40[nm], which means that they have an operating wavelength band between 1024[nm] to 1104[nm]. As a comparison, the dual wavelength DTS system described in [6] has an operating wavelength band between 980[nm] to 1064[nm]. The normal loss in the wavelength band between 980[nm] to 1104[nm] is around 2[dB/km]. With a 1,500[m] deep SAGD well, this translates into a two-way loss of 2 x 1.5[km] x 2[dB/km] = 6[dB] of expected fiber loss for a single ended system. For a double ended system, the two way loss translates into 2 x 3.0[km] x 2[dB/km] = 12[dB] of expected fiber loss. The DTS operating bands must then be mapped on the fiber wavelength dependent attenuation graph, and the Hydrogen induced attenuation in the operating band must be evaluated. If we zoom in on the relevant wavelength band on the fiber in figure 4.2., and map the DTS operating bands, we get figure 6.1.

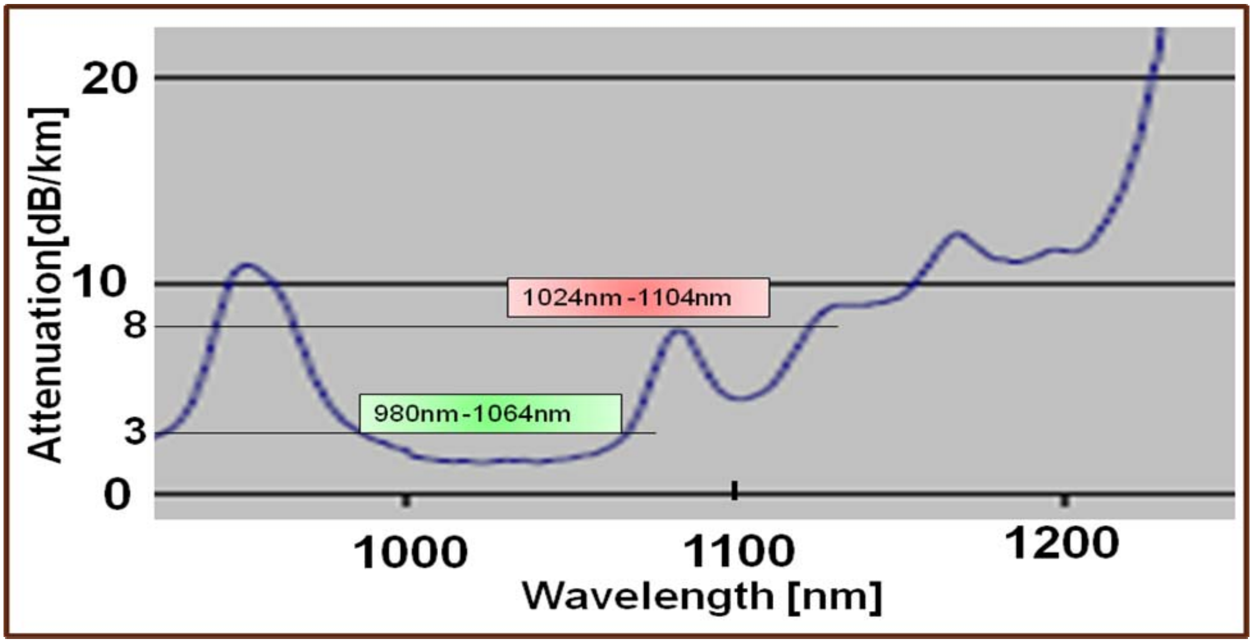

Figure 6.1. Fiber attenuation graph with DTS operating bands.

The Hydrogen induced attenuation peaks increase the highest attenuation level to 3[dB/km] for the 980[nm]-1064[nm] band, and the highest attenuation level for the 1024[nm]-1104[nm] band is increased to 8[dB/km].

The required Hydrogen induced attenuation margin for the single ended dual wavelength system operating in the 980[nm]-1064[nm] is the difference between the original 2[dB/km] and the 3[dB/km] so 2 x 1.5[km] x 1[dB/km] = 3[dB].

The required Hydrogen induced attenuation margin for the double ended single wavelength system operating in the 1024[nm]-1104[nm] is the difference between the original 2[dB/km] and the 8[dB/km] so 2 x 1.5[km] x 6[dB/km] = 18[dB]. This increase is quite considerable and the fiber test conditions for the fiber are quite severe at 200[psi] partial Hydrogen pressure. A 200[psi] partial Hydrogen pressure would translate into a 2,000[psi] well pressure with 10% Hydrogen concentration in the well.

Insufficient power margin will make the system fail when exposed to Hydrogen at elevated temperatures. Free Hydrogen in the optical fiber cause the attenuation peak at 1083[nm], and this peak will be present every time there is free Hydrogen in any optical fiber. The amplitude of the 1083[nm] peak will vary with Hydrogen concentration.

Surface cabling and surface splices may add another 2-6[dB] and will normally not change when properly installed. Any problems with the surface cabling can be diagnosed using the Stokes trace of a DTS system or using a telecommunication grade OTDR.

DTS system aging is normally not a major concern but it is always advisable to check with the DTS system supplier and add a suitable margin based on the recommendations.

The key decision for designing thermal monitoring systems is to select the fiber and DTS as a pair, where the DTS system operates in a wavelength band with minimum fiber attenuation increase during the service life of the asset.

7. CONCLUSIONS

- Multi-wavelength DTS technology offers state of the art performance with extended service life, accurate data and automatic trace by trace mitigation of dynamic down-hole fiber attenuation.

- Hydrogen tolerant Pure Silica Core (PSC) fibers must be used to achieve good service life in Hydrogen rich environments above 150[°C]. Fibers must be qualified by exposure to in-situ conditions while measuring wavelength dependent optical attenuation.

- Deployment with minimum mechanical and chemical exposure to the optical fibers will extend the service life of a system.

- The DTS operating wavelength band must be selected to reside in a low attenuation window in the selected optical fiber when the fiber is exposed to down-hole conditions.

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