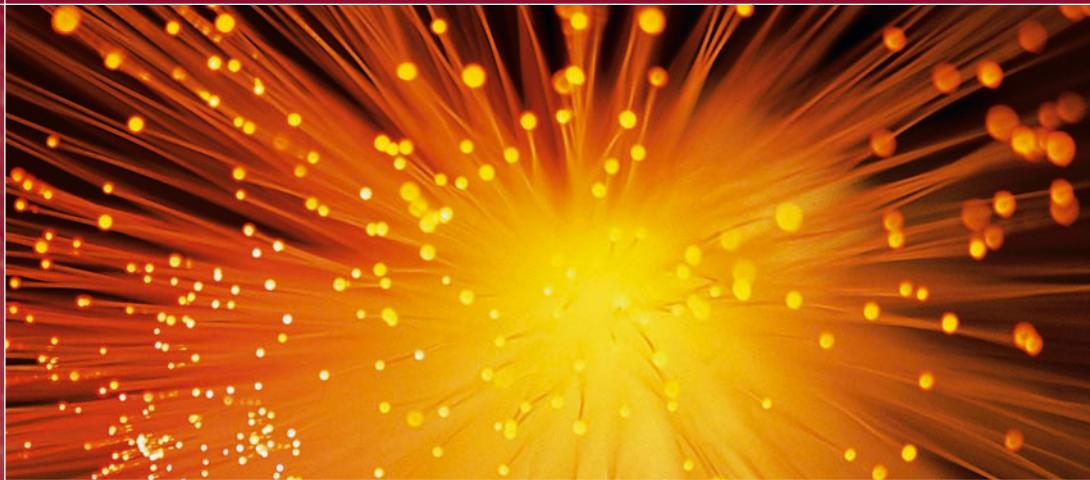


Distributed Temperature Sensing



A DTS Primer for Oil & Gas Production

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PREFACE AND ACKNOWLEDGEMENTS

The intent of this endeavor is to have at hand a readable document to convey the core ideas of DTS technology to the uninitiated reader. DTS stands for Distributed Temperature Sensing. Not only does this technology provide a non-intrusive glimpse of the well's temperature profile, it effectively adds the dimension of time to temperature logging. Periodic or rapid-fire sequences of temperature logs, now possible through DTS technology, suddenly bring clarity to the often murky world of temperature log evaluation and well monitoring. While this technology is seemingly complex, it is hoped that this document achieves its goal to be readable, understandable, and to generate interest in a new and effective technique for well monitoring.

I would like to thank Shell International Exploration and Production B.V. and my co-author, Alex van der Spek, for the opportunity to participate in this document. I must also acknowledge my co-author's brilliant exposition of the mathematics of DTS which permeates this document! I would also like to thank the various service company and equipment suppliers who have taken the time to help me understand the various complexities of DTS. In particular, my thanks go out to Mahmoud Farhadroushan and Tom Parker of Sensornet, to Nigel Leggett, Dennis Carr, and Rodne Setliff of Sensa, to David Johnson, Rick Pruett, and John Maida of Halliburton, to Miodrag Pancic and Kirby Jabusch of Promore, and Doug Norton of Weatherford.

DTS is an amazing technology whose potential is not yet understood. Hopefully this document will inspire others to champion its application in the oil and gas industry.

James J. Smolen
May, 2003

DISTRIBUTED TEMPERATURE SENSING

A DTS PRIMER FOR OIL & GAS PRODUCTION

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DTS—DISTRIBUTED TEMPERATURE SENSING

1. INTRODUCTION TO DTS

1.1 WHAT IS DTS?

DTS stands for Distributed Temperature Sensing. DTS is a technology which provides the user with a technique to measure the temperature distribution along a fiber optic line at any time and to repeat such measurements as required. The fiber optic line can be any length up to about 30km (about 18.5 miles). With the exception of the recording instrumentation at one or both ends of the fiber, there are no electronics, no sensors, no electrical wires or electrical connections along the line. The line may be permanent or reinstalled for each use. It is inherently safe to use in environments where an electrical spark may pose a fire safety hazard.

1.2 HOW DOES DTS WORK?

Once a fiber optic line is installed, that line may be probed by means of a short laser light pulse. That pulse, lasting 10 nanoseconds or less, travels along the fiber. As it does, the light collides with the lattice structure and atoms of the fiber, causing them to emit small bursts of light at slightly shifted frequencies which travel back to the beginning of the fiber. This returning “backscattered” light is then analyzed by the instrumentation box to determine the temperature at the point from which the backscatter originated. Since the velocity of light is constant, even in a fiber, the two-way travel time from the “launch” of the light pulse to the return of the backscattered light determines the position of the recorded temperature along the fiber. Continuous monitoring of such backscattered light allows the construction of a continuous temperature profile along the length of the fiber. Such a temperature profile is called a “Distributed Temperature Survey” or DTS (note that S may also refer to Sensing or Sensor).

1.3 WHERE IS DTS USED?

A DTS has applications wherever the temperature distribution is useful. For example, a fiber optic DTS line may be tied to an electrical power line.¹ The temperature of the power line can indicate overloading or that excess capacity exists, thereby allowing more power to be conveyed safely over the line. DTS is most often used where temperature changes in time indicate the onset of deviant behavior or imminent failure of some system.^{2,3} Pressure vessels wrapped with a DTS line can be monitored to detect hot spots which may precede catastrophic failure. Oil wells can be monitored periodically to detect the onset and location of anomalous fluid production.^{4,5} The use of DTS technology is quite young at this time, and many new and amazing applications can be expected in future years.

1.4 PURPOSE OF THIS MANUAL

This manual is designed to acquaint the engineer with DTS technology, especially its utility in the Petroleum Industry. The emphasis is on the applications and installations of such technology in oil and gas wells, although other applications will be described from time to time. This manual covers the basic fiber optic technology which enables the DTS measurement. It shows how such DTS systems are set up in various types of settings. Oil/gas well installations are discussed in detail as well as the interpretation, quality control, and use of such DTS data. Lastly, vendor names, contacts, and product specifications are listed.

1.5 SOME UNITS COMMONLY USED IN FIBER OPTICS

When working with optics and the passage of light, the lengths and magnitudes commonly encountered are quite unusual to most engineering disciplines. This section provides a very short overview of some major units as well as the prefixes used in the metric system. In the metric system, the Latin prefixes such as deci, centi, milli, and the like are used to indicate a division of the major unit to which they are applied, while the Greek prefixes such as deka, hecto, kilo, and the like are used to indicate the order of multiplication by orders of 10. Some units are used so commonly in

certain sciences that they have received special names.⁶ Some English units may also be used. These are noted below.

LATIN BASE

Deci	1/10	10^{-1}
Centi (c)	1/100	10^{-2}
Milli (m)	1/1000	10^{-3}
Micro (μ)	1/1,000,000	10^{-6}
Nano		10^{-9}

GREEK BASE

Deka	10	10^{+1}
Hecto	100	10^{+2}
Kilo (k)	1,000	10^{+3}
Mega (M)	1,000,000	10^{+6}

SPECIAL NAMES

1 Micron = 1 millionth of a meter (10^{-6} meter)

1 Millimicron = 1 millionth of a millimeter (10^{-6} millimeter)

1 Angstrom = 10^{-8} centimeter (10^{-10} meter)

1 Nanometer = 10^{-7} centimeter (10^{-9} meter)

1 Micrometer = 10^{-6} meter

OTHER COMMON UNITS

1 Kilometer = 0.6214 miles

1 Meter = 39.37 inches

1 Foot = 30.48 cm

1 Inch = 2.54 cm

1 Atmosphere = 14.696 psi

Speed Of Light in a Vacuum = $3 \times 10^{+8}$ meters/sec = 186,000 miles/sec

Attenuation $m^{-1} = 10^{-4} \times \ln(10) \text{ dB/km} = 2.3026 \times 10^{-4} \text{ dB/km}$

2. FIBER OPTIC TECHNOLOGY FOR DTS MEASUREMENTS

2.1 THE LIGHT PULSE

2.1A VELOCITY OF LIGHT IN GLASS

The light pulse is launched by a laser in the surface instrumentation or “instrument box”. This light pulse is typically at a wavelength of between about 800 to 1600 nm, in the infrared and just beyond the visible spectrum.⁷ When this light enters the fiber, it is slowed down somewhat. The degree to which it is slowed is related to the refractive index of the glass in the fiber. The velocity of light in the fiber, v, is related to the speed of light in a vacuum, c, and the fiber refractive index through the following equation.

$$v = c/n = (3 \times 10^{+8})/1.5 = 2 \times 10^{+8} \text{ m/s}$$

Most glass has a value of n between 1.5 and 1.7. Using a value of n=1.5, the velocity of light in a glass fiber is determined to be about $2 \times 10^{+8}$ m/s. If the glass fiber has a larger refractive index than the surroundings, then light within the fiber may be trapped and forced to propagate through the fiber. This occurs when the angle of incidence between the light ray within the fiber and its interface with the surroundings is less than some critical value. This is the principle of “total internal reflection” based on Snell’s Law.⁸

2.1B LENGTH OF THE LIGHT PULSE

The laser light pulse typically has a duration of about 10 ns (nanoseconds) or less. When that pulse enters the fiber, it is said to be “launched”. The length of a 10 ns pulse in the fiber, assuming that the refractive index of the fiber is 1.5, is given by multiplying the velocity of light in the fiber, c/n, times the pulse duration of 10ns.

$$\text{Light Pulse Length In Fiber} = ((3. \times 10^{+8}) / 1.5) \text{m/s} \times (10 \times 10^{-9}) \text{s} = 2 \text{ m}$$

This light pulse is, in effect, a travelling sensor moving through the fiber line and relaying back temperature information (See Fig. 2.1). The length of this pulse is one factor in resolution along the fiber length.

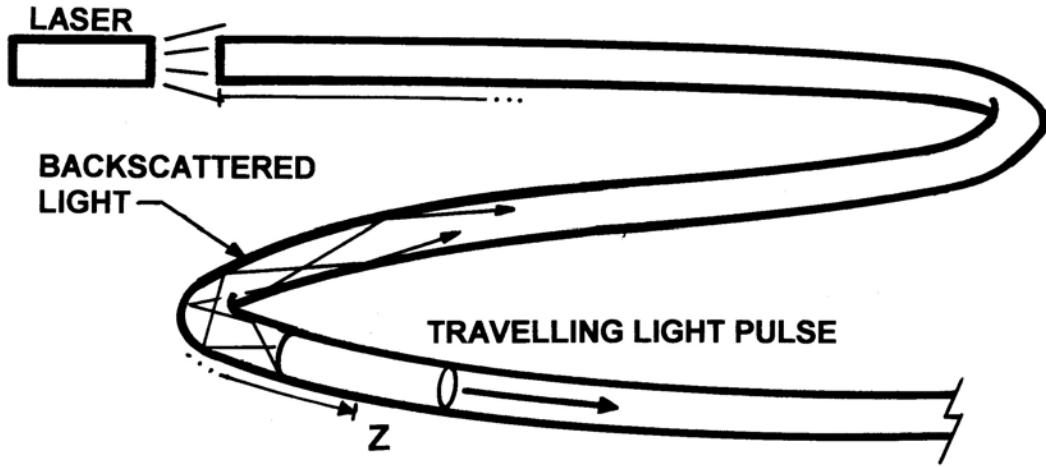


FIG. 2.1. Travelling light pulse sending backscattered light back to the instrument box.

2.2 TRAVEL TIME AND DISTANCE ALONG THE FIBER

2.2A DETECTING THE BACKSCATTERED SIGNAL

The refractive index of the fiber is usually well known before installation. It determines the speed of light in the fiber. When the light pulse travels to some point along the fiber, z , the backscattered light must return along that same path, and the total two-way path length for the signal is $2z$. If the velocity of light in the fiber is v , a window can be opened at some time t to capture that backscattered light. The time t for this window is

$$t = 2z/v$$

The window size required to achieve a one meter length resolution along the fiber ($\Delta z = 1\text{m}$) is

$$\Delta t = 2\Delta z/v = 2 \times 1/(2 \times 10^8) = 10^{-8} = 10 \text{ ns}$$

The instrumentation box must be capable of providing a series of adjacent 10 ns windows. Service companies can provide such windows as small as 1.0 ns. However, smaller windows can be effective only on shorter fiber lengths and the sampling time would be increased.

2.2B SPATIAL AND SAMPLING RESOLUTION

In the previous section it was shown that the samples can be gathered in depth increments of one meter if the backscatter detecting windows are set for a 10 ns duration. This would be called the “sampling resolution”, i.e., the depth increment at which temperature data is gathered. This, however, is not the same as the depth or “spatial resolution” of a DTS system. The difference is easily illustrated by looking at the system’s response to a short (.5m) temperature anomaly.

In Fig. 2.2 below, the 2 meter light pulse in a fiber is shown moving along in 2.5 ns increments. Each of these movements corresponds to .50 meters.

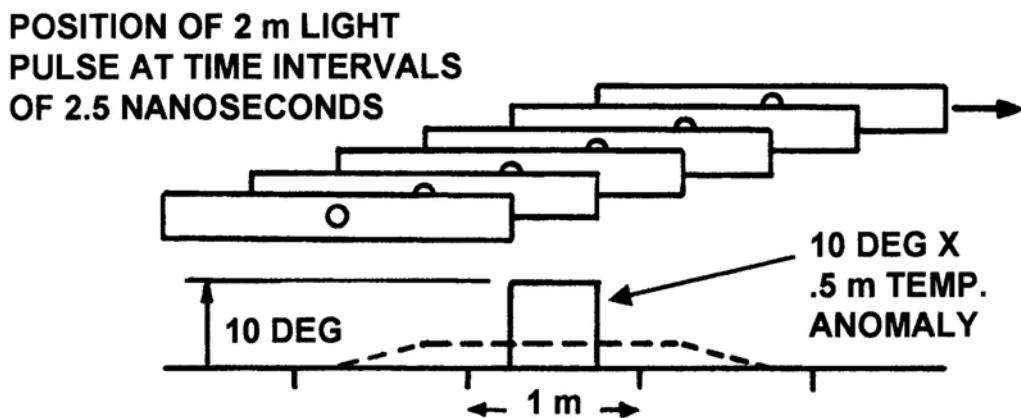


FIG. 2.2. Response of a 2m light pulse to a .5m x 10 deg temperature anomaly.

A temperature anomaly of 10 deg along .5 meter of the fiber is shown. The response from the laser pulse is seen to spread the .5 meter step in temperature over about 2.5 meters and reduce the temperature detected to about 2.5 degrees. The reduction of the temperature anomaly measured is roughly equal to the hot spot width divided by the “spatial resolution”, i.e., the 2 meter length of the light pulse. Shorter laser pulses and smaller time

windows are required to better detect short length high temperature anomalies.

“Spatial Resolution” is more or less defined as the distance it takes a system to fully respond to a sudden or step change in temperature. Considering the circumstances similar to that of Fig. 2-2, it should be easy for the reader to see that spatial resolution to a step temperature anomaly would be 2 meters. Of course, in real world conditions, with variations in backscattered light, filtering, and electronics, the actual transition across a step would not be linear, but would follow a shape like that shown in Fig. 2.3. Under such circumstances, the Spatial Resolution may be defined as the distance between the 10% and 90% points on the temperature ramp.^{7,9,10} This definition is not universal and other definitions exist within the industry.

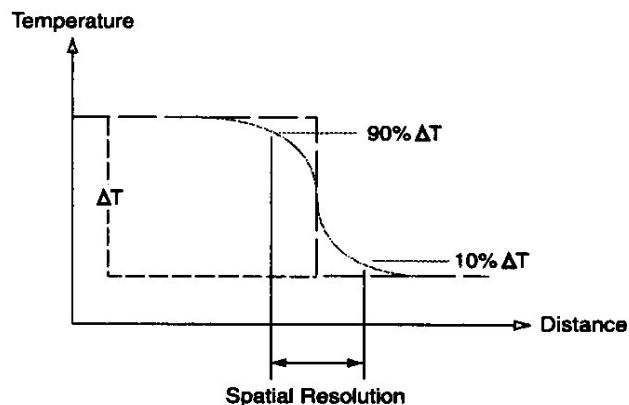


FIG. 2.3 Spatial resolution (Courtesy Sensa, Ref. 7)

2.2B DETERMINING THE LAUNCH REPITITION RATE

Another factor to consider is how often launches should be repeated. To discuss this issue, consider a 3000m (about 10,000 ft) fiber optic line. There cannot be two light pulses in the line at the same time. If this is the case, the backscattered signals would be mixed and the resulting spectrum extremely difficult or impossible to analyze. So, the light must travel to the end of the fiber and the backscattered light return before the next launch. The minimum time between launches is the two-way travel time to the end of the fiber. For a 3000 m line and $n=1.5$,

$$\text{Time between launches} = (2 \times 3000 \text{ m}) / (2 \times 10^8 \text{ m/s}) = 3 \times 10^{-5} \text{ s}$$

This corresponds to about 33,000 launches per second. In actual cases, the launch rate is less, typically about 4000 to 10,000 pulses per second. This is the case to allow for necessary data processing between launches.

2.2C REASONS FOR HIGH PULSE RATE

Why is more than one pulse required? The reason is that the data returning is weak and noisy, i.e., it has a very poor signal to noise ratio. Hence many signals must be stacked on one another to achieve statistically significant data. Typically, a log may take five minutes or longer to run. At 4000 pulses per second, this means that 1,200,000 launches have been completed. This many may be required to achieve a certain degree of temperature resolution, say 1 deg C. To achieve higher temperature resolution would require more launches. DTS systems in general require longer times (more launches) to achieve better temperature resolution. Hence, a DTS system's resolution should be stated in terms of fiber length and sampling time. In general, resolution is improved proportionally to \sqrt{n} , where n is the number of samples. For DTS systems, this is equivalent to the sampling time. To improve the resolution by a factor of two would require four times longer sampling time.

2.3 BACKSCATTERED SPECTRUM

2.3A THE RAYLEIGH, BRILLOUIN, AND RAMAN LINES

As the light pulse propagates along the fiber, it energizes the glass, lattice structure, and molecules. At first glance, the waves which return appear like reflections. They are not. The energized lattice and molecules then give off light having wavelengths at, just above, and just below the wavelength of the incident wave. The main backscattered wave is at the wavelength of the launched wave and is called the Rayleigh peak or band. This is by far the strongest signal returned. Except for certain special quality control tests, this signal is usually filtered and suppressed. Those waves associated with the lattice vibrations show up as Brillouin lines or peaks on the backscatter spectrum. The Brillouin lines are very close to and difficult to separate from the main Rayleigh band. Finally, the weakest of the backscattered waves, resulting from molecular and atomic vibrations, are the Raman Bands. The Backscatter Spectrum is shown on Figure 2.4.^{7,9-12}

2.3B TEMPERATURE FROM THE ANTI-STOKES/STOKES RATIO

The Raman signal is the signal used for evaluation of temperature. It is sufficiently strong and has a unique temperature dependence. Its wavelength is also shifted substantially (about 40/Nm) from the main Rayleigh peak, thereby allowing the dominant Rayleigh and Brillouin peaks to be filtered out.

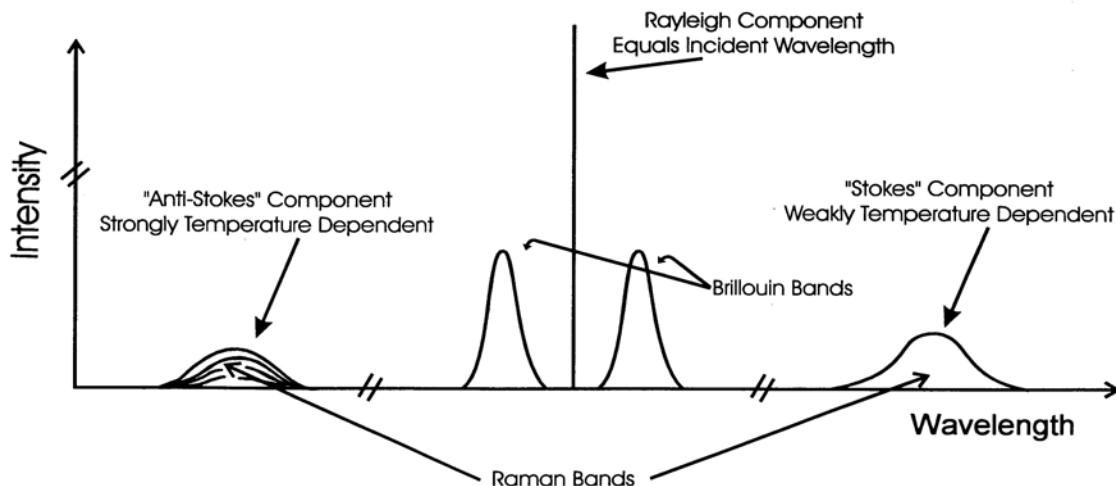


FIG. 2.4. Backscatter spectrum with Rayleigh, Brillouin, and Raman bands as well as the Stokes and anti-Stokes bands. (Courtesy Pruett Industries, now Halliburton, Ref. 11).

The Raman signal is comprised of the so-called “Stokes” and “anti-Stokes” bands. The Stokes band at the higher wavelengths (red shifted) is stable with little temperature sensitivity. The anti-Stokes band at the lower wavelengths (blue shifted) exhibits a temperature sensitivity, where the higher the energy within the band, the higher the temperature and vice versa. A ratio of the energy or area within the Anti-Stokes band to that of the Stokes band can be simply related to the temperature of the fiber optic line at the depth where the signal originated.

The temperature, $T(z)$ (deg K), can be related to the ratio of anti-Stokes to Stokes signals by the equation (This equation is a simplification. See Appendix A for the origin of this equation.)

$$T(z) = T_{ref} \left(1 + \Delta\alpha z / \ln(C_+ / C_-) + \ln(I_+ / I_-) / \ln(C_+ / C_-) \right)$$

Where

$T(z)$ = Temperature along the fiber line at z , deg. K

T_{ref} = Reference temperature, deg. K

$\Delta\alpha$ = Differential attenuation between Stokes and anti-Stokes backscatter, m^{-1} , $__ > 0$ (See Fig. 3.5)

I^+ = Intensity of Stokes band, I^+ is a $f(z)$

I^- = Intensity of anti-Stokes band, I^- is a $f(z)$

C^+, C^- = Constants relating to sensitivity of I^+/I^- to temp.

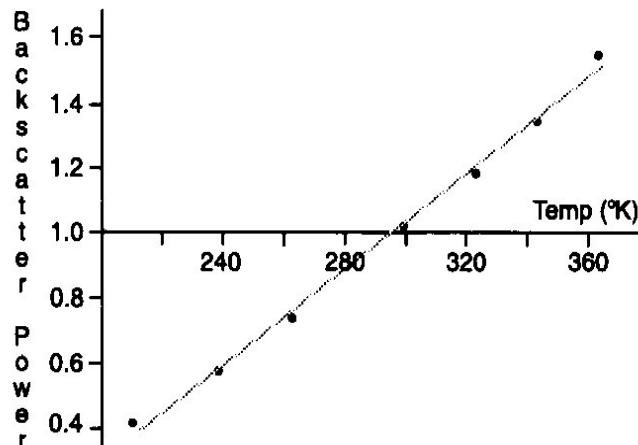
In the above equation and much of the analysis which follows, $__$ is assumed to be constant, whereas in practice it may vary with z . Temperatures are in deg K. The relationships between this and other temperature scales are as follows:

$$T \text{ (deg K)} = T \text{ (deg C)} + 273.15$$

$$T \text{ (deg F)} = 1.8 \times T(\text{deg C}) + 32$$

The temperature term in the equation, sometimes referred to as “backscatter power”, is calibrated to the $\ln(I^+/I^-)$ ratio. Such a response, is shown on Fig. 2-5.^{7,9,10}

FIG. 2.5. Backscatter power vs. temperature calibration.
(Courtesy Sensa, Ref. 7)



2.3C TEMPERATURE CALIBRATION

The equation of the preceding section is linear and can be used to illustrate how the instrumentation is calibrated for linear attenuation along the fiber line. Within the instrumentation box, or nearby, is a known reference temperature bath or oven. $T(0)$ is equal to the bath temperature at $z=0$, which is equal to T_{ref} plus a function of $(\ln^+(0)/\ln^-(0))$. This correction is called the “offset” correction and is shown on Fig. 2.6.

If the fiber line is at a constant temperature, the linear $\Delta\alpha$ correction with z is as shown in Fig. 2.6. If the sensitivity is known, the observed temperature log is made up sum of three components. It is the sum of the offset, plus the presumed linear drift due to differential attenuation, plus the actual measured temperature relative to $T(0)$. Note that if the only tie-in point for measuring accurate temperature is the bath in the instrument box, the temperature log is subject to an unknown amount of drift with depth. This may or may not be a problem depending on the application for which the log is to be used.¹³

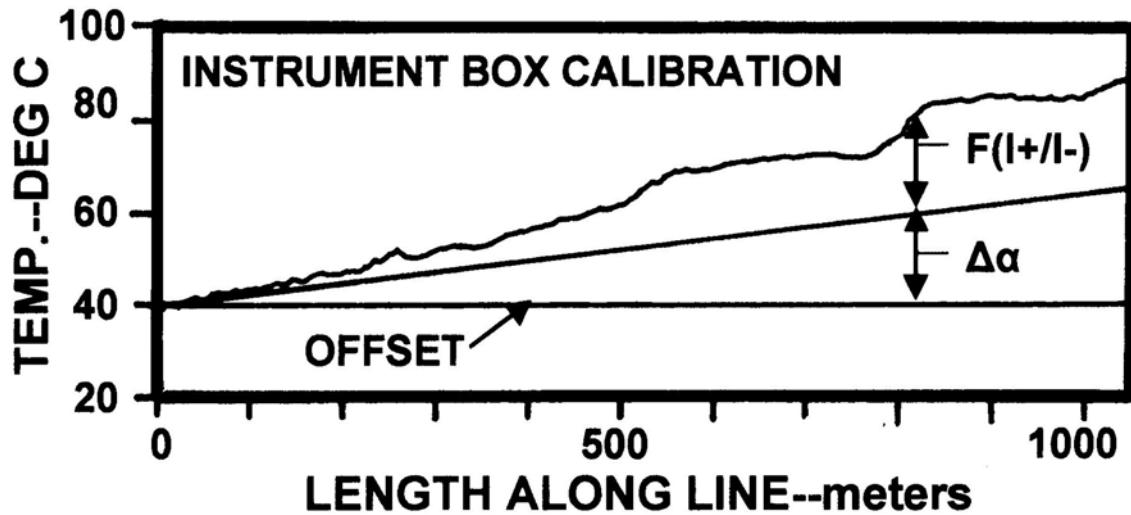


FIG. 2.6. Instrument box calibration for linear attenuation and constant offset.

2.3D OPTICAL DEPTH DISTORTION AND MISMATCH

If the launching laser has a 1064 nm wavelength, then the Raman backscattered signals will be at wavelengths of 1024nm and 1104 nm. This creates a problem, because the refractive index of the glass fiber varies with wavelength. This effect is shown on Fig. 2.7. The problem arises when the anti-Stokes to Stokes ratio is taken. That ratio is not simply the then current ratio, but instead the Raman signals have to be stored and the proper position of the two Raman signals needs to be calculated. This computation should be done in the instrument box. Note that the downgoing laser pulse is the Rayleigh wave travelling at some light velocity c/n. The returning anti-Stokes and Stokes signals are travelling at velocities of c/n- and c/n+ respectively, where n- and n+ are their apparent refractive indices. Instrument boxes should be designed to take into account this effect.

Sometimes an increase in wavelength is referred to as a “red shift” and a shortening is referred to as a “blue shift”. These shifts are highlighted on Fig. 2.7.^{8,14}

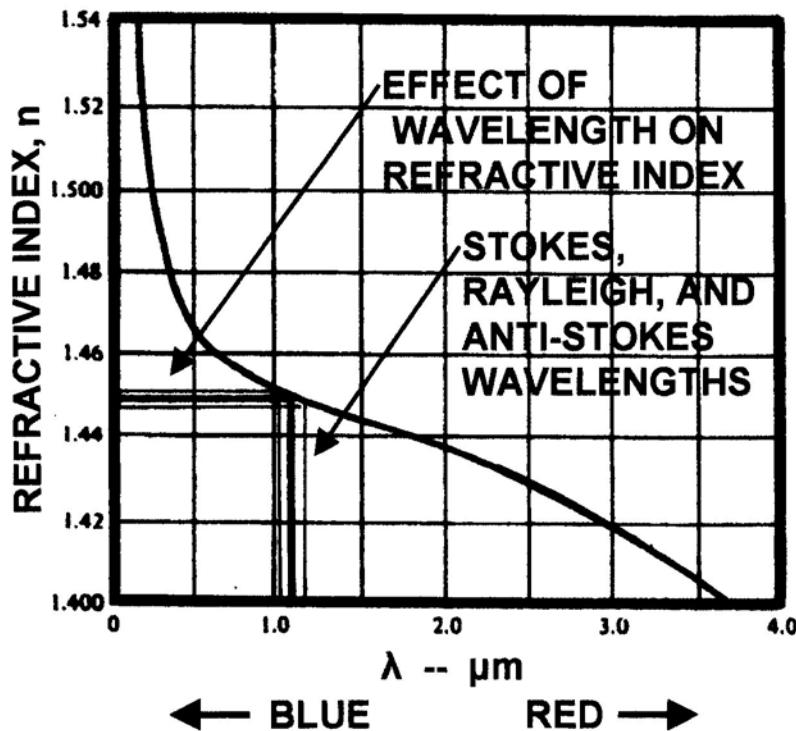


FIG. 2.7. Refractive index changes for backscattered Stokes and anti-Stokes signals.

If this effect is not corrected, the anti-Stokes signal, which contains most of the temperature information, will arrive late, causing a temperature anomaly to be detected at a deeper depth than its actual location. This anomaly is also likely to be somewhat distorted. This mismatch of optical and actual depth is sometimes referred to as “optical overstuff”. There are also mechanical effects which can cause a discrepancy between actual depth and apparent depth of an anomaly on a fiber. These are referred to as “mechanical overstuff”. The effects of mechanical overstuff are discussed in the last section of Chapter 4, following the various types of fiber installations. Optical and mechanical overstuff are discussed again in Chapter 6 under quality control topics.

Another cause of optical mismatch regarding depth is an inaccurate value of the refractive index, n . Recall that $v=c/n$, and therefore if n is too large, v is

too low, and vice versa, leading to an incorrect depth match along the fiber line.

2.3E TEMPERATURE RESOLUTION

Accuracy refers to how close the temperature measurement is to the true absolute temperature. Resolution relates to the repeatability of the measurement. Resolution can be expressed as twice the standard deviation of the temperature measurement, i.e., a range both above and below the measured value. A measurement can have good resolution (low standard deviation) or good repeatability, but still be incorrect regarding the absolute temperature (poor accuracy). As had been shown, the greater the number of launches, the better the resolution of the temperature measurement and the longer time taken.¹⁴

At first glance, it would appear that this resolution is essentially a function of the Raman anti-Stokes and Stokes signal strengths as well as the number of pulses or testing time. The higher the standard deviation of the I^+/I^- ratio, the higher the standard deviation of temperature. However, it can be shown that (See Appendix B), even if the standard deviation of the ratio I^+/I^- is constant, the standard deviation of the temperature measurement increases exponentially with distance, z , from the instrument box at $z=0$.

$$\underline{\sigma}_T(z)/\sigma_T(z) \sim e^{-z}$$

Where

$$\underline{\sigma} > 0$$

The importance of this relationship is that it shows that the temperature standard deviation will increase with well depth even if the standard deviation of the Raman signals are constant. Therefore, deeper wells require longer measurement times to attain temperature resolutions comparable to shallower wells. Along with this, there will likely be some compromise with regard to spatial resolution because of the need to average over time and distance along the fiber. See Fig. 3.5 for the source of .

2.4 THE DTS LOG

The preceding sections show how the signal makes the temperature measurement at a specific point along the fiber, z . It also shows how the temperature, $T(z)$, is determined for that depth. When these are combined, the result is a Distributed Temperature Survey, or DTS. Figure 2.8 shows such a survey along a fiber line. Note that the distance goes from zero to about 1700 m and the temperature varies from about 10 to almost 200 deg C. Note also that at zero length the temperature reading is 40 deg C. This is the reference temperature of the fiber at the oven contained in the instrument box and is a calibration point for such tests.^{2,15}

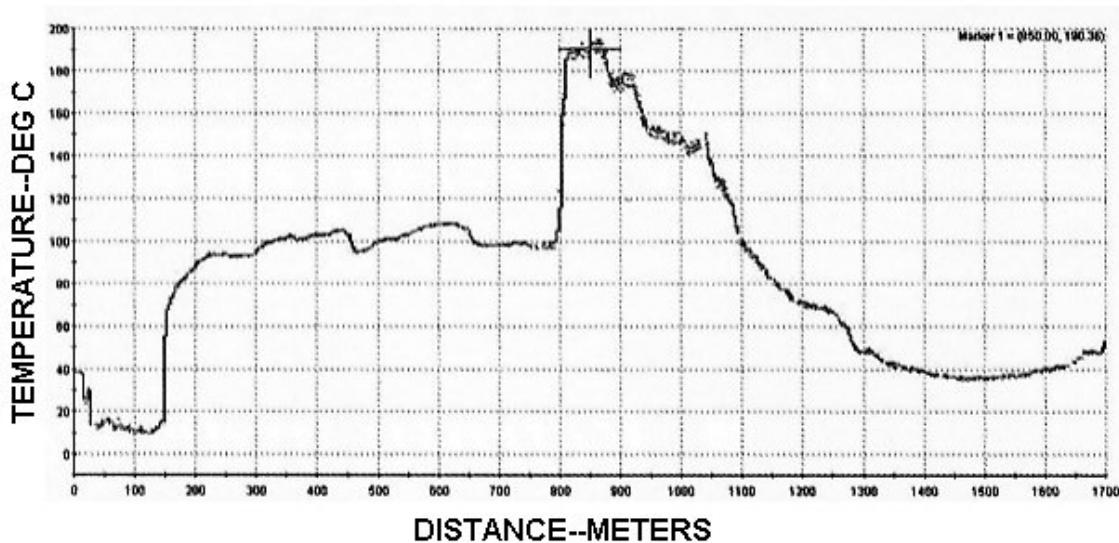


FIG. 2.8. Typical DTS log showing temperature vs position. (Courtesy Sensa, Ref. 15)

3. TYPICAL DTS INSTALLATIONS AND RECORDINGS

3.1 INSTRUMENTATION SET-UP

In order to probe a previously installed fiber optic line, the instrumentation is typically set-up as shown in Fig 3.1. The instrument box contains a pulsed laser source, capable of launching multiple laser light pulses whose duration may be 10 ns or less. These laser pulses are directed to the fiber line by means of a directional coupler. The fiber optic line then passes through an oven or bath of a known reference temperature. The light pulse moves along the line as described earlier, initiating the backscattering of light in the Rayleigh, Brillouin, and Raman bands of the light spectrum.^{7,9,10,12}

Not all light emitted by atomic or molecular structure activation is backscattered to the instrument box. Recall that Snell's law dictates a certain critical angle above which light will not be internally reflected, but lost to the surroundings. Based on this principle, a "cone of acceptance" of such light is backscattered while the remainder is dissipated to the surroundings.

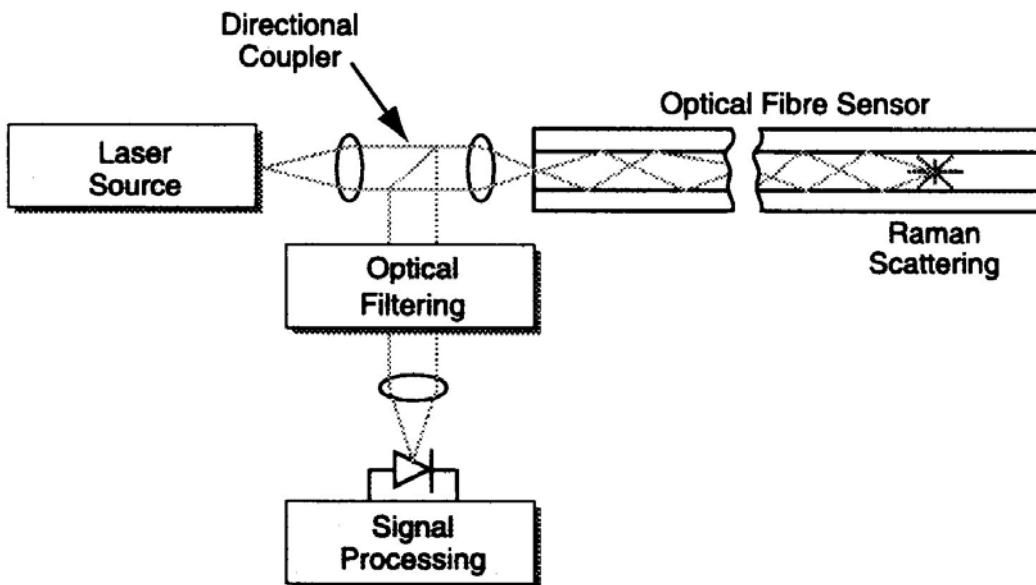


FIG. 3.1. Instrumentation for initiating and analyzing the backscattered light.
(Courtesy Sensa, Ref. 7)

The backscattered light then arrives at the instrument box where the Rayleigh and Brillouin waves as well as background noise are filtered to focus on the Raman bands. The position being examined along the fiber depends on the time after the launch when the backscattered light returns to the box and is processed. As mentioned earlier, a 10 ns window to capture the backscattered light corresponds to a 1 meter segment of the fiber line. The instrumentation must repeat this process many times to achieve statistically significant data. For example, a box which repeats this process 4000 times a second may take five minutes (1,200,000 launches) to achieve a resolution of 1 degC in a 10,000m fiber line. Recall that the resolution varies with the square root of the samples taken (Section 2.C). Therefore it would take four times as long to reduce the standard deviation of the temperature by a factor of 2.

The instrument box is also capable of processing and recording data originating at numerous discrete points along the fiber. A box capable of examining 500 such windows then can examine 500 positions along the line with a sampling resolution of about 1 meter. Note that the segments to be examined do not have to be contiguous. These data can be put into separate T vs. time and depth data files for later processing and analysis. These observed segments can be placed at critical points in a wellbore to monitor certain mechanical functions or to trigger some operational response.

3.2 OPTICAL FIBER, CLADDING, AND CONVEYANCE

3.2A THE OPTICAL FIBER

The fibers most commonly used in industry are the multimode and the singlemode fibers. The multimode fiber is most commonly used in DTS. The core glass fiber is 50 μm in diameter and is surrounded with a glass cladding to a diameter of 125 μm . The refractive index of the core is approximately 0.5% greater than the cladding thereby assuring the containment of the laser light pulse within the core. The fiber cross-section of Fig.3.2a shows a step index fiber in which the

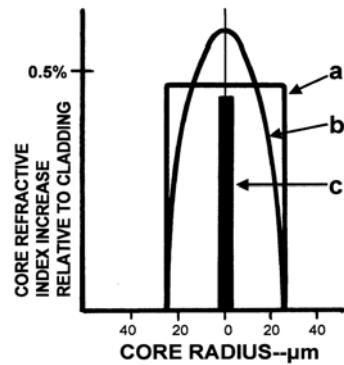


FIG. 3.2. Single and multimode fiber core.

refractive index changes abruptly.^{8,16} This type is called a multimode fiber because the light can move through the fiber in a number of ways as shown in Fig 3.3. The main mode is where the light propagates along the fiber axis. This mode is the one we usually envision when doing optical calculations. However, the initial laser light may enter the fiber at an angle to its centerline. Providing that such light is within the “cone of acceptance”, it will internally reflect through the fiber along a zig-zag path. Another possibility is that the light spirals through the fiber. In both the latter two cases, the optical path is longer and those light rays will generally arrive at a station at a station along the fiber somewhat later than the main mode.

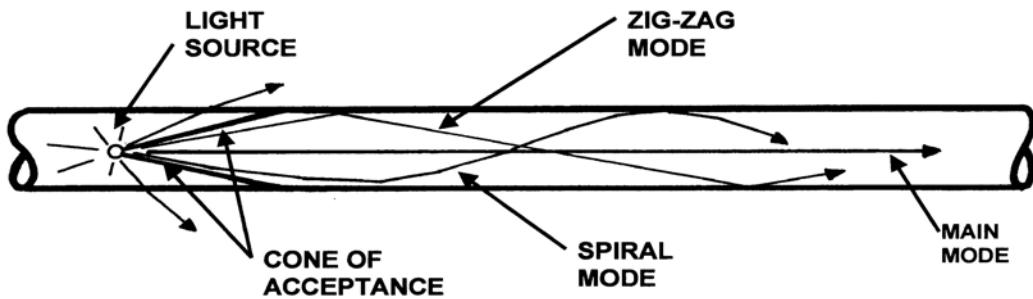


FIG. 3.3. Possible light paths along the multimode fiber.

To minimize this effect in a multimode fiber, the “graded index” fiber was developed, as shown in Fig 3.2b. In this case, the refractive index of the core increases in an approximately parabolic fashion to a maximum of about 0.5% greater than the cladding. This small change allows the zig-zag and spiral modes to travel somewhat faster and thereby better match the arrival time of all the travel modes at a station along the line. Most modern fiber optic communication lines are of the graded index type.

The singlemode fiber is typically a step index design. The glass core is 5 μm in diameter surrounded by glass cladding to a diameter of 125 μm . In this situation, the core diameter is comparable to the wavelength of the optical energy. Hence the light travels only in the main mode along the fiber axis with no oscillations across the core width. Due to its small diameter and negligible cone of acceptance, it is very difficult to put light energy into the fiber and more expensive to use. The backscattered energy is very small and it takes significantly longer for statistically significant Raman band development in most applications. As a result, most DTS applications use a multimode fiber.

3.2B MECHANICAL FIBER PROTECTION

By itself, the clad fiber described above would not last long and is too fragile for the industrial environment. It may be further coated with a carbon or gold layer about 1 μm in thickness followed by successive layers of increasingly robust plastic materials until the jacketed fiber has a diameter of 500 to 900 μm . In this form, the fiber is ready for most communication and DTS applications.

For the fiber to be suitable for oil well operations, it must be further protected. Such mechanical protection is provided by placing the fiber permanently in a semi rigid fiberglass rod or in a stainless steel capillary tube, with a typical diameter of about 1/8 in or 3 mm. Depending on the installation, such rods or tubes may be placed in yet larger tubes (.25 inch dia) which in turn may have yet further external mechanical protection. A

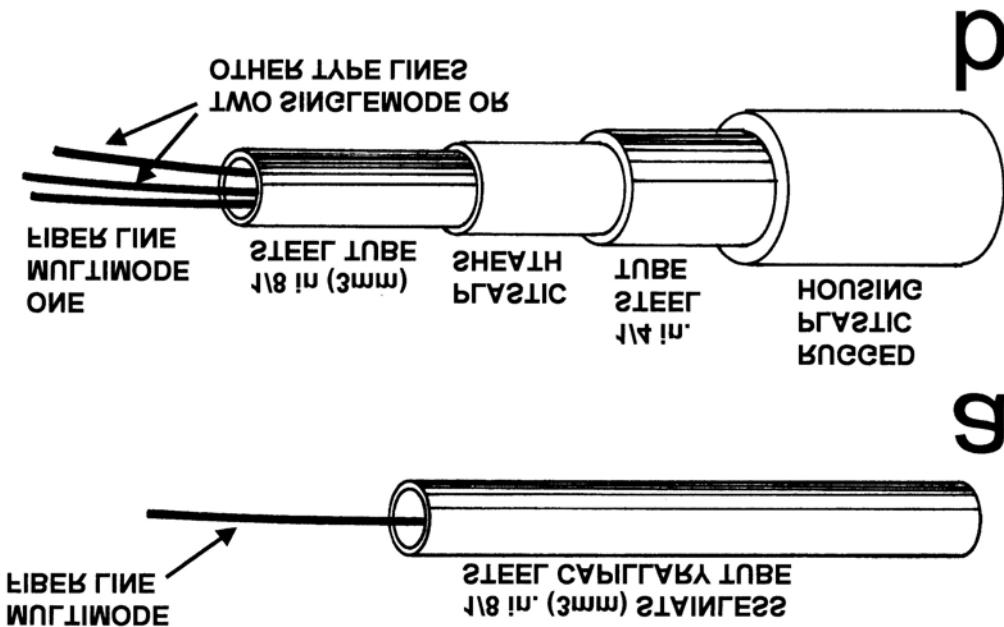


FIG. 3.4. Typical techniques to protect the DTS fiber from the downhole environment.

typical product of this type is shown in Fig 3.4b where one multimode and two single mode fibers are run inside of a steel capillary tube. This capillary tube is wrapped in a plastic sheath and set inside a .25 inch dia. steel tube around which is a plastic housing about .4 inch in diameter. Alternatively, the unprotected plastic coated fiber can be pumped down the larger _ in.

stainless tube with water followed by a silicon oil. The type of mechanical protection will depend on the installation and will be discussed more thoroughly in the section dealing with downhole installations.^{1,4,11}

3.3 SELECTION OF LASER PULSE WAVELENGTH

It is important in DTS technology that the laser light pulse must retain its energy over very long distances along the fiber to assure sufficiently strong backscattered light for analysis. One critical factor is the wavelength of the launched pulse. Expressing the attenuation rate in units of dB/km along an optical fiber, the relationship of attenuation to wavelength is shown in Fig 3.5.^{6,16} While the manufacturing process is very strict, the peaks at approximately 1.28 and 1.41 μm are caused by traces of water (H and OH respectively) diffusing into the glass and causing a dramatic increase in attenuation at those wavelengths. This effect illustrates the sensitivity of the glass to water exposure.

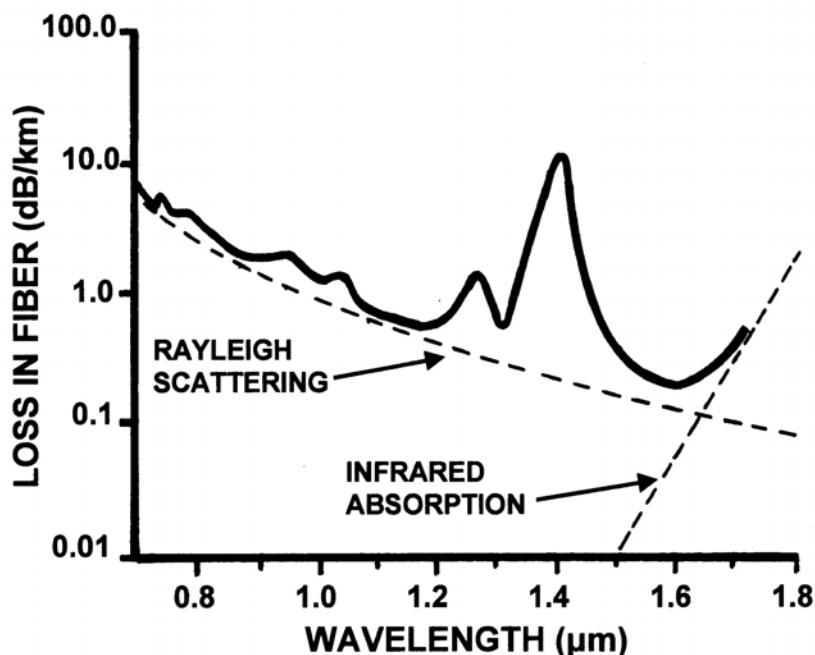


FIG. 3.5. Typical attenuation rate to wavelength relationship for a glass fiber.

Multimode fiber is typically used in installations less than about 12,000m,i.e., most oilwell DTS applications. It can accept large amounts of laser energy to provide a significant backscatter signal and is inexpensive. One major service company uses lasers of 850 nm and 1300 nm, having

attenuation rates of about 2.4 and .6 dB/km respectively for probing multimode lines. See Fig 3.5.

For longer distances, the singlemode fiber is preferred because the light stays coherent and does not have dispersion caused by light rays zig-zagging or spiraling through the fiber. However, the longer length requires less attenuation and longer probing time for the backscattered light. Lasers having wavelengths of 1450, 1550, and 1650 nm are frequently used in long singlemode DTS systems. From Fig 3.5, the attenuation rates for these wavelengths are .32, .22, and .32 dB/km respectively.

3.4 ASSESSING CONDITION OF INSTALLED FIBER (OTDR)

Once fiber is installed, there is a somewhat standard technique used by the telecommunications industry to assess the condition of the fiber line. The technique is called Optical Time Domain Reflectometry (OTDR). This technique is actually the same technique used for DTS, where a light pulse is launched down the line and the backscattered light is analyzed for its rate of attenuation. The OTDR focuses on the Rayleigh rather than the Stokes' waves.

A typical OTDR is shown on Fig. 3-7. Plotted here is the Relative Scattered Power vs. distance along the line. Point (a) is a reflection from the panel connector. Point (b) is a splice or connector in the line. The linear portion between (a) and (b) is the constant attenuation rate between these two points. Note that the slope and hence attenuation rate can change at a splice, and so the attenuation across a splice may not remain constant. The interval highlighted by (c) shows a section of damaged fiber where the attenuation rate is large and varying. Point (d) is again a splice or connector. Point (e) represents a reflection from the end of the fiber. Following the return of the signal from the end of the line is the background noise indicated by (f). Note that the instrument box calibration of Section 2.3C assumes a constant attenuation rate along the fiber line.⁸

It is good practice to run an OTDR on a fiber line before and after an installation (especially where a bare fiber is pumped down into a smooth bore tube) to check the line for installation damage, and to run one before a DTS run.

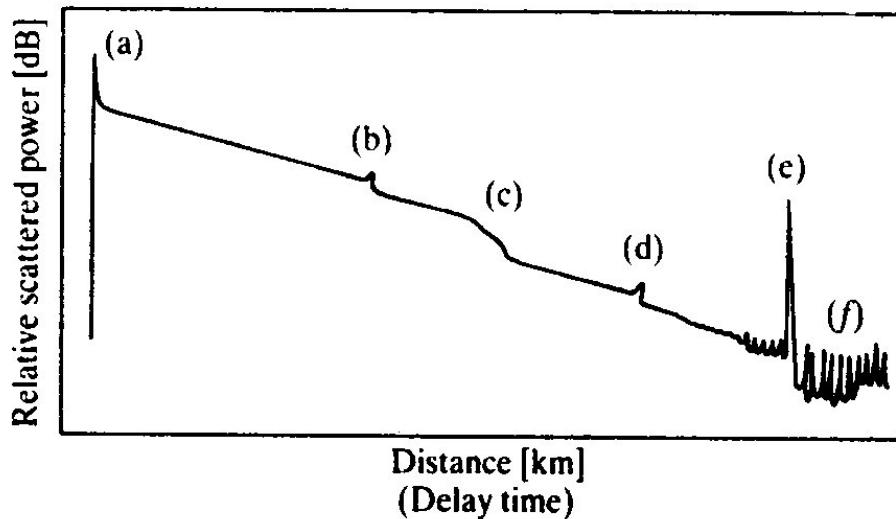


FIG. 3.6. Typical Optical Time Domain Reflectometry (OTDR) run for fiber integrity.

3.5 TYPICAL DTS INSTALLATIONS

3.5A OIL WELL INSTALLATION

Fig. 3.6a shows a typical DTS installation in an oil well. In this case, the fiber line is protected from shock, fluid, and pressure exposure in a manner similar to that shown in Fig. 3.4b. The fiber is fed in through the well head and passes down in the annulus behind and strapped to tubing. It is run through the packer to near the bottom of the well (Total Depth, TD). The DTS line may or may not have further instrumentation at the end of the line in the “rathole” or “sump” part of the well. Many variations for such installations exist and will be discussed at greater length in the next section.

A DTS survey can be run with the well shut-in or flowing. It is usually not run to measure the temperature of a well with great accuracy, but mainly for comparison with earlier DTS logs. The time between surveys can be minutes, weeks, or months depending on the information sought.

In the case of Fig. 3-7, the temperature survey recorded by the DTS fiber line shows both the liquid entry and gas lift valve operating. The liquid entry is characterized by a deviation from the geothermal gradient as shown. The presence of the cooling anomaly at the gas lift valve indicates that it is working and gas is expanding through the valve.⁵

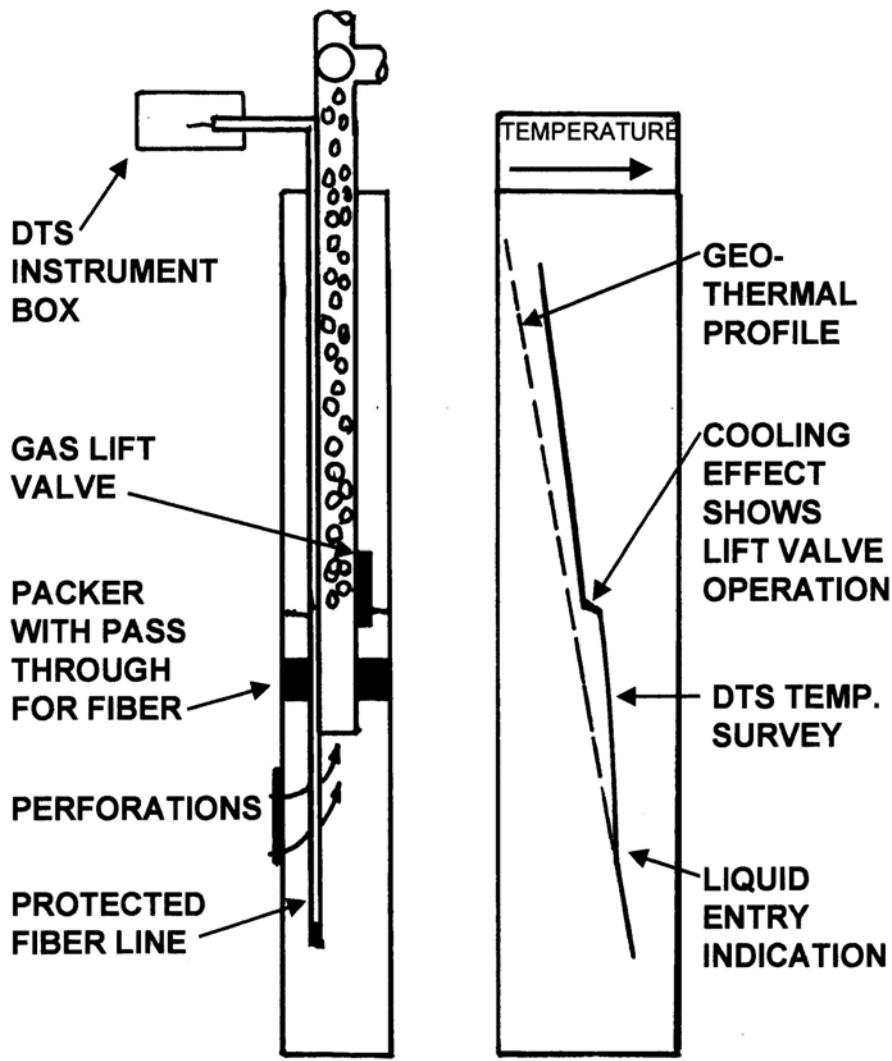


FIG. 3.7. DTS installation in a well showing liquid entry and gas lift valve.

3.5B MONITORING PRESSURE VESSELS

DTS has been used to successfully monitor pressure or reactor vessels. The fiber is contained in a capillary tube and is wrapped around the vessel. The fiber lines can be positioned to fully cover the vessel. The vessel temperature can be measured, depending on the resolution required, as frequently as every 30 seconds. Hot spots as small as 30 cm in diameter can be detected. An increase of temperature on the wall of the vessel may indicate that something has gone wrong with the processes inside the vessel or that the vessel is beginning to fail. The DTS instrument box can be

programmed to activate an alarm when a temperature exceeding some preset amount is detected on the vessel wall. The processing within the vessel can then be shut down for inspection of the vessel and the prevention of catastrophic failure. The schematic of Fig. 3.8 shows such an installation.^{2,15}

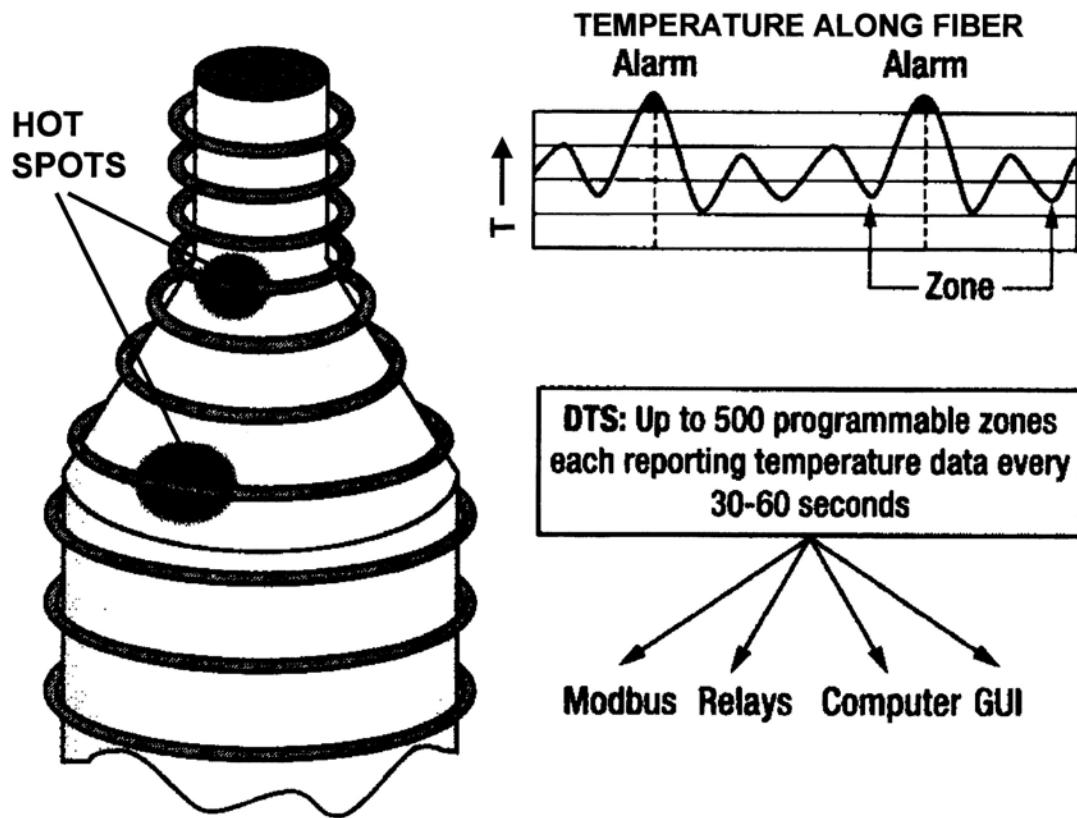


FIG. 3.8. DTS detects hot spots which may precede possible catastrophic failure of the vessel. (Courtesy Sensa, Ref. 15)

3.5C MONITORING FOR LEAKS IN A GAS PIPELINE

Gas leaks have been detected along pipelines using DTS. The leak, of course, can occur anywhere along the pipeline length as well as anywhere on its cross section. DTS is quite suitable for detecting the leak along the length, but how is a leak detected if it could be anywhere on the cross section? One solution is to wrap the pipe like a pressure vessel. However, since pipelines are rather long, wrapping the fiber around the pipe would shorten the length of pipe monitored and eliminate much of the benefit DTS offers.

Rather than wrap the pipeline like a pressure vessel, the pipeline instead is wrapped with a containment wrapper as shown in Fig. 3.9a. If a leak develops, the gas must leak out through the wrapper seam, which is intentionally left open. The DTS fiber is placed at this position and can run parallel with and along the full length of pipe. If a leak develops, the temperature response is expected to behave like that shown in Fig 3.9b at a length of 4215 m. The leak shown is from a test to simulate a leak. Note that the temperature anomaly grows with time.^{17,18}

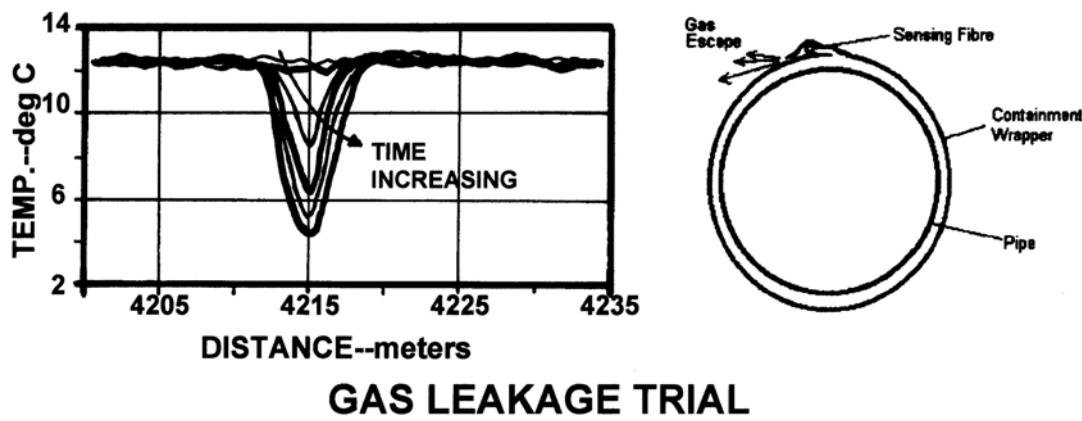


FIG. 3.9. Leak detection along a pipeline. (Courtesy Sensa, Ref. 17)

3.5D OTHER DTS APPLICATIONS

DTS may be used to monitor the temperature along electric power lines. Their temperature is an indication of their electrical load. Monitoring such lines can determine if they are dangerously overloaded or are underutilized and safely capable of carrying more power. DTS can help power companies utilize such assets more efficiently and effectively.

Other applications include fire detection in tunnels, warehouses, buildings, and the like. By frequent probing of the fiber lines, detection of temperature suddenly rising, or rising above some predetermined threshold, would set off an alarm. Early detection and warning will help minimize the damage which such fires could cause.^{1,19,20}

4. OIL WELL INSTALLATIONS AND HARDWARE

4.1 TYPES OF OILWELL/GASWELL INSTALLATIONS

Oil/Gas well DTS installations have been categorized as Retrievable, Semipermanent, and Permanent type installations. These arrangements and their associated equipment are described below. The reader should understand that the installations which follow are merely typical, and that many variations among the service companies exist.

4.1A RETRIEvable INSTALLATION

In a retrievable installation, the fiber optic line is run into any existing well where an electric or slick line survey can be run. Instead of an armored electric cable or a slick line, the fiber is housed in a tiny steel capillary tube coiled onto a winch drum. The capillary tube is typically about .125 inches or slightly greater than 3mm in diameter (See Fig. 3.4A). With either a weight or some sensor on the end of the line, the capillary tube is run into the well, typically to TD, for the DTS run.

Some companies use a line containing both an electrical conductor and fiber for running continuous video logs in wells. If the tool is stopped at TD, the DTS log can be run on the fiber optic part of the line. In all of these cases, the line is retrieved after the DTS run and available for use in another well. Hence, these are “retrievable” installations. Such an installation is shown in Fig 4.1.^{11,21}

When dealing with the horizontal environment, protected fiber optic lines have been built into coiled tubing. The coiled tubing is pushed through the production tubing and across the horizontal interval. One or a number of DTS surveys are taken after which the coiled tubing is retrieved after the job. Such an installation would also qualify as a retrievable installation.

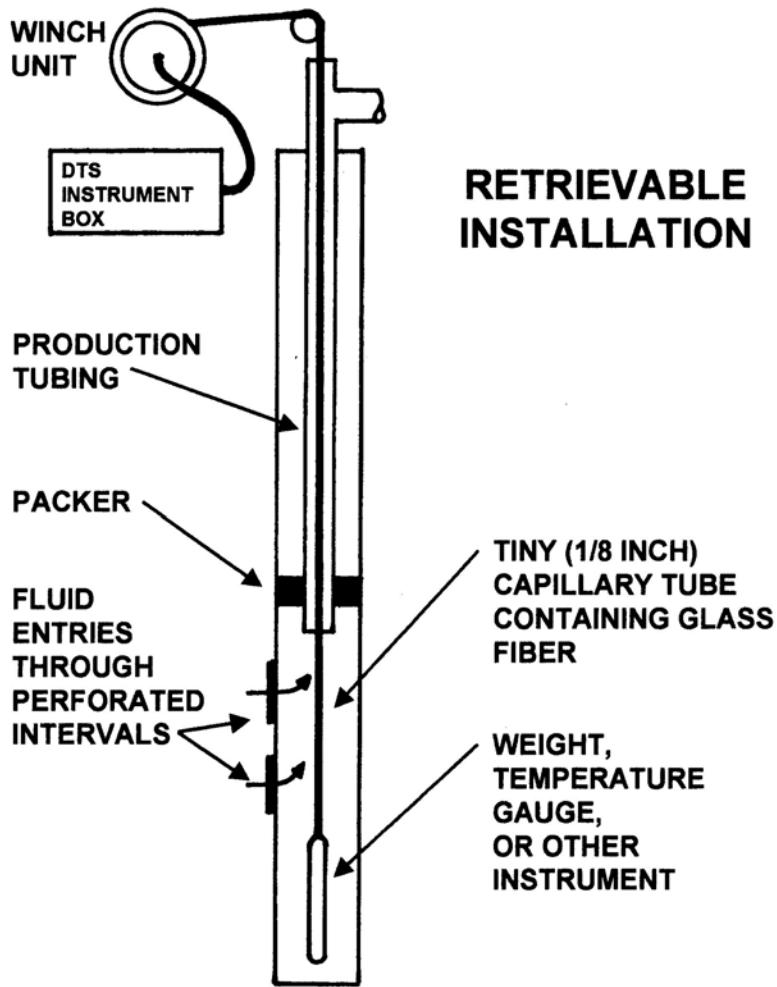


FIG. 4.1. Typical DTS wireline retrievable installation.

4.1B SEMIPERMANENT INSTALLATIONS

Semipermanent installations are shown schematically in Figs. 4.2 and 4.3. In the configuration of Fig. 4.2, the coiled tubing can be permanently seated in the wellhead after having run through a second tubing or guide string to TD. The protected fiber optic line can be pumped down through the coiled tubing and left in place for periodic DTS measurements. The line is typically pumped down in this configuration. This installation is considered semipermanent since the fiber and coiled tubing and other strings can be pulled when the well is recompleted.^{11,23}

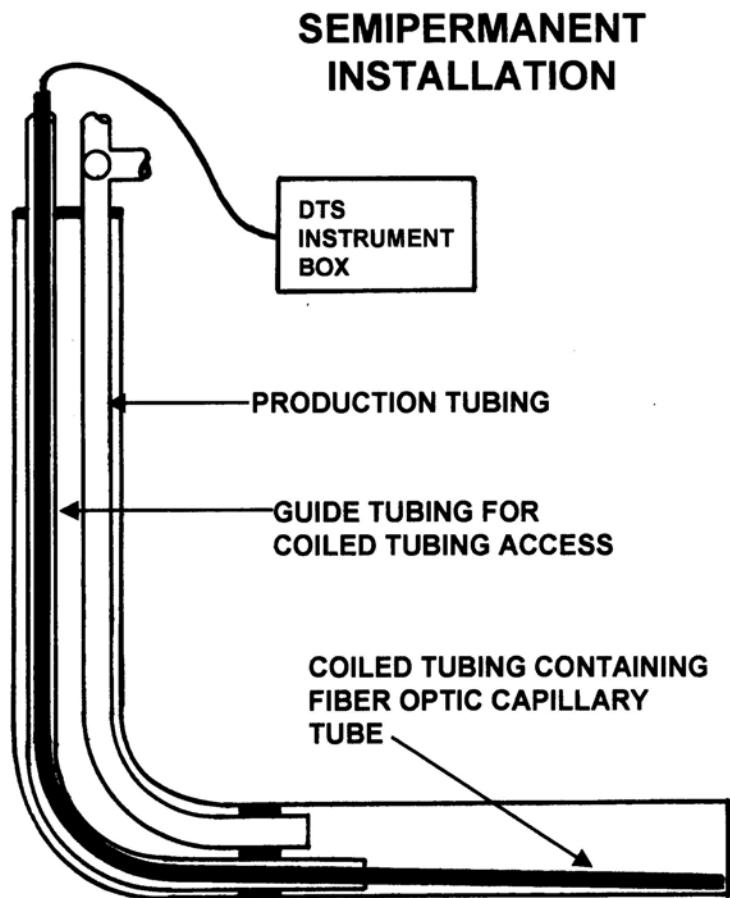


FIG. 4.2. Semipermanent installation using coiled tubing.

Another Semipermanent installation is shown on Fig. 4.3. In this case, a stainless steel capillary tube, typically .25inch diameter or smaller, is strapped to the outside of the production tubing and remains fixed in place. A fiber optic line is then pumped or pushed into the stainless steel tube and is left there for later DTS surveys. Note that this configuration is useful for monitoring gas lift mandrel operation, submersible pump loads, flow profiles through screens and gravel packs, etc. Special packers are available which allow the capillary tube to be fed through the packer or to be connected to a pass through port, thereby leaving a passage for the fiber optic line to also pass through the packer. In this figure, the stainless steel capillary tube is run across the producing interval on a slotted liner.

In the configuration shown in Fig. 4.3, the stainless steel capillary tube is run to near TD where a “turn-around” sub is used to feed the fiber back to the surface. The fiber in this case is not housed in a steel tube, but is protected by only its thin plastic jacket. It is then pumped with water or other fluids through the inch stainless tube until it returns to the surface. Such an installation is called a dual ended fiber installation and may offer some calibration features over a single fiber line as discussed later in this chapter. Note that any of the semipermanent and permanent installations can be designed to be single or dual ended.^{11,22-25}

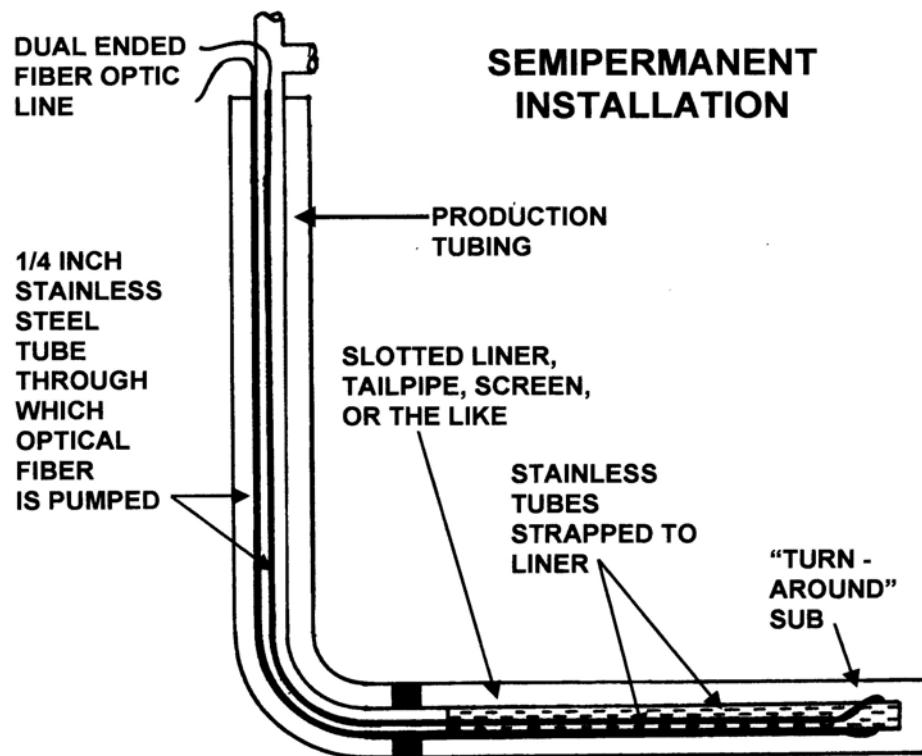


FIG. 4.3. Dual ended semipermanent installation with a turn around sub.

Both of these configurations are called semipermanent since the fiber is a permanent part of the completion, but can be pulled and replaced if the well to be recompleted. Note also that when fibers can be pumped into place, this means that if they become degraded over time they generally can be retrieved and a replacement fiber pumped into place.

4.1C PERMANENT INSTALLATIONS

When adequately protected, a fiber optic line can be permanently installed on the backside of the casing, liner or tubing. It can be strapped to the casing and permanently fixed in place with the cementing of the well. As with the semipermanent installations, the fiber line can be strapped to the tubing, etc. However, in permanent installations the fiber may or may not be fixed within its protective jacketing depending on whether it is pumped into or permanently installed in the capillary tubing. Once installed the fiber optic line or capillary tube stays in place and cannot easily be pulled from the well. Such an installation where the fiber line is immersed in the cement sheath is shown in FIG. 4.4.¹¹

Note that the difference between permanent and semipermanent installations may be somewhat fuzzy. For example, if a steel tube was placed in the cement and a fiber pumped down as in Fig 4.3, such an installation would be permanent by virtue of the non-retrievable stainless tube placed within the cement. The fiber could, however, be replaced if required.

Permanent installations are ideally suited for new wells, especially those which are highly deviated or horizontal.

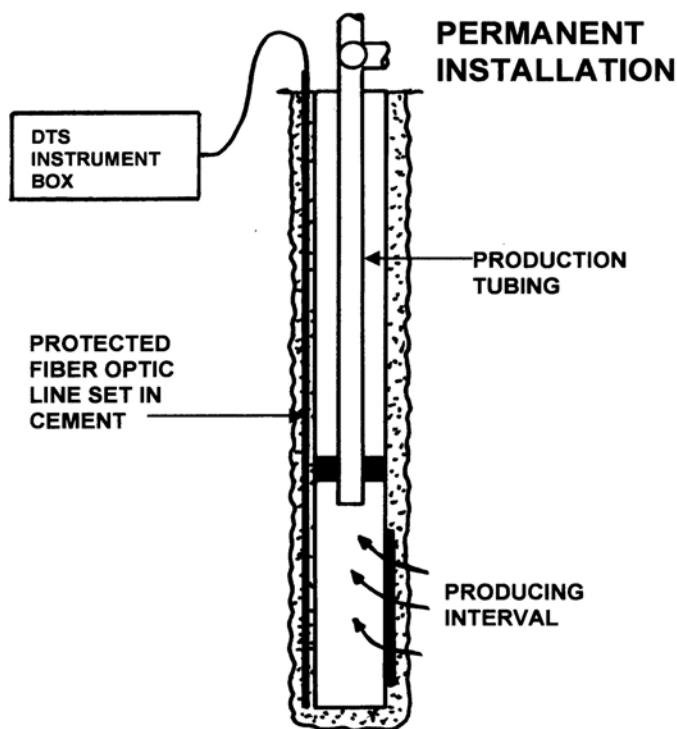


FIG. 4.4. Permanent DTS installation.

4.2 SINGLE OR DOUBLE ENDED FIBER LINE

With the exception of the retrievable installation of Fig. 4-1, virtually all other types of installations of fiber lines in wells can be either single or double ended. Recall that the double ended configuration includes a turn-around sub at the lowest point of temperature evaluation. In this section, the relative merits of each system are examined, especially in terms of what quality of information is required.

Fig. 4.5 shows four typical fiber installations. Fig. 4.5A represents a single straight fiber run to TD with nothing else. Fig. 4.5B shows a single straight fiber coupled with an independent temperature measurement. The black dot on the end of the line represents a temperature gauge. Fig. 4.5C shows a system where the fiber is pumped partially uphole through a turn-around sub, but does not reach the surface. Finally, Fig. 4.5D shows a double ended system where a thin coated fiber pumped is down and around through a turn around sub and back to the surface. The main feature of these systems is their calibration method.¹⁴

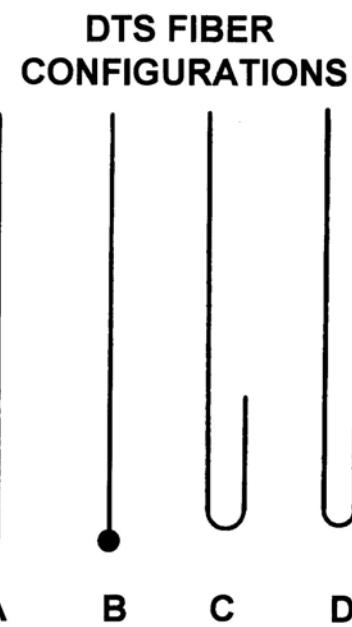


FIG. 4.5. Fiber configurations.

Note that for A, B, and C, if the fiber is to be pumped through the line, a check valve is located at the end of the line to allow fluids to pass and to stop the fiber.

4.2A SINGLE ENDED STRAIGHT SYSTEMS

This group includes both types A and B of Fig. 4.5. The straight system configuration of Fig. 4.5A includes a fiber optic line run over the interval of interest. A system such as this cannot be calibrated to accurate temperatures. However, the resolution of such a system is comparable to any of the others. This means that small changes in temperature can be detected, but the absolute temperature cannot be accurately known.

Wireline temperature logs tend to be poorly calibrated, but can detect changes as small as .1 degF. If the objective is to assess the shape of the temperature profile, and from it to qualitatively infer downhole flowing conditions, then accurate calibration is probably not needed. If repeat runs are to be made over a short period of time (days, not months), then again calibration may not be required if the same instrument box and fiber are used. However, over time the instrument box may change and the fiber attenuation rate may change. So, an uncalibrated line such this is not recommended for longer term evaluations.

There is an exception to the rule stated above. If the rathole in the wellbore is known to be static, then its temperature remains constant, although unknown. If the DTS temperature in the rathole is always overlaid from run to run, then all runs will be tied into the same reference and all temperature changes are detected relative to this fixed, albeit unknown, reference. This technique is valid only if the differential attenuation constant or nearly so.

When DTS runs are to be made over long periods of time, with different fibers as well as instrument boxes, then calibration becomes extremely important for accurately comparable data. Refer to Fig. 2.6. This figure shows the offset ($To @ z=0$), the differential attenuation term, $\underline{\quad}$, and the temperature relative to To based on the anti-Stokes to Stokes backscatter ratio. If no temperature is known downhole, then the straight system cannot be calibrated and the temperature is subject to an error due to the addition of the $\underline{\quad}$ term.

If a separate wire or wires are run in the same capillary tube as the fiber line, the temperature can be measured at the end of the line. This can be done electrically or by use of a Brag Grating fiber or other means. This configuration is shown in Fig. 4.5B, where the black dot is a temperature sensor. If it is assumed that the differential attenuation, $\underline{\quad}$, term is constant, then its effect on the measured DTS temperature is shown on Fig. 4.6.

On the left is shown an uncorrected DTS survey. The well goes from surface, $z=0$, to the bottom of the fiber line, $z=L$. The $\underline{\quad}$ term is shown to be constant. If the fiber is new and undamaged, the assumption of $\underline{\quad}$ being constant is probably reasonable. However, older fibers, fiber which have been pumped in and out a few times, fibers exposed to water or hydrogen, and spliced fibers, may not satisfy this assumption. Suppose that at depth L ,

the temperature measured by the DTS survey is as shown on Fig. 4-6, and an accurate temperature gauge at that depth reads lower than the DTS by the amount a . This difference is attributed to the error at depth L . Since attenuation is linear, the DTS survey is reduced proportionately between $z=0$ and $z=L$. The corrected DTS is shown at the right on Fig. 4-6.

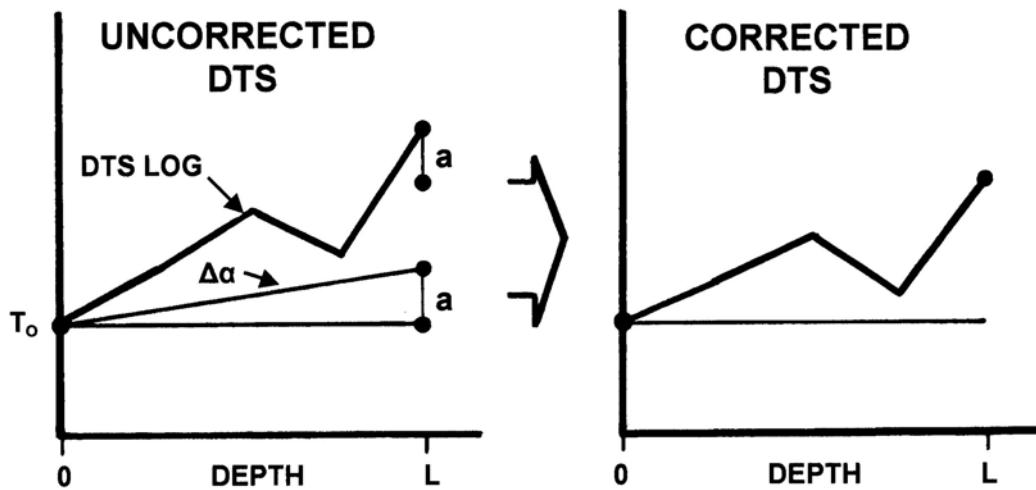


FIG. 4.6. Calibration of a straight fiber with a temperature gauge at L.

4.2B PARTIALLY RETURNED FIBERS

The partially returned fiber is shown in Fig. 4.5C. The fiber is typically pumped down through a turn around sub and partially back uphole. There is usually a valve set at some depth to terminate the fiber movement. The DTS for such a system should exhibit symmetry about the turn around sub. This is the case since both the up and down running fibers are subject to the same temperature profile.

Fig. 4.7 shows a DTS log schematic for such a system. Note that the turn-around sub and line of symmetry are shown. However, due to a linear differential attenuation error, the DTS log is reading too high. No temperature gauge exists downhole. To calibrate such a system, it is first necessary to locate two points on the fiber line at the same depth. Since there is a plane of symmetry, this is easily done by moving uphole an equal amount on each fiber above the turn-around sub/line of symmetry. Suppose that this distance is l , and is equal to the distance between L and the points

where lines **a** intercept the DTS log. Furthermore, if the upgoing fiber temperature is greater than the downgoing fiber at the same depth, and the difference is equal to **b**, then the slope is given by $b/2l$.

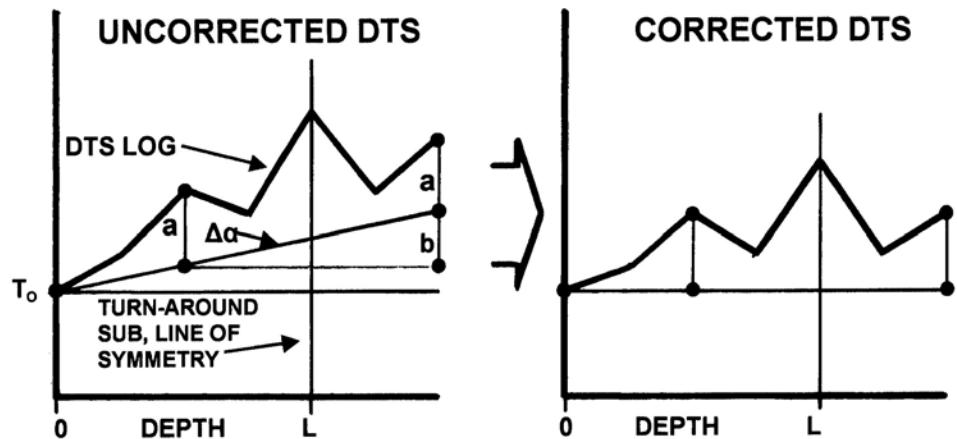


FIG. 4.7. Calibration schematic for a partially returned or wrapped system.

The differential attenuation slope calculated above, when coupled with the instrument box reference temperature, is sufficient to reconstruct the true line. Subtracting this line from the measured DTS yields the corrected DTS survey at the right. Again, implicit in this computation is the assumption that the attenuation is linear over the full length of the fiber.

4.2C DOUBLE ENDED FIBER INSTALLATIONS

Double ended fibers offer the possibility of calibrating the temperature even in the presence of a differential attenuation which varies along the length of the fiber. There are both good and bad features to the use of double ended fibers. On the negative side, the double ended installation is more costly since it uses twice the length of fiber in the well. Furthermore, the fiber may be pumped in and out more frequently. The fiber is not well protected except with a thin plastic sheath, and such handling may cause scratches or other attenuation increasing damage to the fiber. Furthermore, the fiber is pumped in with water, followed by a silicon based fluid to fully (?) displace the water. It would appear likely that some residual water may remain in the capillary tube. Referring to Fig. 3.5, water in the presence of damaged fiber can be highly detrimental to the fiber attenuation rate.

This system also does offer some unique advantages. One is that if the fiber should break, then the remaining fiber is no worse than a partially returned single ended installation. As with many other types of installations, a new fiber can be pumped down should it be needed. The main advantage, however, is that this double ended system offers a means of calibrating the system easily, even if the attenuation is non-linear.

The calibration of the two ended system, with a linear differential attenuation, is shown on Fig. 4.8. Note that the turn-around sub/line of symmetry is at the center of the DTS survey. The base line indicates the temperature at which each of the two DTS surveys is initiated. Note that it is initiated at each end (depth 0 and 0) and the corresponding DTS #1 and DTS #2 curves are shown. The average of the two curves yields the corrected DTS survey. However, this corrected survey has been shifted up an amount equal to the average of the upgoing and downgoing attenuation. At any point along the fiber, the sum and therefore the average of these two attenuation curves is constant. See Fig. 4.8.

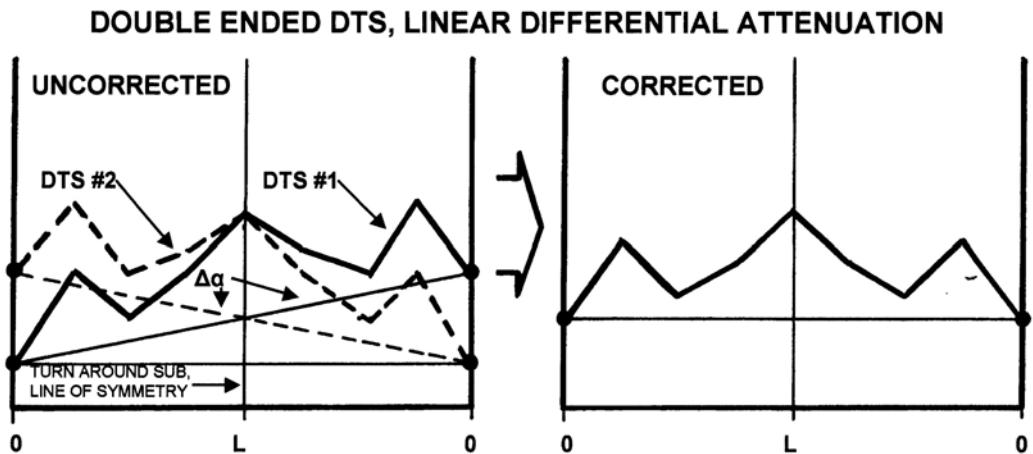


FIG. 4.8. Calibration of double ended DTS system with linear differential attenuation.

After correction, the DTS is symmetrical about the turn-around sub. The resultant survey should then be shifted back to T(0).

Fig. 4.9 shows the use of the double ended system for a non-linear differential attenuation condition. This is a condition which cannot be handled by conventional single ended DTS systems. In this example, the attenuation rate increases from one end of the fiber to the other. The slope

essentially doubles over L/2 length of fiber. Note that the attenuation curve for DTS #1 is essentially the mirror of the attenuation seen by DTS #2. As in the previous example, the average of the attenuation curves is the midpoint between the reference temperature, T_0 , and the temperature detected at $z=0$ in the return line. Again, the average of the DTS #1 And #2 curves yields a resultant corrected curve which should now be returned to T_0 due to the average attenuation offset. See the figure below.

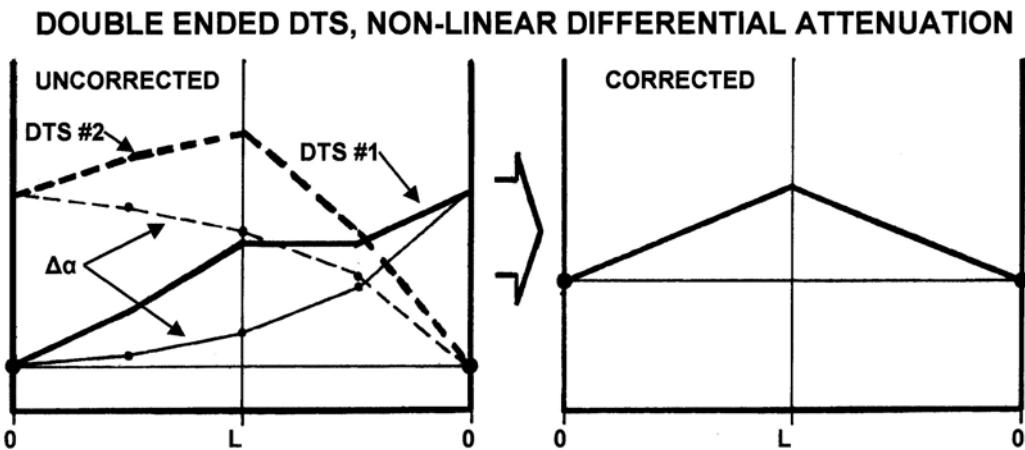


FIG. 4.9. Calibration of double ended system with non-linear differential attenuation.

4.2 D COMPARISON OF FIBER DEPLOYMENT SYSTEMS

A comparison of fiber deployment systems is shown on Fig. 4-10. To a great extent, it summarizes the information of this and previous chapters relating to installation and measurement integrity. It should be pointed out that even a single ended straight fiber can be installed in a number of different ways from a permanent installation in the cement outside of casing to that of a slickline. Clearly the comments about cost and simplicity and perhaps others will not apply across the board.

COMPARISON OF FIBER DEPLOYMENT SYSTEMS	SINGLE END STRAIGHT FIBER	SINGLE END STRAIGHT FIBER WITH DOWN-HOLE TEMP. GUAGE	PARTIALLY RETURNED FIBER	DOUBLE ENDED FIBER
* DEPENDS ON SYSTEM CONFIGURATION ** SYSTEM DEGRADED				
SIMPLE AND LOW COST	YES*	YES*		
CAN BE RUN AS WIRELINE IN MOST WELLS	YES*	YES*		
MAY BE ATTACHED TO TUBING OR CASING	YES	YES	YES	YES
CAN BE PUMPED IN AND RETRIEVED	YES*	YES*	YES	YES
CAN BE ACCURATELY CALIBRATED (LINEAR)		YES	YES	YES
LINEAR CALIBRATION OK BETWEEN BOX AND CONSTANT RATHOLE--RELATIVE CALIBRATION	YES	YES	YES	YES
LINEAR CALIBRATION WITH DOWNHOLE TEMPERATURE GUAGE		YES		
LINEAR CALIBRATION WITH REPEAT TEMP & PARTIAL RETURN FIBER			YES	YES
NON-LINEAR CALIBRATION W/O DOWNHOLE TEMP GUAGE				YES
CAN TOLERATE FIBER NON-LINEARITY AND MINOR DAMAGE				YES
REQUIRES HANDLING WHICH MAY CAUSE FIBER DAMAGE			YES	YES
CAN TOLERATE FIBER BREAKAGE				YES**

FIG. 4.10. Comparison of fiber deployment systems.

4.3 MECHANICAL DEPTH ISSUES—OVERSTUFF

There are two mechanical issues which might affect proper depth correlation between the fiber and true depth in the well. One relates to the fiber optic line coiling up within the tube through which it is pumped. Such “overstuff” can amount to as much as 3%, i.e., the fiber length is 3% longer than the tube within which it rests. Mathematically, such overstuff, $\underline{\text{—}}$, is defined as the excess of the fiber length over the tube length.¹⁴

$$\underline{\text{—}} = (\text{Fiber Length}/\text{Tube Length}) - 1$$

This type of overstuff would be most common in double ended systems and certain single ended systems where the unprotected fiber is pumped through a $\underline{\text{—}}$ inch capillary tube. Those systems using a 1/8 inch tube would tend to have much less overstuff. Finally, systems using a semirigid protected fiber such as the fibertube system of Halliburton, would tend to have little apparent overstuff. This system consists of a fiberglass coating around the glass fiber for protection and injection into a fixed capillary (1/4 in) tube.

In any case, the position of the end of the fiber or the turn-around sub is generally well known, and so the depth can be corrected to match downhole. It is then assumed that the per cent overstuff is constant. Therefore any correction is proportional to depth.

Another factor is stretch of the fiber optic cable under its own weight.¹⁴ For a hanging fiber, the overstuff, $\underline{\text{—}}$, is defined as

$$\underline{\text{—}} = (\mathbf{g} \times \underline{\text{—}} \times \mathbf{l})/\mathbf{E}$$

where

$\underline{\text{—}}$ = Stretch (multiply by 100 to get % overstuff)

\mathbf{g} = Gravitational constant, 9.8 m/sec²

$\underline{\text{—}}$ = Density of glass minus surrounding fluid $(2.5-1)\times 10^3$ kg/m³

\mathbf{E} = Young's modulus for glass, 70×10^9 Nwt/m²

\mathbf{l} = Well depth, meters

Using the values above, the overstuffed due to fiber line stretch for a 5000m well is less than .1%.

A more detailed discussion of how to compute the mechanical overstuffed is presented in Appendix C.

The question might arise as to how close the depth should be. While the answer depends on the application, it would appear that DTS depth measurements should be comparable to wireline measurements. On this basis, the author feels that a depth accuracy of + or - .5 m would be realistic for most applications.

5. APPLICATION AND INTERPRETATION OF DTS IN OIL AND GAS WELLS

5.1 INTERPRETATION OF TEMPERATURE LOGS IN PRODUCING WELLS

This section reviews the basics of temperature log interpretation. This section is not quantitative for flow evaluation. It is intended to show how various flow situations appear on a log and to train the reader to think of what happens to a fluid's temperature as it enters and flows along the borehole. The first two common situations considered are the flow of a liquid or a gas in a vertical or deviated well. The effects of shutting in an injection well is also observed, as well as some aspects of temperature logs in horizontal wells.

In all cases discussed in this section, it is assumed that the temperature survey is taken within the fluid flow, as would be the case if a logging tool is run in the well. This somewhat obvious statement is mentioned since a DTS survey is usually taken either in the annulus or in the cement sheath (See Chapter 4 on types of installations). Therefore, the temperature measured by a DTS is not the flowing fluid temperature, but some value between the flowing borehole fluid and the formation. While the borehole flow may mask much of this effect, outside flows may become more apparent when a well is shut in.

5.1A CLASSIC LIQUID ENTRY

The effects of liquid flow on a temperature log are illustrated on Fig. 5.1. As the earth is penetrated to deeper depths, the temperature increases. This rate of temperature increase, called the "Geothermal Gradient" or "Geothermal Profile" may vary, depending on the adjacent formation or depth. Such effects may be noticeable with wireline or DTS measurements over very long intervals or over long periods of time when a well is shut-in. However, it is generally assumed that the geothermal gradient is constant over the logged interval, and the effects of liquid movement cause some deviation from the geotherm. All discussions to follow are based on wireline observations unless otherwise specified. Geothermal gradients vary from about .5 to 2.0 degF/100ft or .9 to 2.7 degC/100m.

In Fig. 5.1, the borehole below B is static, and referred to as a “static rathole”. However, there is a liquid flow (no solution gas) in a channel behind pipe from A to A'. The liquid enters the channel at the temperature of the geothermal gradient, i.e., it's formation temperature. As the liquid moves from A downward, it is moving into a channel which grows hotter with depth, and as a result the liquid heats up a bit before exiting into a formation at A'. Since the borehole fluid in this interval is static, it soon takes on the temperature of the nearby channel. Both above A and below A' the rathole temperature is that of the geothermal gradient. Note that if flow entered the wellbore and flowed from A to A' the temperature log would look qualitatively the same.^{26,27}

LIQUID FLOW

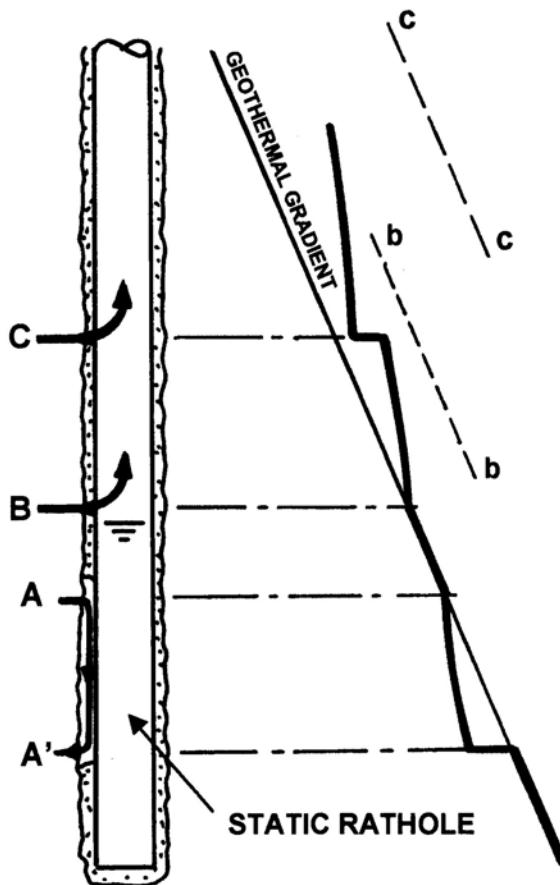


FIG. 5.1 Schematic showing liquid crossflow, A to A', and entries at B and C

The first entry into the wellbore occurs at B. The liquid enters at its formation temperature and moves uphole. It is flowing into a borehole

which is cooler. As a result, the liquid temperature is greater than the geothermal and cooling as it moves uphole. When another entry occurs, as at C, the effect is to mix the two flows, thereby causing a cooling effect on the log at C. The relative position of the resultant mixture between the geotherm and the upcoming flow from B may be a quantitative indication of the relative proportions of the two flows in the new mixture above C. Any quantitative evaluation would require that the fluids from below and entering at C have the same heat capacity.

Note the dashed lines bb and cc in the figure. If the wellbore didn't change and the flow from B could proceed uphole, it would asymptotically approach a straight line parallel to the geothermal profile. The displacement of bb from the geotherm would be greater with increasing flowrates. Note that the resultant flow from mixing B and C would approach an asymptote further to the right, indicated by the line cc.

There may be some exceptions to the above guidelines. A liquid entry may cause a heating anomaly at the point of entry. This often occurs when a water entry is the first entry from the well bottom. This effect is called a Joule-Thompson heating and can be as much as 3 degF per 1000 psi pressure drawdown from the formation. This is often referred to as friction heating. It is less likely at oil entries since a large drawdown may cause solution gas to be released and result in a cooling anomaly at the point of entry.

5.1B CLASSIC GAS ENTRIES

The Effects of a gas flow are shown on Fig. 5.2. The flow profile is much like the previous section. There is a downmoving channel from A to A'. The entry of gas into the channel causes a cooling effect due to the adiabatic expansion of the gas. This cooling effect is detected in the static rathole as is the temperature along the channel.

The entry at B causes a cooling effect. When the gas moves uphole, it is moving into a hotter environment and begins to heat up. The entry at C causes another cooling effect as shown. Strictly speaking, the entry at C need only be cooler than the geothermal and so may cause a slight heating of the fluid moving up from B. In any case this resultant flow crosses the geothermal where it is cooled by a new entry at D. Note that the entry at D must be a cooling anomaly. Once above the geothermal gradient, every

entry (with the possible exception of the Joule-Thompson heating effect mentioned above) must be a cooling anomaly on the log.^{26,27}

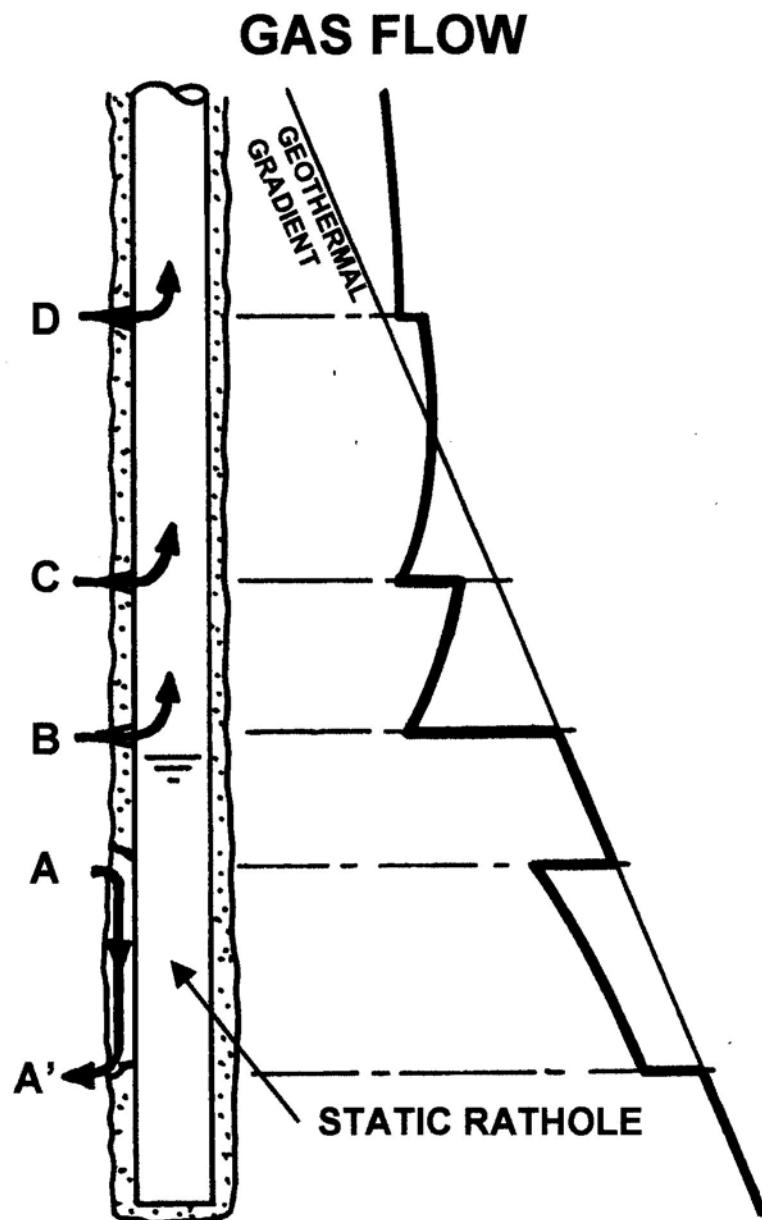


FIG. 5.2. Schematic showing gas crossflow (A to A') and gas entries at B, C, and D.

5.1C SHUT-IN INJECTION WELLS

Fig. 5.3 shows an example of a water injection well. On the left is the well profile, with isotherms (lines of constant temperature) shown around a well during injection. The immediate vicinity around the well is cooled slightly during injection, and the zone between the 105 and 110 deg F isotherms is taking all of the injected water. If this is 5.5 inch, 17 lb/ft, casing, one foot of casing contains about one US gallon (4 liters) of water. Supposing that the zones of injection have taken thousands of barrels of water per foot, then obviously the large mass of injected water would heat back up to geothermal profile much more slowly than the one gallon per foot.

This effect is shown by the logs at the right of Fig. 5.3. The temperature log during injection is labeled “Injecting”, and shows the injected water heating up somewhat until below the zone of injection after which the borehole temperature returns to the geothermal (static) temperature. Upon shut-in, the small mass of fluid returns toward the geothermal rather quickly due to heat conduction from the formation. The large mass of injected cold water in the zone of injection, however, returns toward the geothermal much more slowly, leaving a “bump” on the shut-in log. This technique is important in that it doesn’t matter how the injected water got into the zone, the zone of injection will lag in returning to geothermal in all cases.^{26,27}

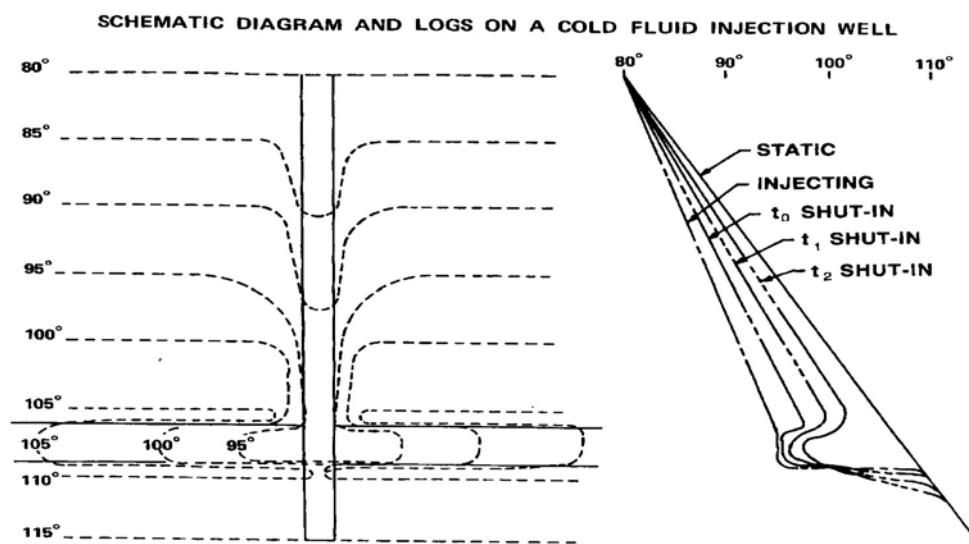


FIG. 5.3. Effects of injection zone on temperature log.

5.1D HORIZONTAL PRODUCTION WELLS

Horizontal wells pose some unique problems for temperature logs. If a well is truly horizontal, it should track a geotherm and there is no temperature gradient along the horizontal section. Under such conditions, it is sometimes possible to detect points of entry at shut-in. Flows from deeper around the wellbore will tend to heat up the rock at the point of entry. While flow may mask this effect, it may show up when the well is shut-in. Similarly, a small cooling anomaly may be detected if flow originates above the well trajectory.

If flows are high enough, there is a Joule-Thomson heating effect which takes place along the wellbore. This is only a small effect. To show a 2.0 degF increase in temperature in 2000m of 7.0 inch ID casing would require an oil flow rate of over 45,000 BOPD (30 deg. API oil). For 5.5 inch ID casing, 22,000 BOPD flow is required. For 4.5 inch ID, nearly 14,000 BOPD is required for the same 2 degF effect. The effect on a horizontal temperature log is shown on Fig. 5.4. In Fig. 5.4A, a single point entry causes a slight deviation from the condition of constant temperature, i.e., the temperature increases as the flow moves to the heel of the well. This shows up as a change of slope in the temperature log. If a second entry is present, the two flows mix, thereby causing a cooling anomaly at the point of the second entry. Since the total flow rate is now higher, there is also an increase in slope of the temperature log, as shown in Fig. 5.4B.²⁶

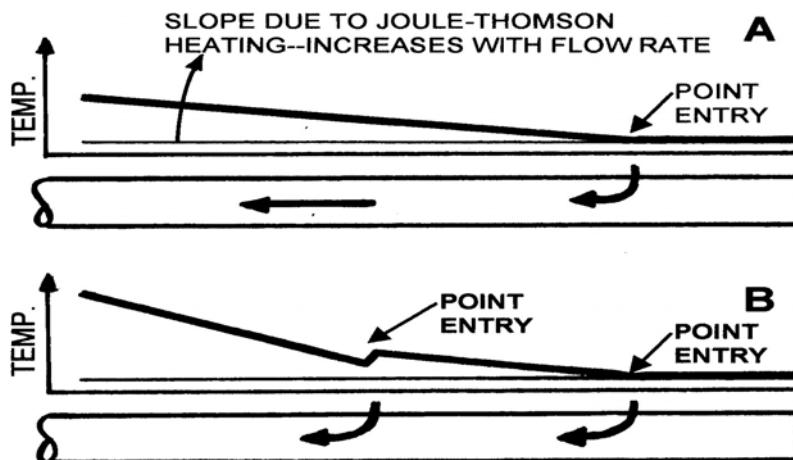


FIG. 5.4. Temperature effects on high flow horizontal well. (Courtesy Sensa, Ref. 26)

5.2 EXAMPLES OF DTS TEMPERATURE LOGS USED FOR VARIOUS APPLICATIONS

The following sections show various oil/gas well applications of DTS logs.

5.2A COMPARISON OF CONVENTIONAL WIRELINE AND DTS SURVEYS

The following example shows a comparison between a wireline temperature log and a pair of DTS surveys. On Fig. 5.5, runs 1 and 2 represent two DTS surveys taken in a static horizontal well. The DTS surveys are taken one day apart. The DTS surveys overlay quite well, showing good repeatability. Note that such repeatability is possible since both the same fiber and DTS Instrument Box were used and a relatively short period of time intervened between the runs.

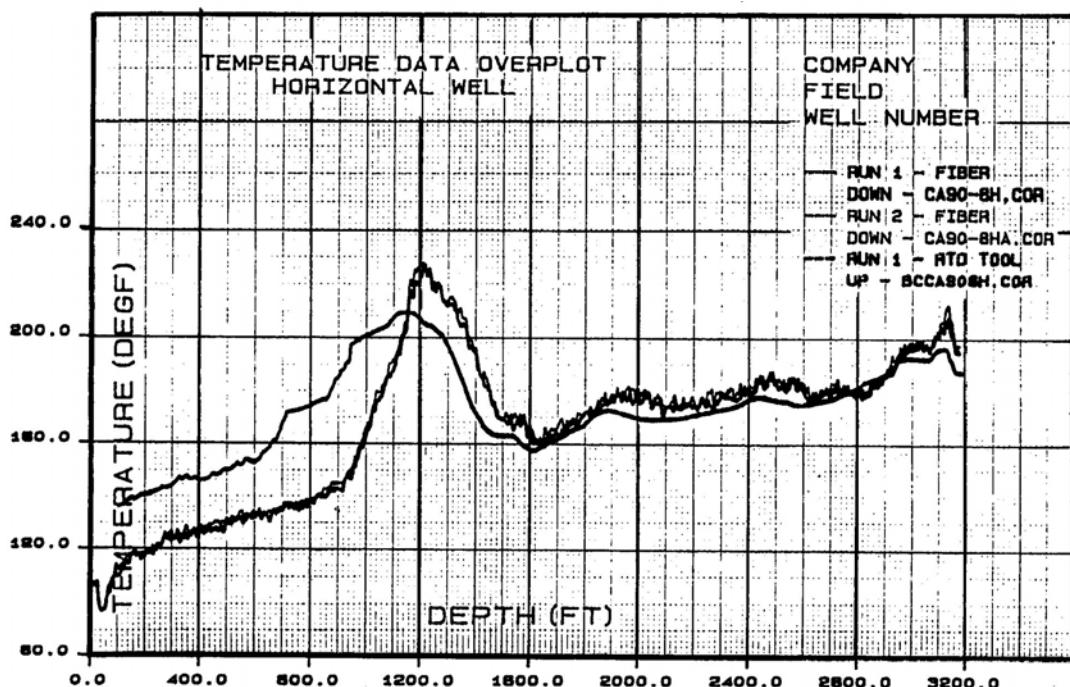


FIG. 5.5. DTS/wireline temperature log comparison. (Courtesy Pruett Industries, now Halliburton, Ref. 11)

The third log shown on Fig. 5.5 is a Resistive Temperature Device (RTD Tool). This is a resistive platinum wire the resistance of which is measured

and related to temperature. Note that the RTD survey is run in the up direction. There also appears to be a few degrees disagreement in the calibration of the RTD and DTS systems. While it is uncertain which is more accurate, note that the peaks in temperature on the RTD run appear shifted uphole relative to the DTS logs. This “lag” effect occurs since it takes time to heat or cool the resistive wire, and hence the anomaly will be shifted uphole relative to its true depth in an up run.¹¹

The water-gas contact is located at about 800 feet depth in Fig. 5.5. Note that the lag or shift appears larger above this depth. This is due to the fact that the rate of heat transfer to a gas is less and therefore it will take longer for the sensor to reach thermal equilibrium.

5.2B DETECTION OF A CHANNEL

This example comes from the M-17 well at Wytch Farm. This is a horizontal well which could not be economically logged in the traditional sense. Instead, a Sensa DTS system was installed and provided insight into the problem at a fraction of the cost of coiled tubing production logs. Shown on Fig. 5.6 is the flowing profile, the shut-in profile (one day shut-in), and the static profile (ten day shut-in).

This well very quickly began to produce water at a temperature below the geothermal temperature. The source of this water was attributed to a nearby (200 meters distant) seawater injection well. The cooling anomaly appearing at about 4350 m, i.e., the “rabbit ears” at that depth are taken to be the point of water entry.

When the well is shut-in, notice that the static wellbore section from about 3800 m to TD is beginning to warm back toward the static profile. Notice also that a similar effect is occurring above about 2700m. In this upper interval, the well flow is hotter than geothermal and therefore the temperature is cooling down toward the static profile. However, the interval from about 2800m to about 3800m nearly conforms to the static profile after the first day. For this to occur, the wellbore cannot merely be warming back toward geothermal or static condition. Instead, fluid originating at or near the static or geothermal temperature is flowing from the zone at 2800m to the perforations from 3650 to 3800m. The slight cooling of the flow

observed in the channel is due to the flow moving into the cooler part of the well.^{28,29}

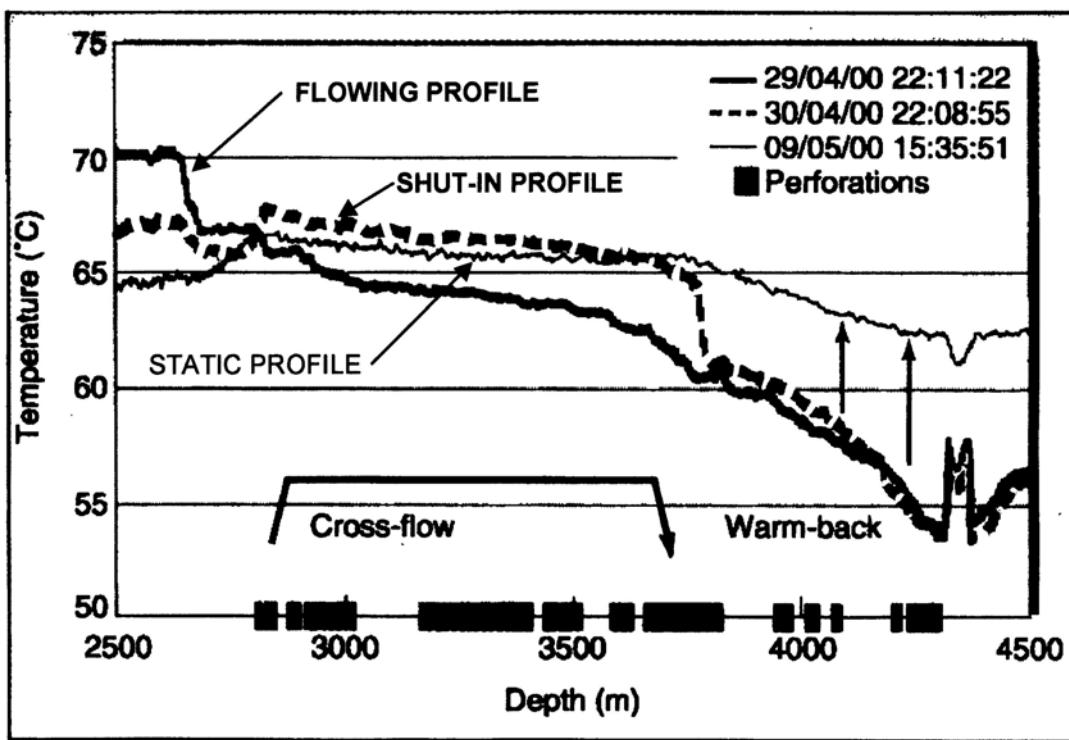


FIG. 5.6. DTS survey showing crossflow at shut-in. (Courtesy Sensa, Ref. 29)

5.2C DTS USED FOR WELL MONITORING

One obvious use for DTS surveys is to monitor wells on a pad or production platform. Weekly monitoring can detect changes in the well temperature profile. When such changes occur, the well's production can be tested to determine the cause of the temperature change. Immediate action can be taken to remedy or shut-in the non-performing well. If needed, more focussed production logs may be run to better evaluate the problem.

The example of Fig. 5.7 is just such an example.³⁰ This example is a well on a production platform. Shortly after installation of the DTS fiber line, the temperature in the zone below about 1450 meters was observed to decrease from previous DTS runs by about 5 degC. This is attributed to breakthrough of injected water. In Fig. 5.7, it is apparent that the effect on the log is to cool the resultant production mixture by about 2-3 degC. Testing the

platform's production indicated an increase water cut from below 20% to above 35%. The remedy to minimize water production from this well is apparent. The lowest zone needs to be plugged back or otherwise isolated.

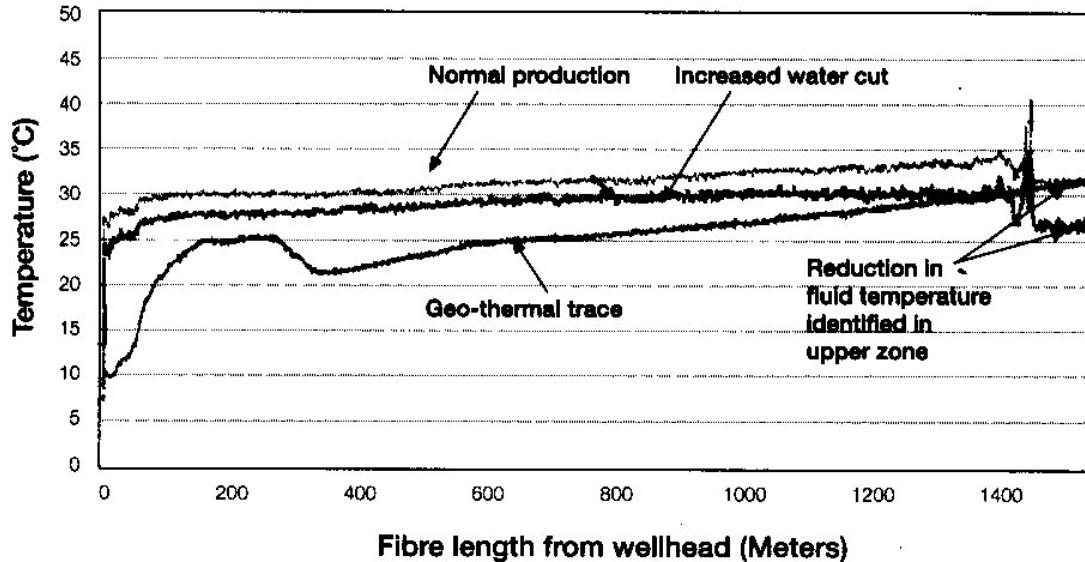


FIG. 5.7. Periodic monitoring of this well detected a cooling anomaly associated with a significant increase of water production. (Courtesy Sensa, Ref. 30).

5.2D ELECTRIC SUBMERSIBLE PUMPS (ESP), ETC.

This example comes from the same well as the previous section. In this case, shown in FIG. 5.8, the previously installed DTS line is detecting the start up of the ESP motor and pump sections.³⁰ Similar applications include the detection and monitoring of gas lift valve opening and continued operation (See Fig. 3.6).

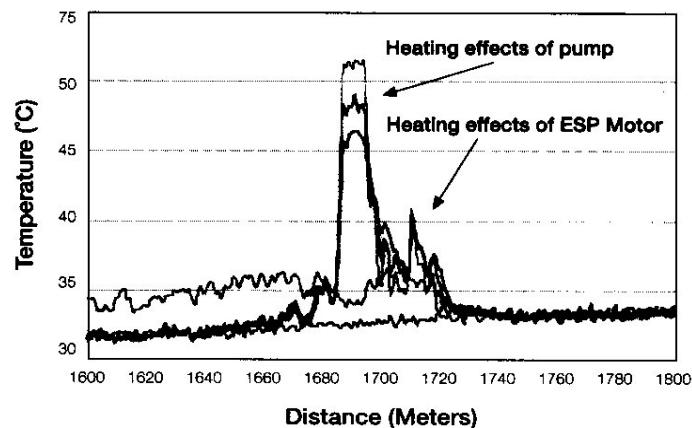


FIG. 5.8. DTS monitors the temperature of an ESP pump and motor downhole. (Courtesy Sensa, Ref. 30).

5.2E STEAM BREAKTHROUGH

This is an example of DTS used to locate steam breakthrough in a production well. Steam injection is taking place in adjacent wells and the location of steam breakthrough is relevant to effective steam and flood front management. The technique used is to inject cold water into a producing well to cool down the wellbore. The DTS survey of 10:51 in Fig. 5.9 shows the wellbore after cooling it down and at the time injection is stopped. Notice the peak developing in the interval between 800 and 850 ft in the 10:53 and especially the 10:54 DTS surveys. The later surveys from 10:56 to 11:16 show the steam moving uphill toward the surface. Individually, any of these surveys would be difficult if not impossible to interpret for steam breakthrough. However, the rapid time lapse logs now available through DTS technology have clarified the flowing conditions and made the location of steam breakthrough easy to find.³¹

COOLED WELLBORE STEAM BREAKTHROUGH DTS SURVEY

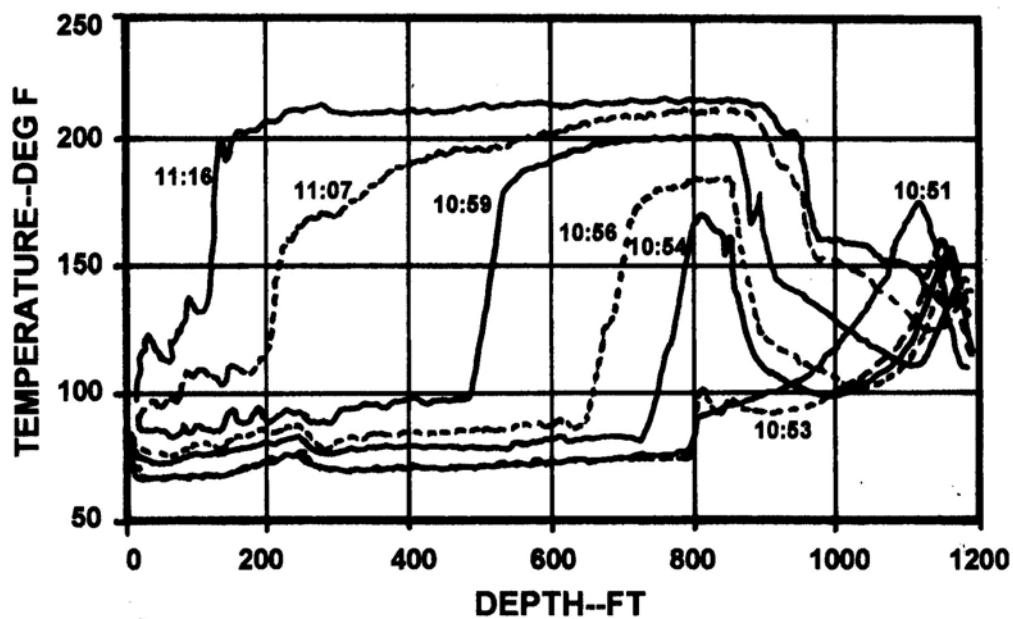
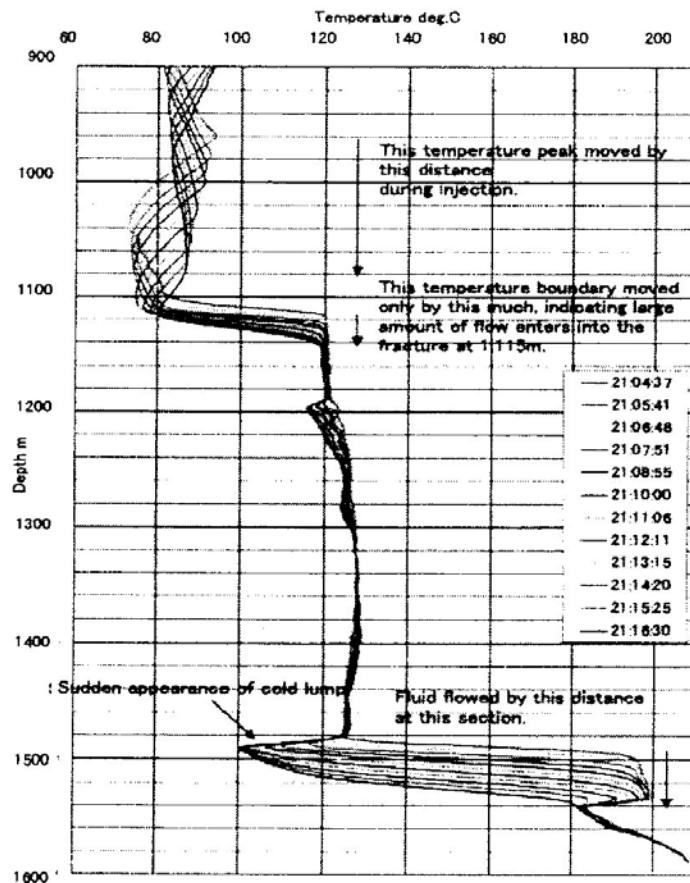


FIG. 5.9. Rapid sequence of DTS runs showing steam breakthrough at 800-850 ft.
(Courtesy SPE, Ref. 31)

5.2F VELOCITY INDICATIONS USING DTS

Fig. 5.10 shows a sequence of DTS logs run in a water injection well. The initial survey at time 21:04:37 has some notable features or anomalies at 960 m at 92 degC, 1110 m at 100 degC, and 1490 at 160 degC. The effect of injection is to displace these features downward. The rate at which these features move downward is an indication of the water velocity in the wellbore at their location. In this example, the down pointing arrows indicate, by their length, the approximate velocity of the wellbore flow.³²

FIG. 5.10. Sequence of DTS runs indicate injection velocity by downward anomaly movement between runs. (Courtesy SPWLA, Ref. 32).



5.2G FLUID VELOCITY USING SENSA FLO-TRAK™ SYSTEM

Sensa/Schlumberger has developed a system to measure flow velocities downhole using a preinstalled DTS fiber optic line and heating coils to increase the temperature of the fluid. This system is suitable for single phase flows and can be used to measure low velocities at specific points downhole.

The mechanical part of this system is shown on Fig. 5.11. This apparatus is preinstalled and consists of a line for injecting nitrogen gas through the valve and into the pressure drop coil. The gas is injected at a rate of perhaps 30 MSCfd at a pressure of 7000 psi. As the gas passes through the pressure drop coil, the friction of its movement causes it to heat up. When it passes

into the heat transfer coil, much of that heat is imparted to the flowing stream. A DTS survey is made at intervals of one minute or less between surveys. The position of the heating anomaly can be tracked in terms of position and time. Note that more than one set of coils can be placed in a well, and so velocity measurement can be made at numerous stations within a well. This technique is probably best suited for slower flow rates of a few meters per minute.

Fig. 5.12 shows the results of a Flo-Trak™ test conducted by Sensa. Generally, the darker the area, the hotter the temperature. The presentation shows a map of DTS surveys taken in intervals of less than one minute plotted against distance along the pipe. The dark area before about 11:40 is the heat from the heating coil. The flow carries this heated water uphole and the heavy line approximates the movement of this anomaly with time. Based on this example, the fluid is moving up at a velocity of about 21 meters in about 10 minutes or 2.1 meter/minute.³³

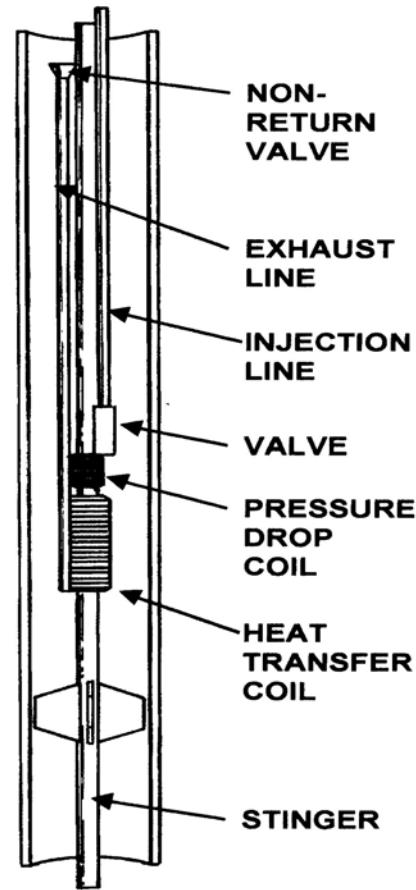
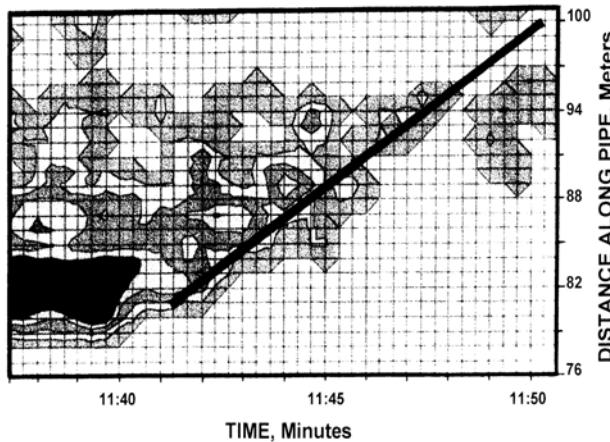


FIG. 5.11. Sensa Flow Trak™ heating element. (Courtesy Sensa, Ref. 33)

FIG. 5.12. Map of successive DTS runs showing thermal anomaly movement. (Courtesy Sensa, Ref. 33)

6. QUALITY CONTROL

6.1 OVERVIEW OF QUALITY CONTROL

With DTS systems, there are many areas where small errors can emerge. These can arise from the instrumentation, the fiber, the nature of the installation, the age of the installation, the laser wavelength used, and other sources. Such errors show up as depth discrepancies, temperature errors, poor resolution, and the like. Some installations are more sensitive to such errors than others, and the degree of QC attention required may vary somewhat with the installation. The intent of this section is to highlight some quality control techniques and to present information check lists to remind the user of desired QC data. When questions come up after the job is long completed, detailed information is usually required to resolve new or remaining issues.

6.2 SOME QUALITY CONTROL TECHNIQUES

6.2A DEPTH MATCHING

This depth matching technique can be used in double ended systems or in partially returned systems across the overlapping interval. When the temperature log is displayed as shown in Fig. 6.1, fold the temperature log at the location of the turn around sub (line of symmetry). If the profiles do not overlay and characteristic events such as hot spots due to setting cement do not appear at the same depth, then the depth can be matched as follows.

If the turn around sub is located at depth Z, and the feature to be matched occurs at depths L₁ and L₂ along the fiber, then the overstuff follows from the requirement that the corrected depths L₁(1+_) and L₂(1+_) are at equal distances from the turn around sub depth Z.

$$_ = (L_1 + L_2)/2Z - 1$$

In the example of Fig. 6.1, L₁=4590m, L₂=8330m, and Z=6355m (from the completion schematic). In this case, _ = 1.6% (See section 4.3). Helical buckling was suspected due to fiber standing up against the bottom of the wet connector.

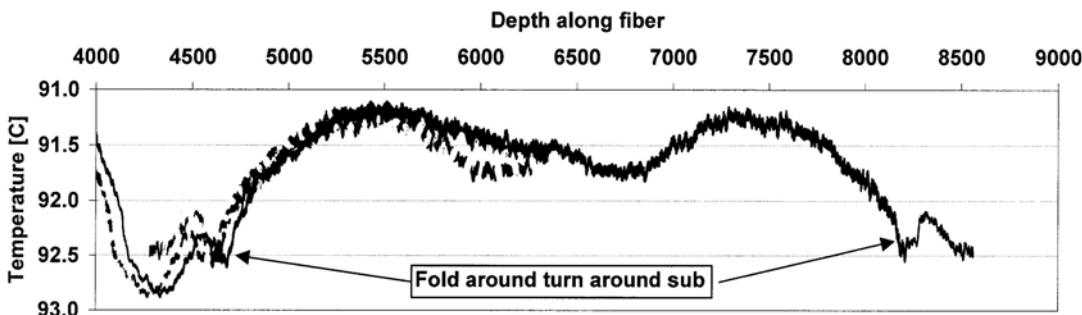


FIG. 6.1. Baseline temperature (solid) not symmetrical when folded (dashed) around turn around sub at 6355.

6.2B DETERMINING THE END OF THE FIBER DEPTH

The end of fiber depth can be found by inspecting the raw data curves that give the intensity of backscattered light versus depth. At the fiber end, either a big spike due to reflection or a drop in signal to zero is found depending on the refractive index match at the bare fiber end. Such raw data curves should be supplied by the service company. Depth is calculated from the measured two way travel time by (See sections 2.1, 2.2)

$$Z = (c/n) \times (t/2)$$

Where c is the speed of light in a vacuum, n is the refractive index of the fiber, and t the two way travel time.

The raw curves of Fig. 6.2 show that the end of the fiber is located at 8452 for the red shifted backscatter and 8454 for the blue shifted backscatter. The difference is due to a small change in the refractive index for the backscattered light (See section 2.3). Correcting for this and bringing the end of the fiber depth to 8451m results in an optical overstuff of 0.01%.

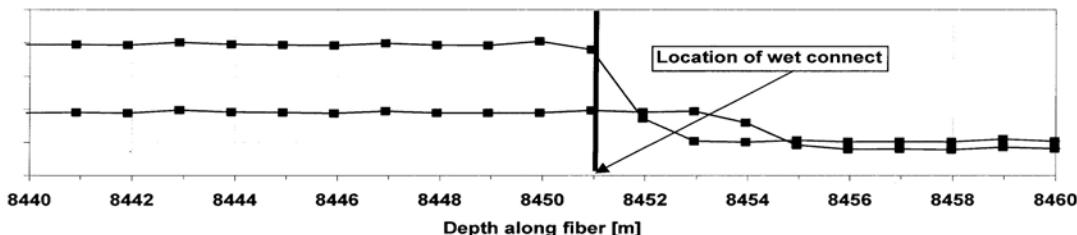


Fig. 6.2. Fiber end is at the wet connect. Optical overstuff is 1m for the red shifted (upper) and 3m for the blue shifted (lower) backscatter.

6.2C FIBER DAMAGE/LINEAR CALIBRATION

The ratio of the backscattered intensities for the blue and red shifted light, I_+ and I_- , at the same depth basically gives a temperature profile (See Appendix A). Assuming that the attenuation is linear, i.e., that the differential attenuation μ is constant, two corrections are necessary. One for the offset and one for the differential loss (See section 2.3C). The offset correction will move the whole temperature profile up or down. The differential loss correction removes any spurious linear trend with depth. The offset and differential loss corrections are apparent from the equations shown in section 2.3C and Appendix A.

In the absence of proper offset correction, there will be a difference in temperature between DTS and a downhole gauge (if any). In the absence of a proper differential loss correction, the $T(z)$ profile will “fan out” at the location of the turn around sub (line of symmetry). Such “fanning out” is observed in Fig. 6.3 where the turn around sub is located at about 6400m and the temperature does not repeat in the overlap section (6400m to 4500m).

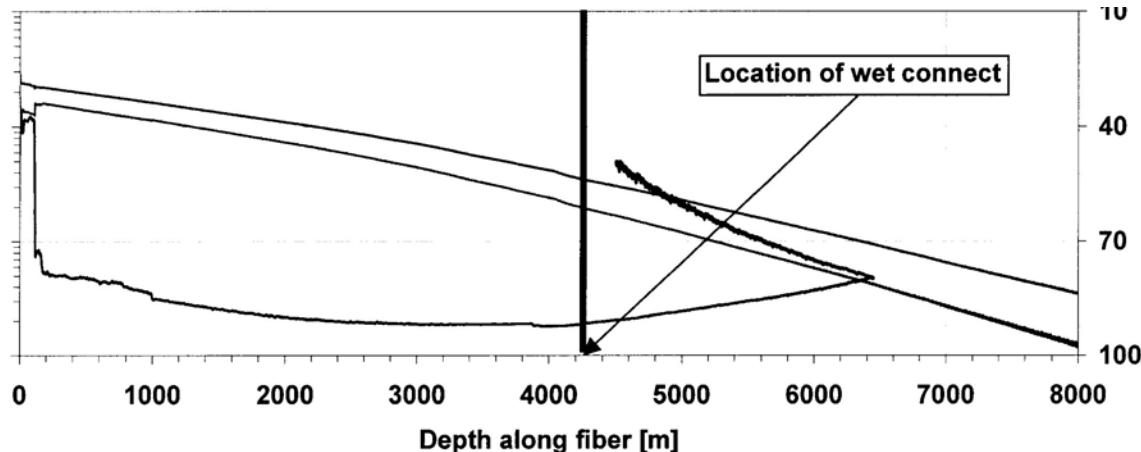


Fig. 6.3. Example of “fan out” effect.

6.2D DETERMINING DIFFERENTIAL LOSS

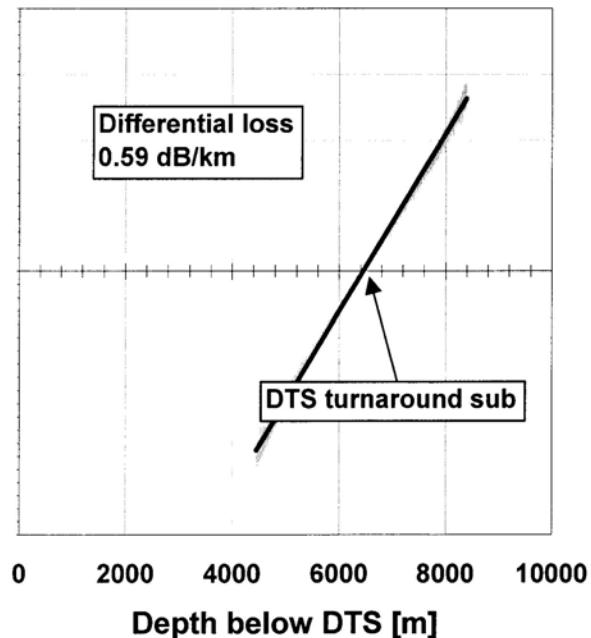
Standard 50/125 multi-mode fiber has a differential loss of about 0.3 dB/km. The differential loss can be determined if there is a wrap back section in the well by applying the symmetry that exists around the turn around sub. If the

turn around sub is at $z=L$ and y is the distance from this point, then $T(L+y)=T(L-y)$. Applying this to the temperature formula gives (See Appendix C):

$$\Delta\alpha = \frac{\ln\left(\frac{I_+}{I_-}\right|_{L-y}) - \ln\left(\frac{I_+}{I_-}\right|_{L+y})}{2y}$$

Hence, a constant differential loss $\underline{\alpha}$ follows as half the slope of the regression line as shown in Fig. 6.4. Potentially this value can then be used to calculate a new profile $T(z)$ that must fulfill the symmetry around the turn around sub. Note that the new profile must be reasonable. If the differential loss is not constant, then the attenuation rate becomes non-linear and this technique cannot be used.

FIG. 6.4. Plot of backscatter ratio difference vs depth to determine $\underline{\alpha}$ (slope is $2\underline{\alpha}$).



6.3 THE PUMPING PROCESS

The key to reliable DTS measurements is a stable, undamaged fiber. Present day fiber is coated with water blocking materials (gold or carbon) that have been shown to work reliably. A number of quality control measures are suggested to maintain the quality of a pumped fiber.

1. Always perform a drift run with a mock-up cable. Flush line if drifting is unsuccessful.
2. Always seal the end of the fiber being pumped.

3. Always pump with a fluid at a temperature equal to the bottom hole temperature in order to prevent differential drag arising from changing pumped fluid viscosity with depth.
4. Always record the pump pressure and fluid temperature (in and out) versus time.
5. Always record the length of fiber pumped versus time and the fiber velocity versus time.
6. Always record a pre- and post-pump OTDR.
7. Always have a baseline attenuation spectrum of the fiber being pumped. If damage is suspected, record an attenuation spectrum after pumping.
8. Attempt to pump fiber with a water free fluid.
9. If the fiber stands up against a block, do no attempt to pump back. Leave the fiber as it stands in order to prevent further damage.
10. In a pump around system, pump an excess length of fiber. Inspect the retrieved excess length for mechanical damage. If mechanical damage is suspected, then send to lab for testing. Always store the excess length of fiber under stable conditions.
11. In a single ended system, when damage is suspected, pull out and inspect the bottom fiber end.

6.4 DATA GROUPS

These groups provide historical data of the equipment used and details of its condition. Such groups are especially important when trying to reconstruct the DTS log/interpretation after the fact. The following sections describe a series of listings of desired or required information. These listings are appropriately filled for purposes of illustration. Blanks of these forms are included in Appendix D.

6.4A WELL INSTALLATION DATA GROUP

Most of the information requested here can be copied from the well schematic or well file. The extra bit of information requested is the position of the fiber in the well which can be recorded as depth below a reference. In a pump around system this will require that the well schematic is extended below TD to include the wrap back section. The End Of Fiber (EOF) depth must be recorded on the sketch. It is recommended to include in the sketch

both the depth below THF (Top of Tubing Hanger Flange) as well as depth along fiber from the beginning of the fiber. This is done to ensure that the T(z) profile can be correlated with items in the well and items on the surface. If other depth reference systems are used, they should be noted. Other systems include Kelly Bushing (KB), Rotary Table (RT), Mean Sea Level (MSS), and the like. The well installation data group is shown in Fig. 6.5.

Item	Value	Remarks
Well name	ID23-ST1	
Field	Iron Duke	
Company	BSP	
Country	BN	
Latitude		
Longitude		
Reference system		
Elevation		
Depth reference	THF	

FIG. 6.5. Well Installation Data Group.

6.4B FIBER DATA GROUP

Maintain a log of the fiber installed in the well from manufacturing to installation and beyond when the fiber is retrieved and inspected after use. Post installation inspection will help build experience with estimating fiber lifetime and reliability.

Pre-pump and post-pump OTDRs should be run. The pre-pump OTDR shows that the fiber is in good condition, and that there are no hidden breaks. It furthermore gives an overall optical return loss. Comparison with a post-pump OTDR should show that the pumping process did not break or damage the fiber in any mechanical or optical way.

If the fiber is suspected to have degraded or if it's storage and manufacturing history is unknown, then an attenuation spectrum should be recorded. This can be used to gauge future performance of the fiber and may be used as a

baseline. If the post-pump OTDR highlights any events or differences with the pre-pump OTDR, then a post-pump attenuation spectrum is recommended to check the condition of the fiber.

The fiber data group base is illustrated in Fig. 6.6 below. A blank copy is included in Appendix D.

Item	Value	Remarks
Fiber type	50/125 multimode	
Fiber coating	gold	5 um thickness
Fiber jacket	hytrel	
Fiber diameter	900 um	
Refractive index	1.4976	@ 1064 nm
One way loss	0.18 dB/km	@ 1550 nm
Spool number tag	19764AX4	
Spool length	10000m	
Manufacturing date	6 apr 1961	
Manufacturer	Corning	
Installation date	NA	

FIG. 6.6. Fiber Data Group.

6.4C INSTRUMENT DATA GROUP

This table maintains a log of the surface system identity, capability, and calibration. See Fig. 6.7. A blank version of this data sheet is shown in Appendix D.

Item	Value	Remarks
Manufacturer	York	
Type	DTS800 – M12	4 channel, 10 km range
Serial number	123456789	
Software version	1.2	
Manufacturing date	24 aug 1987	
Calibration date	16 jan 2001	
Calibration protocol	2.1	la test protocol is 2.3
Calibrated by	Alex van der Spek	
Internal oven location	35 – 85 m	from beginning of fiber
Oven set point	45 degrees C	
Test cable	AXBZ231	
Offset	0.5 degrees C	@ 4500m
Differential loss setting	0.345 dB/km	fixed value

FIG. 6.7. Instrument Data Group.

6.4D PUMPING DATA GROUP

The pumping data group is intended to record operational details of the pumping process. It is recommended that a log of cable speed and length of fiber pumped versus pumping time also be recorded. Such a log should also include pump pressure and pumped fluid temperature both in and out. This data group is shown in Fig. 6.8. A blank version of this data sheet is illustrated in Appendix D.

Item	Value	Remarks
Date of pumping	6 apr 1961	
Engineer	Alex van der Spek	
Service company	SepTAR	
Pump fluid type	sea water	
Control line fluid	silicone oil	
Pump direction	Port 1 → Port 2	
Pumping log	Available	Plid23st2.dat
Fiber end seal	epoxy	
Cable meter type	Kent	
Cable meter serial no		
Cable meter calibration date		
Drift run performed	OK	Pressure high at 1500m
Excess fiber recovered	100 m	

FIG. 6.8. Pumping Data Group.

6.4E FIBER INSTALLATION SCHEMATIC GROUP

An adapted well schematic showing important items along the fiber depth measured in two depth referencing systems. Items that should certainly be included in the schematic are all items that may cause thermal events on the DTS log, e.g., downhole ESP pumps, downhole ICV valves, downhole ECP packers, etc.

Recording the depth in two reference systems and extending the schematic below TD to include a wrap back section of fiber below the turn around sub and below TD will help ensure that thermal events are correctly interpreted and that folding the DTS profile around the turn around sub is done

correctly. An example of such a schematic is shown in Fig 6.9, and a blank copy is in Appendix D.

Item	Schematic	Depth BTHF	Depth BDTS
DTS laser			0
DTS ref oven			35
DTS bulkhead			85
DTS bulkhead			120
Surface cable splice			125
Splice box			200
Wellhead connect Port 1			205
Tubing hanger flange		0	206
Downhole gauge		2200	2406
PBR wet connect		2350	2556
Turn around		5350	5556
PBR wet connect		2350	8556
EOF			8557
Downhole gauge			
Tubing hanger flange			
Wellhead connect			
Splice box			
Surface cable splice			
DTS bulkhead			
DTS ref oven			
DTS ref oven			
DTS laser head			

FIG. 6.9. Fiber Installation Schematic Group.

6.5 QC QUEST TRACK AND CHECK LIST

The QC quest track and check list (Fig. 6.10) is a simplified list to remind the user of the desired data. It is called a “Quest Track” since it is a list of hoped for, but not always available informational items relating to the job.

**QC QUEST TRACK
AND
CHECK LIST**

GROUP	DESIRED INFORMATION	✓	REMARKS
DTS INSTALLATION	DATE OF TEST _____ WELL DATA _____ FIBER DETAILS _____ INSTRUMENT BOX _____ PUMPING RECORD _____ WELL/FIBER SCHEMATIC _____		
FIBER CHECK	PRE/POST PUMP OTDR _____ PRE/POST PUMP _____ ATTENUATION SPECTRUM _____ FIBER PUMPING LOG _____		
DEPTH PARA- METERS	DEPTH REFERENCE _____ END OF FIBER DEPTH _____ SAMPLING _____ RESOLUTION _____		
TEMPERATURE PARAMETERS	TEMP. PROFILE _____ AVERAGED _____ NON-AVERAGED _____ S & AS BACKSCATTER SIGNALS _____ OFFSET CORRECTION _____ DEPTH OF OFFSET _____ MATCH REF. TEMP. GAGE _____ GEOTHERMAL PROFILE _____ TEMPERATURE _____ DEPTH _____ GRADIENT _____		
RESOLUTION DATA	TEMP. RESOLUTION _____ TIME REQUIRED _____ NUMBER OF LAUNCHES _____ LAUNCH/PULSE DURATION _____ LAUNCH WAVELENGTH _____		

FIG. 6.10. QC Quest Track and Check List.

7. VENDOR LIST AND PRODUCT SPECIFICATIONS

7.1 VENDOR LIST

This listing contains the vendors which are known to the authors at the time of this writing. Other vendors may exist. Note that the locations listed are for the vendor's main office plus perhaps one other location with which the author's may have had communications. If the reader would like to contact a vendor in his area, please contact the vendor's main office to determine if that vendor has an office nearby.

The vendors are listed in alphabetical order.

1. HALLIBURTON (formerly PRUETT INDUSTRIES, INC.)

Halliburton is a full service supplier. It provides fiber installation and DTS services. It uses other vendor instrument boxes.

MAIN LOCATION:

David O. Johnson, P.E.
Product Manager
Reservoir Performance Monitoring
Halliburton
3000 N. Sam Houston Parkway E.
Houston, Texas, USA 77032
281 575-3934 Office
512 431-4177 Mobile
david.johnson3@halliburton.com

ALTERNATE LOCATION:

Rick Pruett
Business Segment Manager
Halliburton/Pruett
8915 Rosedale Highway
Bakersfield, California, USA 93312
661 589-2768 Office
661 303-9143 Mobile
rick.pruett@halliburton.com

2. PROMORE ENGINEERING INC. (A CORE LABORATORIES COMPANY)

Promore is a full service supplier. It provides fiber installation and DTS services. It uses other vendor instrument boxes.

MAIN LOCATION:

Ivan Mombourquette
VP of Business Development
Or
Miodrag Pancic
Project Coordinator
Promore Engineering Inc.
1550, 520 – 5 Ave. SW
Calgary, Alberta, Canada T2P-3R7
403 264-4246 Main Office
imombourquette@corelab.ca
mpancic@corelab.ca

ALTERNATE LOCATION:

Kirby Jabusch
VP Engineering
Promore Engineering Inc.
5708 – 54 Street NW
Edmonton, Alberta, Canada T6B 3G1
780 988-5105
kirbyj@promore.com

www.promore.com

3. SENSA (A SCHLUMBERGER COMPANY, formerly SENSOR HIGHWAY Ltd.)

Sensa is a full service supplier. It provides fiber installation and DTS services. It uses its own York instrument boxes.

MAIN LOCATION:

Nigel Leggett
Business Development Manager
Or
Glynn Williams
Sensa Manager
Sensa
Gamma House
Chilworth Science Park
Southampton, Hampshire
United Kingdom SO16 7NS
44 (0)23 8076 5500 Main Office
nleggett@slb.com
gwilliams@slb.com
www.sensa.org

ALTERNATE LOCATIONS:

Aberdeen 44 (0)1224 785810
enquiries.aberdeen@sensa.org
Houston USA 1 713 996 8280
enquiries.houston@sensa.org
California USA 1 661 834 7915
enquiries.bakersfield@sensa.org
Venezuela 58 212 993 5096
enquiries.caracas@sensa.org
Oman 968 561 850
enquiries.muscat@sensa.org
Australia 618 9226 1493
enquiries.perth@sensa.org

4. SENSORNET LIMITED

Sensornet is a supplier of DTS instrument boxes.

MAIN LOCATION:

Mahmoud Farhadiroushan, Managing Director

m.farhadiroushan@sensornet.co.uk

Tom Parker, Technical Director

tom.parker@sensornet.co.uk

James Hampson, Production Manager

james.hampson@sensornet.co.uk

Sensornet Limited

198 Providence Square

Jacob Street

London SE1 2DZ, UK

44 (0)20 7394 3555 Main Office

www.sensornet.co.uk

5. SENSORTRAN

Sensortran is a supplier of DTS instrument boxes.

MAIN LOCATION:

Sensortran

101 West Sixth Street, Suite 200

Austin, Texas, USA 78701-2932

512 479-7732 Main Office

extension 2248 for Sales/Marketing

bussear@sensortran.com (sales/marketing)

www.sensortran.com

6. SUMITOMO ELECTRIC INDUSTRIES, LTD., JAPAN

Sumitomo is a supplier of DTS instrument boxes.

MAIN LOCATION:

Sumitomo Electric U.S.A., Inc.
U.S. Regional Headquarters
One North Lexington Ave.
White Plains, NY 10601
914 467-6001 Main Office
Toshiyuki Furuhashi, 914 467-6012
www.sumitomoelectricusa.com
www.jpowers.co.jp/pdf/Opthermo_Ev3.pdf (for box specifications only)

7. WEATHERFORD COMPLETION SYSTEMS

Weatherford is a full service supplier. It provides fiber installation and DTS services. It uses other vendor instrument boxes.

MAIN LOCATION:

Graham Makin
Director-Sales and Marketing
Or
Doug Norton
Senior Project Engineer
Intelligent Completion Technologies
Weatherford Completion Systems
16600 Park Row
Houston, Texas, USA 77084
281 646 7184 Main Office
graham.makin@weatherford.com
douglas.norton@weatherford.com
www.weatherford.com

ALTERNATE LOCATIONS:

Aberdeen 44 (0)1224 225200
john.gaskell@weatherford.com
Stavanger 47 5181 4400
gisle.vold@weatherford.com
Dubai, UAE 971 4 3325999
quentin.morgan@weatherford.com
neale.carter@weatherford.com
Kuala Lumpur 60 3 2168 6000
roger.catherall@weatherford.com
Houston 1 281 646-7184
paul.langley@weatherford.com
steve.mathias@weatherford.com

8. YORK

York instrument boxes are manufactured and used exclusively by Sensa. See Sensa for further information.

7.2 INSTRUMENT BOX USE

In this section, the instrument box currently used by each service provider is listed. The specifications for such boxes are listed in section 7.3. Note that numerous boxes exist. Those most frequently used in the oilfield with multimode fiber are listed. However, there are others which are used for very long length installations and typically with single mode fibers. These are mostly used for non-oilfield applications, but there are exceptions. Furthermore, service providers may switch to other instrument boxes as improved technology and lower cost boxes become available. Again, the service providers are listed in alphabetical order and they may use boxes other than those listed.

DTS SERVICE PROVIDER	INSTRUMENT BOX SOURCE AND MODEL NUMBER
HALLIBURTON.....	Various types
PROMORE.....	Sensortran
SENSA.....	York DTS 800 M Series and DTS 320 Series and other York boxes for industrial applications.
WEATHERFORD.....	Sumitomo SUT-E10, SUT-2

7.3 INSTRUMENT BOX SPECIFICATIONS

The specifications which follow were generally provided by the service companies or instrument box vendors. Note that all vendor's instrument boxes appear to have adjustable __, and this is indicated by an A under the default value. In at least two cases, both Sensa (York) and Sumitomo provide a much more detailed set of specifications at their websites, especially regarding depth resolution and time required to achieve a specific temperature resolution (See for example Fig. 7.1). The various vendor websites are:

- Sensa (York)..... www.sensa.org
- Sensornet..... www.sensornet.co.uk
- Sensortran..... www.sensortran.com
- Sumitomo..... www.jpowers.co.jp/pdf/Opthermo_Ev3.pdf

INSTRUMENT BOX TYPE MAKE AND MODEL #	DEPTH RANGE km	LASER WAV-LGT nm	DEFAULT dB/km	TEMP. RES. deg. C	TIME TO T sec
SENSONET	10.0	1064	A	1.0	
SENSORTRAN	5.0	1064	A	2.0	120
SUMITOMO					
SUT-2	2.0	860	A	1.0	60*
SUT-E10	10.0	1552	A	1.2	60*
SUT-300	32.0	1552	A	6.0	300*
SUT-310	16.0	1552	A	1.8	180*
YORK (SENSA)					
DTA 320(DE)	3.0	904	A	2.0	70*
				0.5	600*
DTS 800M(SE)	12.0	1064	A	2.0	600*
				0.5	9600*
DTS 800S (Single mode fiber only)	30.0	1550		2.0	

*See Fig. 7.1, or refer to vendor spec sheets on web sites listed earlier in this section

Note in the above chart that the resolution indicated is at the maximum specified depth.

7.4 TEMPERATURE RESOLUTION AND TEST TIME

As was shown earlier in this text, the temperature resolution improves with the \sqrt{n} , where n is the number of samples. If the instrument box sampling rate is constant, the number of samples taken is directly proportional to the time of the test period. So, to improve the temperature resolution by a factor of two requires that the sampling time be quadrupled, i.e., it takes four times as long to achieve this improved resolution.

Instrument boxes may claim a certain resolution, but clearly a time must be specified for such a claim. Oftentimes only one pair of time and temperature points is specified. For example, suppose a company claims a 2 degC resolution in 120s or 2 minutes of sampling. How long will it take to resolve 1 degC? Following the sampling rule of the previous paragraph, to improve the temperature resolution by a factor of two will require four times the time, or 480s (8 minutes).

Consider the specification sheet for the Sensa DTS 800M series shown in Fig. 7.1. The terms D/E and S/E stand for double ended and single ended respectively. Consider model M10, with a single ended line. 2 degC resolution requires 600s to achieve. To improve to 1 degC requires 2400s and to improve to 0.5 degC resolution requires a DTS time of 9600s. While one can estimate the time necessary for a certain resolution, it is highly desirable that the service company have this information available.

Model	Range	0.5°C		1.0°C		2.0°C	
		D/E	S/E	D/E	S/E	D/E	S/E
M2	2 km (6,500 ft)	44 s	240 s	15 s	60 s	10 s	20 s
M4	4 km (13,000 ft)	44 s	240 s	15 s	60 s	10 s	20 s
M8	8 km (26,000 ft)	480 s	1200 s	120 s	300 s	35 s	75 s
M10	10 km (32,500 ft)	2400 s	9600 s	600 s	2400 s	150 s	600 s
M12	4 km (13,000 ft)	20 s	20 s	10 s	10 s	5 s	5 s
M12	8 km (26,000 ft)	120 s	120 s	60 s	60 s	30 s	30 s
M12	12 km (39,000 ft)	4800 s	9600 s	1200 s	2400 s	300 s	600 s

FIG. 7.1. Chart showing temperature resolution vs. time for the Sensa DTS-800 Series instrument box. (Courtesy Sensa, Ref. 7)

7.5 RELATIVE COST OF DTS

There appears to be a great reluctance on the part of service providers to discuss the cost of DTS installations. The reason stated is that there is no stable cost to compare it to. If stated as a percent of well costs, then it could be misinterpreted since well costs depend on location, formation, how the well is to be completed, and the like. When asked to compare it to the cost of, say, a production log survey, again the reference cost is highly variable

depending on the service company, the contract, and other considerations. Perhaps underlying this reluctance is the fact that DTS installations may be expensive. Yes, they are expensive, but probably not in light of the benefit derived.

After numerous discussions, some very rough numbers have emerged which could guide the user as to whether DTS is worth considering. The reader should understand that these cost estimates are extremely poor quality numbers and should not be taken too seriously.

For expensive offshore or arctic operations involving high value wells, the cost of a DTS installation may be in the 1-2% of well cost range. For a typical land well in the 2500m (8000ft) range, the DTS installation can cost as much as 5-15% of the well cost. For shallow wells monitoring steam breakthrough, the cost can be in the 10-20% of the well cost range. These cost estimates do not include the cost of the DTS instrument box or the cost of the service company to read a DTS log. The DTS boxes cost, depending on the vendor and features (wavelength, multiplexing capability, etc.) from \$US50,000 to \$US150,000 each. Client companies will often purchase a box for frequent or continued monitoring of high value smart wells or for use in locations where numerous DTS installations are grouped together such as an offshore platform or arctic pad. Alternatively, service companies can usually perform DTS surveys on demand and regardless of which company installed the DTS fiber line. Such “drive by” DTS surveys can cost as little as \$1000 or less, depending on the location, number of wells, service agreement, and what needs to be done.

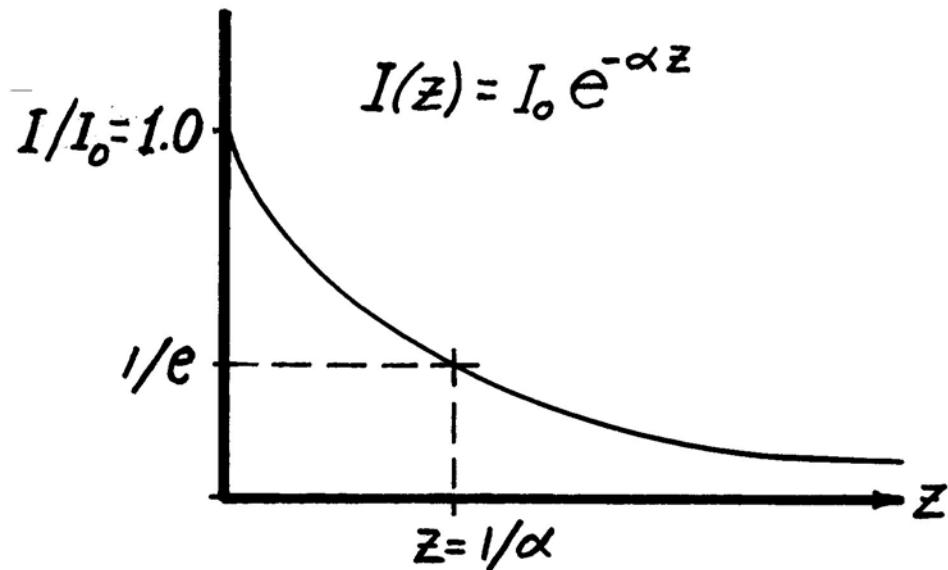
Interestingly enough, the greatest current application of DTS appears to be in the shallow steam wells and the high value wells. In both cases, the rationale for DTS is the high benefit it brings to the operation. In any producing environment where well monitoring is beneficial to effective reservoir production, DTS should be considered.

APPENDIX A

A. DETERMINATION OF TEMPERATURE

A1. ATTENUATION IN A GLASS FIBER

Light is attenuated in a glass fiber in an exponential manner, and can be described by the following equation (Law of Lambert Beer):



While the unit of attenuation is $1/m$, a more convenient unit is dB/km . The attenuation in $1/m$ is related to dB/km as follows:

$$\alpha [m^{-1}] = \left(\frac{10000}{\ln(10)} \right)^{-1} \alpha [\text{dB/km}]$$

A2. DETERMINATION OF TEMPERATURE

To determine the temperature at some point z along a fiber line, first look at the two Raman Backscatter peaks. $I+(z)$ represents the Stokes band energy while $I-(z)$ represents the anti-Stokes band. The equation of the intensity for

the returning waves is given below for each.^{14,34} For both the Rayleigh wave, from launch to position z, the attenuation is equal in both equations. However, for a commonly used laser having a wavelength of 1064 nm, the Raman peaks are shifted +/- 40 nm to 1104 and 1024 nm. Since the attenuation is a function of wavelength (See Fig. 3.5), the attenuation of the returning waves is different. As will be shown, this effect can cause some error in the temperature determination.

$$I_+(z) = C_+ e^{-\alpha_R z} e^{-\alpha_+ z} \langle n_k \rangle$$

$$I_-(z) = C_- e^{-\alpha_R z} e^{-\alpha_- z} (\langle n_k \rangle + 1)$$

PRIMARY PULSE ATTENUATION BACKSCATTER ATTENUATION QUANTUM MECHANICAL TERM

Where C_+ and C_- are constants, and

$$\langle n_k \rangle = \frac{e^{-\hbar\Omega/kT(z)}}{1 - e^{-\hbar\Omega/kT(z)}}$$

And

$$\begin{aligned}
 \hbar &= h/2\pi \\
 h &= \text{PLANCK CONSTANT} \\
 k &= \text{BOLTZMANN CONSTANT} \\
 2\pi\Omega &= \text{RED OR BLUE SHIFT/FREQUENCY} \\
 \frac{\hbar\Omega}{k} &\approx 600^\circ\text{K}
 \end{aligned}$$

Taking the ratio $I_+(z)/I_-(z)$ gives the following.

$$\frac{I_+(z)}{I_-(z)} = \frac{C_+}{C_-} e^{-\Delta\alpha z} e^{-\frac{\hbar\Omega}{kT(z)}}$$

Where $\Delta\alpha = \alpha_+ - \alpha_-$ and is greater than zero. For a 1064 nm laser, this “differential loss” amounts to about 0.347 dB/km.

Solving the preceding equation for $T(z)$ yields an equation of the form:

$$T(z) = \frac{\hbar\Omega/k}{\ln(C_+/C_-) - \Delta\alpha z - \ln(I_+(z)/I_-(z))}$$

Which, can be further rewritten using the power series approximation $1/(1-x) = 1 + x + x^2 + \dots$, assuming that x is small and higher order terms in x can be neglected.

$$T(z) \cong \frac{\hbar\Omega/k}{\ln\left(\frac{C_+}{C_-}\right) - \ln\left(\frac{I_+(z)}{I_-(z)}\right)} \left\{ 1 + \frac{\Delta\alpha z}{\ln\left(\frac{C_+}{C_-}\right) - \ln\left(\frac{I_+(z)}{I_-(z)}\right)} \right\}$$

Applying the power series two more times yields an equation of the form

$$T(z) = \frac{\hbar\Omega}{k \ln\left(\frac{C_+}{C_-}\right)} \left(1 + \frac{\Delta\alpha z}{\ln\left(\frac{C_+}{C_-}\right)} + \frac{\ln\left(\frac{I_+(z)}{I_-(z)}\right)}{\ln\left(\frac{C_+}{C_-}\right)} + \dots \right)$$

Which can be reduced to the equation shown in section 2.3B.

$$T(z) \cong T_{REF} \left(1 + \frac{\Delta \alpha z}{\ln \left(\frac{C_+}{C_-} \right)} + \frac{\ln \left(\frac{I_+(z)}{I_-(z)} \right)}{\ln \left(\frac{C_+}{C_-} \right)} \right)$$

This equation is a linear combination of the offset (first term), the differential attenuation (second term), and temperature measured from the anti-Stokes to Stokes ratio (third term).

APPENDIX B

TEMPERATURE RESOLUTION

B1. HOW DEPTH AFFECTS TEMPERATURE RESOLUTION

In this appendix, the sensitivity of temperature resolution to depth is examined. Begin with the basic expression for temperature shown in Appendix A and restated below.

$$T(z) = \frac{\hbar\Omega/k}{\ln(C_+/C_-) - \Delta\alpha z - \ln(I_+(z)/I_-(z))}$$

Using the above equation, the standard deviation of temperature, $\sigma_T(z)$, can be calculated using error propagation laws, in the form of the expressions below.

$$\begin{aligned} (\Delta T(z))^2 &= \left\{ \frac{\partial T(I_+/I_-)}{\partial (I_+/I_-)} \right\}^2 (\Delta(I_+/I_-))^2 \\ &= \left\{ \frac{\partial T(I_+/I_-)}{\partial \ln(I_+/I_-)} \frac{\partial \ln(I_+/I_-)}{\partial (I_+/I_-)} \right\}^2 (\Delta(I_+/I_-))^2 \\ &= \left\{ \frac{1}{(I_+/I_-)} \frac{\partial T(I_+/I_-)}{\partial (I_+/I_-)} \right\}^2 (\Delta(I_+/I_-))^2 \end{aligned}$$

It can be shown that

$$\frac{\Delta T(z)}{T(z)} = \frac{T(z)}{\hbar\Omega/k} \left\{ \frac{\Delta(I_+/I_-)}{(I_+/I_-)} \right\}$$

Noting that I_+/I_- can be expressed as (See Appendix A)

$$\frac{I_+}{I_-} = \frac{C_+}{C_-} e^{-\Delta\alpha z} e^{-\frac{\hbar\Omega}{kT(z)}}$$

Then

$$\frac{\Delta T(z)}{T(z)} = \frac{C_-}{C_+} \frac{T(z)}{\frac{\hbar\Omega}{k}} e^{\Delta\alpha z} e^{\frac{\hbar\Omega}{kT(z)}} \Delta(\frac{I_+}{I_-})$$

And this can be simplified to the expression shown in Section 2.3E.

$$T(z)/T(0) \sim e^{-z}$$

The importance of these last two expressions is that even if the temperature and the Raman Ratio I_+/I_- are constant, the standard deviation of temperature increases exponentially with distance along the fiber line.

B2. A QUANTITATIVE LOOK AT TEMPERATURE RESOLUTION

To get a physical sense of how depth can affect the standard deviation of the measured temperature, consider the following situation using a 1064 nm laser. The value for $\Delta\alpha$ had been discussed earlier as have the values for the other terms. The value for C_-/C_+ is empirically measured at the temperature reference oven in this instance.

$$\Delta\alpha = 0.35 \text{ dB/km} = 8.06 \times 10^{-5} \text{ m}^{-1}$$

$$\left. \begin{array}{l} T(z) = 300^\circ K \\ \frac{\hbar\Omega}{k} = 600^\circ K \end{array} \right\} \frac{e^{\frac{\hbar\Omega}{kT(z)}}}{\frac{\hbar\Omega}{kT(z)}} = \frac{e^2}{2} = 3.7$$

$$\frac{C_-}{C_+} = 0.22$$

Suppose that a short time of sampling is used and that $\frac{I_+}{I_-}$ is observed to be 0.192 or approximately 0.2. Then applying the equation of the last section,

$$\frac{T(z)}{T(z)} = 0.16 e^{-z}$$

And

$$T(z) = 46.9 e^{-z}$$

If $z = 1000\text{m}$, then $T(z) = 50.8 \text{ Deg K}$! Of course, this value corresponds to a short sampling period and hence the high value of $T(z)$. Recalling that the resolution is improved proportionally to the \sqrt{n} , where n is the number of samples, then a measurement time 10,000 times longer would result in $\frac{I_+}{I_-} = .002$, i.e., being reduced by a factor of 100. Using this value would indicate that

$$T(z) = 0.47 e^{-z}$$

Then for

$z = 1000\text{m}$	-----	$T(z) = 0.5 \text{ deg K}$
$z = 5000\text{m}$	-----	$T(z) = 0.7 \text{ deg K}$
$z = 10000\text{m}$	-----	$T(z) = 1.1 \text{ deg K}$

These values may seem quite reasonable. However, suppose the fiber is damaged and the differential loss is $= 0.7 \text{ dB/km}$, twice what it was before. Repeating the previous computations now shows that the resolution deteriorates to the following values (Note that for this demonstration the attenuation rate is assumed constant throughout the fiber line).

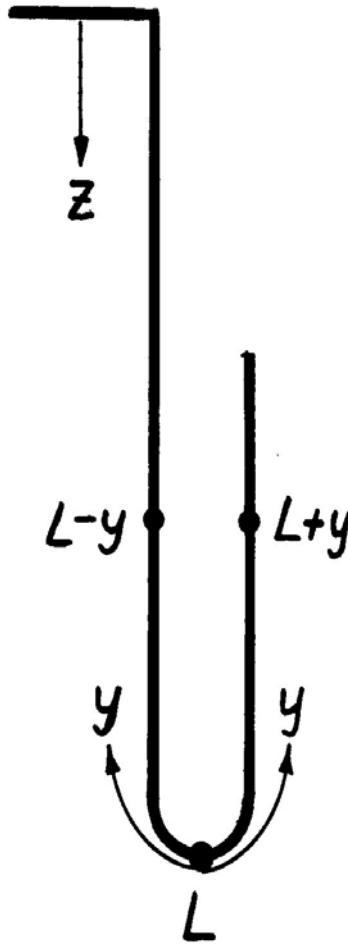
$z = 1000\text{m}$	-----	$T(z) = 3.7 \text{ deg K}$
$z = 5000\text{m}$	-----	$T(z) = 5.1 \text{ deg K}$
$z = 10000\text{m}$	-----	$T(z) = 8.1 \text{ deg K}$

While the assumption of linear signal attenuation was made and may be clearly not reasonable in real life, these computations nevertheless show that fiber damage, even though it may appear slight, can have dramatic effects on the resolution of the measured temperature.

APPENDIX C

DETERMINING DIFFERENTIAL LOSS

C1. DIFFERENTIAL LOSS FOR PARTIAL WRAP SYSTEMS



To determine the differential loss (assumed linear) for a partial wrapped system when the raw data, (I_+/I_-) , is available, consider the schematic of Fig. A.1. The turn around sub is situated at L . The distance y is measured from the turn around sub. By symmetry around the turn around sub,

$$T(l-y) = T(l+y)$$

The value of (I_+/I_-) at any depth z is

$$\ln\left(\frac{I_+}{I_-}\right)_z = \ln\left(\frac{C_+}{C_-}\right) - \Delta\alpha z - \frac{\hbar\Omega}{kT(z)}$$

If the symmetry condition is applied to this equation, then

$$\begin{aligned} \ln\left(\frac{I_+}{I_-}\right)_{L-y} &= \ln\left(\frac{C_+}{C_-}\right) - \Delta\alpha(L-y) - \frac{\hbar\Omega}{kT(L-y)} \\ \ln\left(\frac{I_+}{I_-}\right)_{L+y} &= \ln\left(\frac{C_+}{C_-}\right) - \Delta\alpha(L+y) - \frac{\hbar\Omega}{kT(L+y)} \end{aligned}$$

The difference between these terms is a result of the differential attenuation. From that difference, it can be shown that

FIG. C.1. Partial Wrap System

$$\Delta\alpha = \frac{\ln\left(\frac{I_+}{I_-}\right)_{L-y} - \ln\left(\frac{I_+}{I_-}\right)_{L+y}}{2y}$$

In practice, the value of $\Delta\alpha$ can be determined by plotting the term

$$\ln\left(\frac{I_+}{I_-}\Big|_{L-y}\right) - \ln\left(\frac{I_+}{I_-}\Big|_{L+y}\right) \quad \text{vs. } y \text{ (See section 6.3).}$$

If the raw data is not available, but only temperature data is available, then, if the fan out is small (a few deg K), this correction can be applied to the temperature data directly.

The measured well temperature is (assuming linear loss)

$$\underbrace{T(z)}_{\substack{\text{MEASURED} \\ \text{WELL} \\ \text{TEMPERATURE}}} = \underbrace{t(z)}_{\substack{\text{TRUE} \\ \text{WELL} \\ \text{TEMPERATURE}}} + \underbrace{\beta z}_{\text{LINEAR TERM}}$$

Applying the symmetry condition

$$t(L-y) = t(L+y)$$

then

$$\begin{aligned} T(L-y) &= t(L-y) + \beta(L-y) \\ T(L+y) &= t(L+y) + \beta(L+y) \end{aligned}$$

Proceeding as done earlier, then it can be shown that

$$\beta = \frac{T(L+y) - T(L-y)}{2y}$$

Using this value of β , the true well temperature can be calculated.

C.2. DOUBLE ENDED SYSTEMS/NON-LINEAR LOSSES

Fiber damage may lead to non uniform differential loss, i.e., α is a function of the distance along the fiber. Virgin undamaged fiber is usually sufficiently constant and uniform to be used in a single ended system. Previously described methods are used to correct for uniform differential loss, i.e., constant α . However, it appears that when a fiber is pumped down a smooth bore control line, non uniform differential loss is likely to occur. Similarly, continued exposure to the harsh well environment can cause the fiber to become damaged, even though strong measures are taken to protect it. The following demonstrates how a double ended system can be used to correct for non-linear differential loss.

For this analysis, assume $\alpha(z)$ is not constant. Define

$$\gamma = \hbar \Omega / k$$

Then

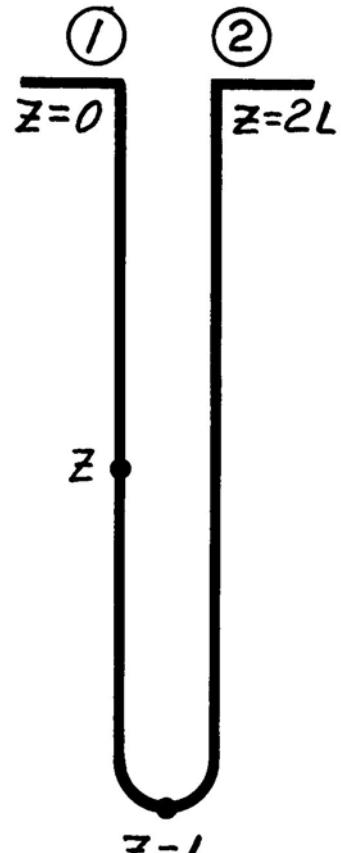


FIG. C.2. Double end system

$$\ln\left(\frac{I_+}{I_-}\right)_1 = \ln\left(\frac{C_+}{C_-}\right) - \int_0^z \Delta\alpha(u) du - \frac{\gamma}{T(z)}$$

$$\ln\left(\frac{I_+}{I_-}\right)_2 = \ln\left(\frac{C_+}{C_-}\right) - \int_z^{2L} \Delta\alpha(u) du - \frac{\gamma}{T(z)}$$

Adding these terms yields an expression which shows that in a double ended system the differential loss leads to a constant error term.

$$\ln\left(\frac{I_+}{I_-}\right)_1 + \ln\left(\frac{I_+}{I_-}\right)_2 = 2 \ln\left(\frac{C_+}{C_-}\right) - \int_0^{2L} \Delta\alpha(u) du - \frac{2\gamma}{T(z)}$$

Correction for differential loss is therefore much easier in a double ended system. Since the error due to differential loss is a constant in a double ended system, differential loss shows up as an offset error rather than a slope error.

It is also possible to determine $\gamma(z)$ with a double ended system. The following demonstrates the development for the differential loss profile. Taking now the difference between the backscatter equations earlier mentioned in this section yields

$$\ln\left(\frac{I_+}{I_-}\right)_1 - \ln\left(\frac{I_+}{I_-}\right)_2 = - \int_0^z \Delta\alpha(u) du - \int_{2L}^z \Delta\alpha(u) du$$

Differentiating the above and applying the theorem

$$F(x) = \int_a^x f(x) dx \implies F'(x) = f(x)$$

Yields the expression

$$\frac{d}{dz} \left[\ln\left(\frac{I_+}{I_-}\right)_1 - \ln\left(\frac{I_+}{I_-}\right)_2 \right] = -2 \Delta\alpha(z)$$

As a result, it can be shown that the loss profile is

$$\Delta\alpha(z) = -\frac{1}{2} \frac{d}{dz} \left[\ln\left(\frac{I_+}{I_-}\right)_1 - \ln\left(\frac{I_+}{I_-}\right)_2 \right]$$

APPENDIX D

GROUP CHECK LISTS

This section contains blanks of the group check lists for reproduction.

FIBER DATA GROUP

INSTRUMENT DATA GROUP		
ITEM	VALUE	REMARKS
MANUFACTURER _____		
TYPE _____		
SERIAL NUMBER _____		
SOFTWARE VERSION _____		
MANUFACTURE DATE _____		
CALIBRATION DATE _____		
CALIBRATION PROTOCOL _____		
CALIBRATED BY _____		
INTERNAL OVEN LOCATION _____		
OVEN SET POINT _____		
TEST CABLE _____		
OFFSET _____		
DIFFERENTIAL LOSS SETTING _____		

PUMPING DATA GROUP		
ITEM	VALUE	REMARKS
DATE OF PUMPING _____		
ENGINEER _____		
SERVICE COMPANY _____		
PUMP FLUID TYPE _____		
CONTROL LINE FLUID _____		
PUMP DIRECTION _____		
PUMPING LOG _____		
FIBER END SEAL _____		
CABLE METER TYPE _____		
CABLE METER SERIAL NO. _____		
CABLE METER CALIBRATION DATE _____		
DRIFT RUN _____		
PERFORMED _____		
EXCESS FIBER _____		
RECOVERED _____		

**QC QUEST TRACK
AND
CHECK LIST**

GROUP	DESIRED INFORMATION	✓	REMARKS
DTS INSTALLATION	DATE OF TEST _____ WELL DATA _____ FIBER DETAILS _____ INSTRUMENT BOX _____ PUMPING RECORD _____ WELL/FIBER SCHEMATIC _____		
FIBER CHECK	PRE/POST PUMP OTDR _____ PRE/POST PUMP _____ ATTENUATION SPECTRUM _____ FIBER PUMPING LOG _____		
DEPTH PARA- METERS	DEPTH REFERENCE _____ END OF FIBER DEPTH _____ SAMPLING _____ RESOLUTION _____		
TEMPERATURE PARAMETERS	TEMP. PROFILE _____ AVERAGED _____ NON-AVERAGED _____ S & AS BACKSCATTER _____ SIGNALS _____ OFFSET CORRECTION _____ DEPTH OF OFFSET _____ MATCH REF. TEMP. GAGE _____ GEOTHERMAL PROFILE _____ TEMPERATURE _____ DEPTH _____ GRADIENT _____		
RESOLUTION DATA	TEMP. RESOLUTION _____ TIME REQUIRED _____ NUMBER OF LAUNCHES _____ LAUNCH/PULSE _____ DURATION _____ LAUNCH WAVELENGTH _____		

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