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Selection Criteria for Pipeline Leak Detection Methods using Distributed Fiber Optic Sensing

Alex de Joode > AP Sensing

Abstract

Distributed Fiber Optic Sensing (DFOS) has expanded current pipeline leak detection technologies (LDS), providing a significant set of new capabilities. This paper briefly reviews the main types of DFOS technologies used for pipeline monitoring. There are different types of Distributed Acoustic Sensing (DAS) and Distributed Temperature Sensing (DTS) that make LDS selection somewhat complex for a specific application.

The DFOS LDS selection process must take into consideration the correlation between the "leak signature" of a particular pipeline and the LDS methods provided by different DFOS technologies. DFOS LDS can play a significant role in modern pipeline leak management, improving performance, and regulatory compliance.

1. INTRODUCTION

Special optical technologies and software can transform fiber optic cables into sensing cables, solving the main challenge of monitoring long assets such as pipelines, power cables, tunnels, and train lines. With a fiber optic sensor cable, the sensing capability is always close to the asset where a potential leak event or external threat occurs. **Figure 1** illustrates Distributed Fiber Optic Sensing (DFOS) technology. An interrogator sends a laser pulse through the fiber optic cable and the associated backscattered light travels back to the interrogator. The backscattered light can be analyzed at certain wavelengths, bringing back acoustic/vibration and thermal information.

Distributed Fiber Optic Sensing (DFOS) is better known as an external pipeline leak detection method that detects effects on the external environment of the pipeline caused by leaks. These effects include changes in temperature, noise, or vibration. However, leak-related **events occurring inside the pipe can also be sensed**, like Negative Pressure Waves (NPW) and other internal acoustic signals. Similarly, DFOS detects internal events including PIG/scrapper tracking, liquid accumulations in gas pipelines, slugs, and flow constrictions caused by waxing, solid accumulations, or hydrate formation.

Today the use of **DFOS**-based pipeline **Leak Detection Software** is well established, covering a wide variety of pipeline applications. LDS systems using data provided by **Distributed Acoustic Sensing (DAS)** and **Distributed Temperature Sensing (DTS)** are already installed in hundreds of projects across tens of thousands of kilometers of pipelines.

In this paper, we discuss the criteria for the selection of the best DFOS-based LDS technology, taking into consideration the following:

- **Suitability of DFOS** technologies for pipeline applications
- **DFOS** role in Pipeline Leak Detection Management
- How pipeline characteristics affect **leak signature** characteristics
- **DAS and DTS** leak detection methods and performance
- Additional **DFOS** functionalities

2. DFOS TECHNOLOGIES

DFOS technologies use laser interrogators which can present risks to eyes or skin, and fire/explosive hazards. Lasers are classified according to the laser power in four classes and subclasses; **Laser Class 1** is the safest, while Class 3B poses risks to eyes and skin, also presenting a fire hazard in certain conditions. For many different reasons, **Laser Class 1** is recommended for pipeline applications.

There are many different DFOS technologies in the market addressing specific applications. Pipeline leak detection tends to focus on the detection of thermal and acoustic signatures. In the first stage of the selection process, the

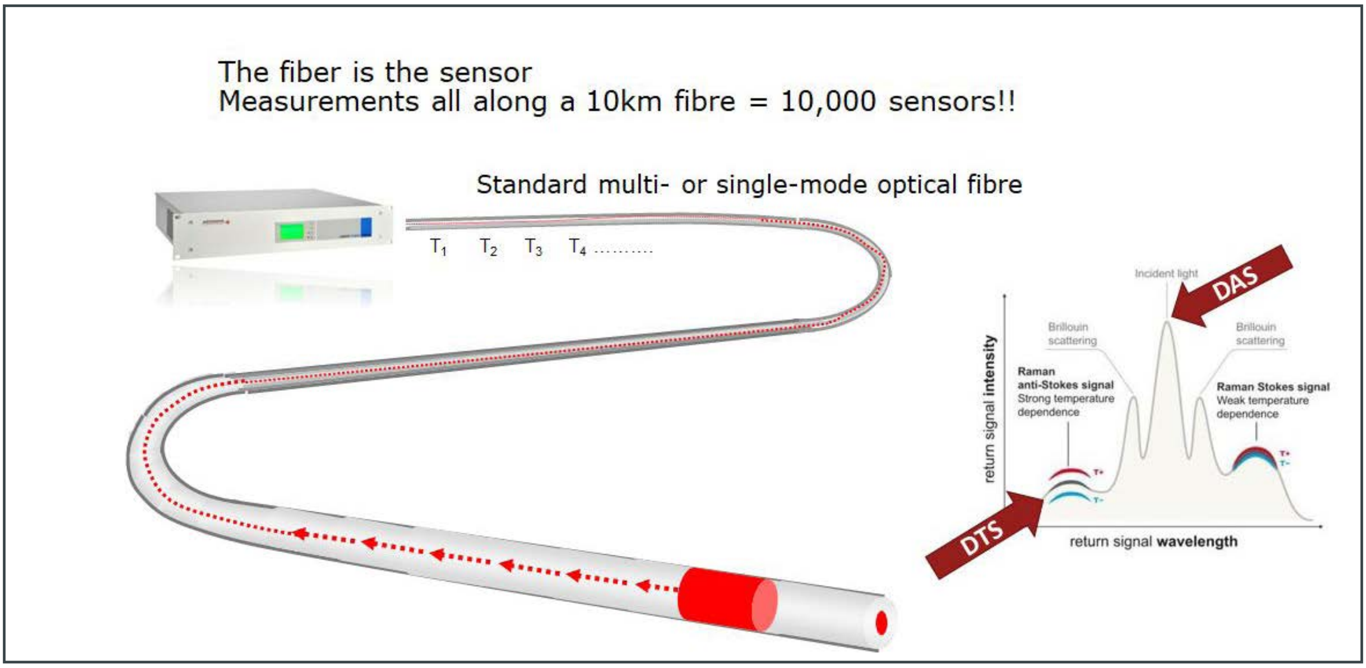

Figure 1: DFOS Backscattering

DFOS technologies can be grouped according to thermal and acoustic capabilities. The ability to use different types of standard fiber optic cables is also considered.

Detection of thermal signals:

- **Raman DTS – Distributed Temperature Sensing**
  Measures accurate temperature values with no cross-talk between temperature and strain.
  Raman DTS can be used with Single Mode (SM) or Multimode (MM) fibers. MM fibers provide a stronger scattering signal, thus achieving better accuracy and can be used up to 50 km.
- **Brillouin DTS – Distributed Temperature Sensing**
  Measures strain and temperature values with possible cross-talk between temperature and strain. Brillouin DTS has a stronger backscatter signal than Raman. It is often used in a loop configuration requiring a return fiber and halving the monitoring range. Special cables should be considered to avoid cross-talk between strain and temperature.
  Brillouin DTS uses SM fibers only.
- **DTGS – Distributed Temperature Gradient Sensing** – as part of Quantitative DAS (also known as Phase-Based DAS) or DFBG (Distributed Fiber Bragg Gratings).
  Measures temperature gradients very quickly over finite timespans with very high resolution (0.001K) without measuring absolute temperatures.
  DTGS, when part of Quantitative DAS, uses SM fibers. When part of DFBG, DTGS uses specially-treated FBG sensing fibers.
- **eDTS – Enhanced Distributed Temperature Sensing** – uses DTGS Quantitative DAS + Raman DTS.
  eDTS uses absolute temperature measurements from the Raman DTS with fast temperature variation measurements of DAS-DTGS to provide enhanced and faster DTS leak alarms.
  eDTS uses SM fibers or a combination of SM and MM fibers.

Detection of acoustic/vibration signals:

- **Non-Quantitative DAS (Amplitude-Based) – Distributed Acoustic Sensing**
  These are simpler DAS systems that only detect the presence of a vibration signal, but not the true signal amplitude or phase of the acoustic signal. Amplitude DAS is mainly used for perimeter protection, does not provide DAS-DTGS, and has difficulty in classifying acoustic events among other shortcomings for pipeline applications.
  Non-Quantitative DAS uses **SM** fibers.
- **Quantitative DAS (Phase Based) – Distributed Acoustic Sensing**
  Quantitative DAS is suitable for applications that require DAS-DTGS and delivers the high-quality acoustic signal (low–fading, quantifiable, high repeatability) required for event classification. Quantitative DAS provides the true signal amplitude or phase of the acoustic signal and is sometimes called "True-Phase DAS" systems. In addition to multi-LDS detection methods, Quantitative DAS includes additional functionalities such as PIG tracking and Third-Party Interference Monitoring.
  AP Sensing's Quantitative DAS uses 2 polarizations, enabling quantitative measurement with superior quality over extended distances of the sensor cable.
  Quantitative DAS uses **SM** fibers.
- **DVS – Distributed Vibration Sensing**
  Unlike DAS that is using a "Coherent-Optical Time Domain Reflectometry" concept, DVS is based on a hybrid interferometer technology (Michaelson/Mach-Zender Interferometer). Similar to Non-Quantitative DAS, DVS is often used for simpler applications such as perimeter protection. It does not provide DTGS and has difficulty in classifying acoustic events among other shortcomings for pipeline applications.
  DVS uses **SM** fibers.
- **DFBG – Distributed Fiber Bragg Grating Sensing**
  Some types of DFBG are occasionally called DAS, but must use special types of fiber and are heavily dependent on the fiber composition, fiber complex manufacturing processes, and variation of specific FBG optical fiber properties. DFBG can provide DTGS.
  DFBG **cannot** use standard **SM or MM** fibers. DFBG requires specially-treated FBG fibers.

From the summary above, the selection of **Raman DTS** (absolute temperature measurement) and **Quantitative DAS** (superior event classification and DTGS) results in a better fit for most pipeline leak detection applications. Brillouin DTS could be considered as a compromise in some specific circumstances where higher signal strength or strain monitoring is required. Standard fiber optic cable is available with suitable **SM** and **MM** fibers or a combination of **SM** + **MM** fibers in a single cable.

3. RAMAN DTS & LEAK DETECTION SOFTWARE CAPABILITIES

Figure 1 illustrates a laser pulse traveling through the fiber optic cable and the associated backscattered light traveling back to the interrogator. At the **Raman** Anti-Stokes wavelength, the intensity of the backscattered light is only strongly correlated with the temperature; this effect can be calibrated to provide absolute temperature readings along the fiber optic cable length. Thanks to the RADAR-like OTDR measurement concept, the location of the temperature readings can be calculated with an accuracy of 0.5 meters to a few meters, depending on the measurement time required and length monitored by the fiber optic cable.

One of the main advantages of Raman DTS is its insensi-

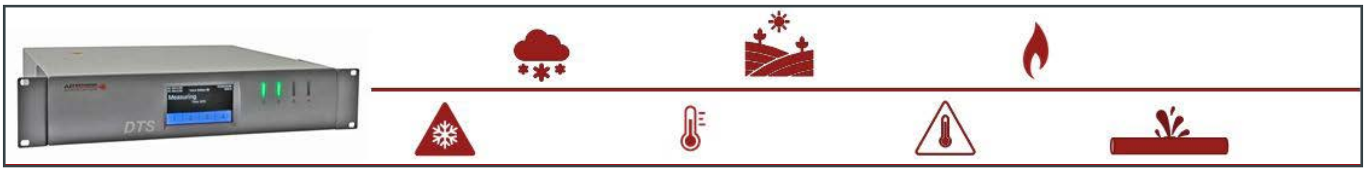

Figure 2: RAMAN DTS

tivity to any acoustic and strain inputs, delivering reliable temperature readings even in noisy conditions. Raman DTS is widely used for fire detection in car/train tunnels and metros where noise and vibration are a concern. For pipeline leak detection applications, LDS software uses DTS measurements together with smart algorithms to calculate if the temperature variations around the pipe are consistent with a leak event, disregarding normal temperature changes caused by the weather, day-night variations, pipeline operations, and other causes of thermal transients.

Raman DTS provides a powerful external LDS method for liquid leaks that cause significant temperature changes to the environment. DTS is widely used as the primary LDS method in hot or cold applications involving insulated pipes where the fiber optic cable is attached to the outside of the thermal insulation. Leaks from insulated pipes result in a localized, fast, and sharp change of the temperature outside the insulation and can be detected rapidly, even in the case of small leaks. Thermally insulated applications include cryogenic tanks, LNG/LPG tanks and associated pipelines, as well as liquid ammonia, liquid hydrogen hot sulfur, bitumen, and heavy crude.

Leaks from non-insulated pipes transporting hot liquids can also cause significant temperature changes in the adjacent environment. By placing the sensor cable a few centimeters away from the pipe, it is possible to measure changes in temperature due to a leak as the ground itself acts as insulation. For small diameter pipelines, ground temperature variation due to a leak can be detected relatively quickly.

DTS is used for high-pressure natural gas, CO2 and LPG. In these cases, the temperature of the transported fluid is not necessarily different from the ambient. The depressurization causes a cooling effect due to the gas expansion (Joule-Thomson effect) or change phase (liquid/gas phase transition).

DTS is often used as a secondary method to detect seeping leaks that can cause a suspicious temperature discontinuity which can be confirmed by advanced LDS software. Seeping leaks are very small leak rates usually detected by periodic inspections (aerial or foot patrol) which rely on a much larger total spill volume to be detected when compared to DTS.

The unique capabilities of DTS allow leak detection in situations when flow metering is unreliable or impossible, such as in open channel waterways or partially filled low-pressure sewage systems.

4. QUANTITATIVE DAS & LEAK DETECTION SOFTWARE CAPABILITIES

Pipeline leak detection software, when used together with Quantitative DAS, can provide three leak detection methods:

- Negative Pressure Wave (NPW)
- Acoustic and Orifice Noise
- DTGS - Distributed Temperature Gradient Sensing

NEGATIVE PRESSURE WAVE

NPWs are rarefaction waves generated during the onset of the leak. NPWs propagate in the fluid at the speed of sound in both directions away from the leak origin. API 1130 NPW CPM (Computational Pipeline Monitoring) software has historically relied on instrumenting multiple locations with two sensor-like pressure meters to detect the presence and direction of the propagation of such waves. DAS of NPWs brings several benefits for the sensing of NPWs:

- **Resilience to obstacles to the NPW path**
  Point sensors are normally installed many kilometers apart and NPW propagation can be interfered with or stopped entirely by obstacles. Pressure-regulating

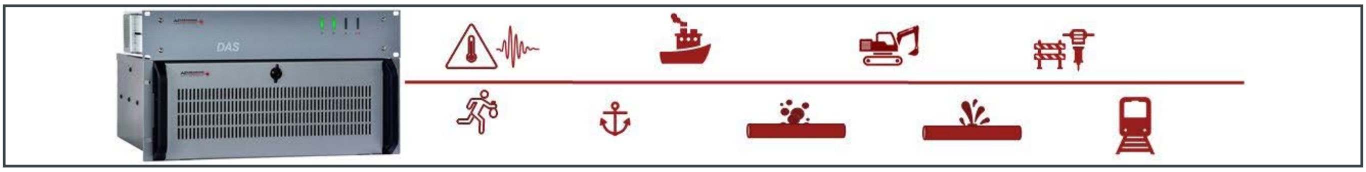

Figure 3: Quantitative DAS

valves, pigs, slack flow vapor pockets, changes in diameter, booster stations, and other factors can interfere with or stop the arrival pressure pulse at a remote sensor. Distributed sensing ensures sensitivity on all segments of the pipeline.

- **Pressure wave attenuation**
  Pressure wave attenuation is a limiting factor that restricts the maximum distance between pressure sensors. Distributed sensing delivers the sensor at closer proximity to the leak origin and therefore provides high sensitivity even with DAS interrogators placed 120 km apart.
- **Event duration and confirmation**
  AP Sensing's enhanced Quantitative DAS can monitor not only the onset of NPWs, but also the progress of the NPWs as they travel over many kilometers. NPW monitoring time using DAS is a thousand times longer than using point sensors, clearly showing travel direction and point of origin. DAS can also provide further leak confirmation at the leak location by acoustic and DTGS LDS methods.

NPW sensing is an important leak signature of high-pressure pipelines. This method is particularly important for the detection and location of high-pressure liquid pipelines and the NPW leak signal will be detected before thermal effects change the temperature around the fiber.

ACOUSTIC AND ORIFICE NOISE

Continuous flow through the leak orifice generates noise and vibrations outside the pipe, and produces pressure instabilities within the fluid. API 1130 Acoustic CPM (Computational Pipeline Monitoring) can benefit from DAS sensors. Acoustic/Orifice Noise signals are present during the duration of the leak but are weaker than signals from NPWs and attenuate faster. Acoustic signals from small leaks do not travel long distances inside the fluid and require specialized transducers capable of detecting the frequencies. The proximity of the sensor cable provides a much greater probability of detection of acoustic leak signals compared to sensors placed kilometers apart.

Orifice noise detected outside the pipe is an important leak signature of high-pressure pipelines. This method is particularly important for the detection and location of high-pressure gas leaks in buried, above ground, and underwater conditions. The acoustic leak signal will be detected before thermal effects change the temperature around the fiber.

DTGS – DISTRIBUTED TEMPERATURE GRADIENT SENSING.

DTGS is an external leak detection method provided by DAS, detecting thermal variations similarly to DTS. Using

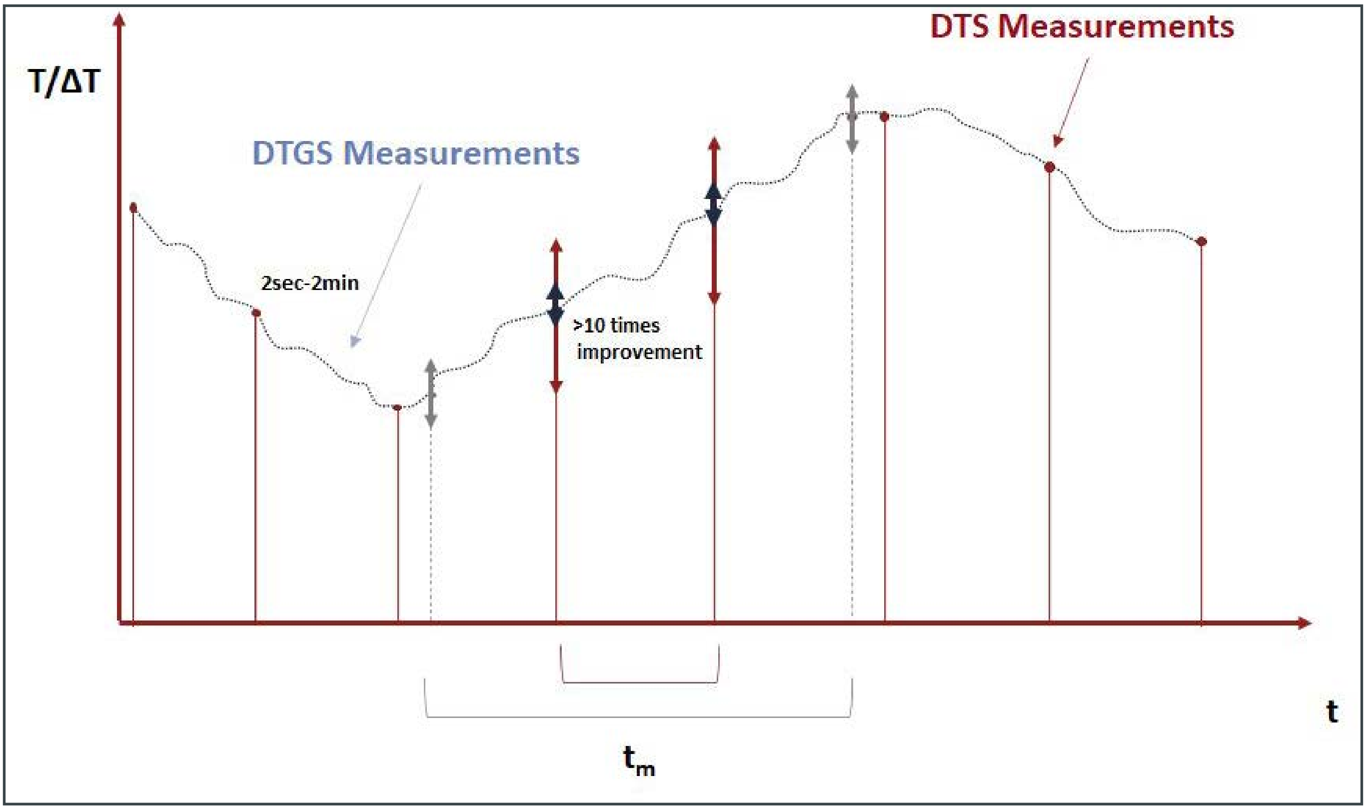

Figure 4: eDTS – merging DTS and DTGS measurements

the same DAS interrogator, the data provided by a Quantitative DAS can be analyzed to determine temperature variations. DTGS can detect very small changes in temperature with very high resolution.

The selection between DTS or DTGS takes into consideration the other DAS LDS methods, as well as additional functionalities provided by DAS and their relevance for the leak signature being considered. The DTGS leak detection method is particularly important for the confirmation of leak alarms from Acoustic/Orifice Noise and NPW from high pressure gases, LPG, and LNG pipelines.

EDTS – ENHANCED DISTRIBUTED TEMPERATURE SENSING

DAS and DTS technologies can be used on their own or together on the same cable, each bringing unique benefits for pipeline leak detection and pipeline monitoring. DAS and DTS used together allow synergies like eDTS, where the fast and sensitive response of DTGS is used to improve the temperature monitoring accuracy of DTS.

The decision between DAS and DTS does not always involve excluding one system, as DTS can be selected as the primary LDS and DAS selected for TPI capabilities. DTS is often used together with DAS, either as a complimentary LDS or as a redundancy. In these cases, the DTGS capabilities of DAS can be used to improve DTS in a unique way. The DTSs capability to measure accurate temperature values is augmented with the DAS system's capability to quickly measure small temperature variations. The result is very sensitive, fast, and accurate DTS measurements with improved performance that is particularly useful for pipeline leak detection among other applications.

5. DFOS ROLE IN THE PIPELINE LEAK DETECTION PROGRAM

DFOS can support the Pipeline Leak Detection Program Management as a primary LDS, secondary LDS, or one component of a multi-LDS system.

DFOS systems are normally used as real-time applications providing continuous LDS monitoring even when used as an external method to detect seeping leaks. Table 1 shows an example where DFOS is used as part of a Leak Detection Program Analysis using different LDSs for different leak rates. Industry best practices recommend that a combination of internal and external leak detection methods should be considered to improve the leak size detection threshold, reduce the time to detect a leak, and/or define the leak location more accurately. Both DAS and DTS can be used together or on their own as external LDS methods and will, in most cases, extend the capabilities of CPM (Computational Pipeline Monitoring) LDSs.

DTS is often considered as a primary LDS for pipeline applications where leak events generate a fast and strong thermal signature. In these cases, and especially for small diameter pipes, the DTS-based LDS software alarms are easy to understand and can provide a very sensitive, reliable method with unparalleled performance. DTS monitoring solutions can be engineered to provide fast alarm response with the accurate temperature and location readings required from a primary LDS.

Quantitative DAS-based Leak Detection Software can be used as an internal LDS method for both CPM Acoustic and CPM Negative Pressure Wave methods. The Fiber Optic Cable is the sensor capable of monitoring conditions inside the pipe using DAS. AP Sensing NPW software

	Continuous LDS			Non-Continuous LDS			
Leak Rate Type	SCADA Monitoring	CPM	Continuous DFOS LDS	Public Awareness	Aerial Surveillance	Non- Continuous DFOS LDS	In-line Inspection
Rupture	•	•	•	•	•	•	N/A
Medium Leak	O	•	•	•	•	•	•
Small Leak	X	O	•	O	O	•	•
Seep	X	X	O	O	O	O	•

X Detection improbable
• Detection probable
O Detection possible

Table 1: Example of a Leak Detection Program including DFOS

uses the input from DAS to analyze the wave propagation direction, calculate the wave speed and the wave point of origin, and determine if the patterns are consistent with a pipeline leak.

6. CONCLUSIONS

The selection process of a DFOS LDS technology for pipelines considers the different DFOS technologies, their suitability to the specific application, and performance requirements. Some of the main aspects to evaluate are:

- Fiber Optic Cable Considerations: standard fiber optic cables using single-mode fibers are suitable for DAS and DTS. Standard fiber optic cable using multi-mode fibers can enhance the performance of Raman DTS.
- Laser Class Type: DAS and DTS using Laser Class 1 should be preferred.
- Type of DAS or DTS technology: Quantitative DAS and Raman DTS should be considered preferred choices in most cases.
- Correlation between Leak Signature type and DFOS Technology:
- Thermal: If the leak causes a significant temperature change in the external environment, the LDS selection should consider DTS, Quantitative DAS-DTGS, and eDTS. LDS software incorporating "Machine Learning" should also be considered to improve performance.
- Acoustic: If the pipeline is pressurized, a leak will generate Acoustic and NPWs signals that can be detected and classified by Quantitative DAS and suitable LDS software. Thermal + Acoustic: If both leak signals are present, Quantitative DAS with DAS-DTGS should be the primary choice. Often Raman DTS is selected in conjunction with DAS for redundancy and independent confirmation
- DFOS role in the LDS Program: Depending on pipeline characteristics, DFOS can be used as a primary, secondary, or single component of a multi-LDS system. Industry best practices recommend that a combination of internal and external LDSs should be considered to improve sensitivity, detection time, and location accuracy.

Author

Alex de Joode
AP Sensing
Head of Pipelines & Terminals
alex.dejoode@apsensing.com

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