AN OVERVIEW OF PIPELINE LEAK DETECTION TECHNOLOGIES

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INTRODUCTION

Pipelines have transported water, oil and gas for hundreds of years, serving residential communities, industrial sites and commercial centers reliably and silently. Leak detection systems (LDS) are needed because pipeline spills occur more frequently as infrastructure ages and more hazardous products are transported. Leak detection systems cannot prevent leaks, but they can certainly help minimize the consequence of leak. Regrettably, too many leak detection systems fail to detect leaks, and other leak detection systems are ignored by the operators because they are unreliable. Thus, leaks that should have been small spills become disasters that cost pipeline owners millions of dollars.

The key to the successful operation of pipeline leak detection systems is management commitment that assures the allocation of sufficient resources to the ongoing maintenance of leak detection systems and their supporting components. Every pipeline operator should consider a role for a leak detection champion who understands how their system works, continually monitors its performance, and supports the Pipeline Controllers. The leak detection system is not "fit-and-forget" and it requires ongoing management which is best achieved in-house with vendor support. When selecting a leak detection technology, it is critical to remember that every pipeline is different and the technology that is best for one pipeline may not serve well on another pipeline.

EXTERNAL AND INTERNAL LEAK DETECTION METHODS

Largely leak detection technologies can be divided into two groups:

- Externally based methods that operate on the non-algorithmic principle of physical detection of an escaping commodity, and
- Internally based methods that utilize field sensor outputs to monitor internal pipeline parameters such as: pressure, temperature, viscosity, density, flow rate, product sonic velocity, etc. These inputs are then used for inferring a commodity release by computation

Figure 1.1 summarizes the common types of the above two methods.

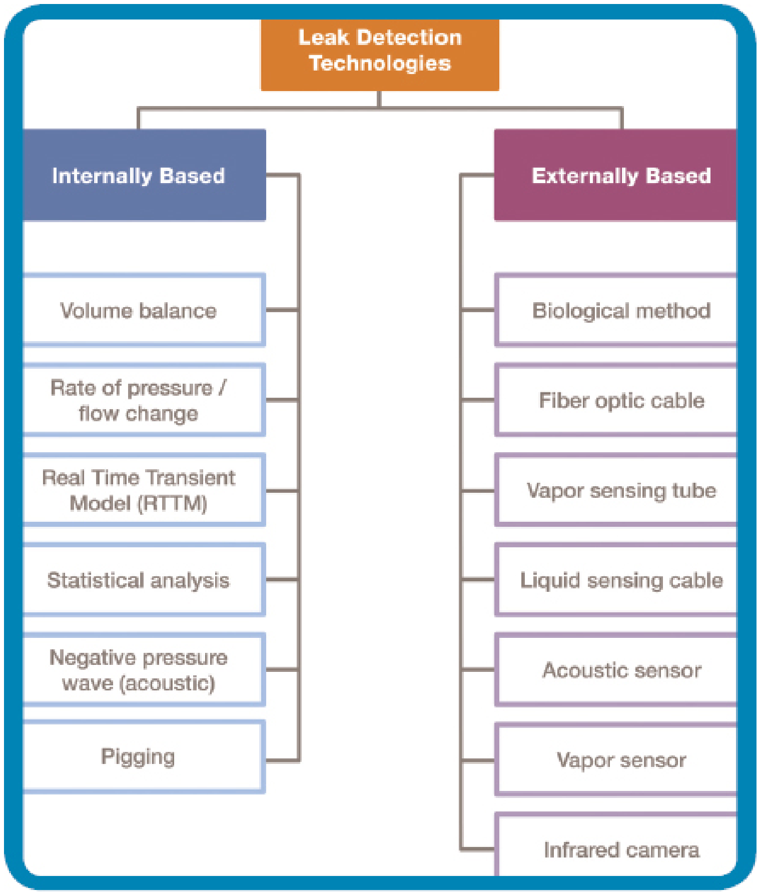

FIGURE 1: Summary of internal and external methods

The main externally based methods include:

Biological method; visual inspection along the right-of-way can find signs of a leak such as damaged vegetation or an oily sheen on water. Both pipeline company personnel and the public may see, hear, or smell a leak. Most companies use an aircraft to fly over the pipeline at regular intervals (e.g. weekly).
Fiber optic cable; fiber optic cables laid alongside a pipeline can be used to detect leaks in three different ways: distributed temperature sensing, distributed acoustic (or vibration) sensing, and distributed chemical sensing.
Vapor sensing tube; a small diameter perforated tube is laid along a pipeline, gas samples are drawn from the tube and analyzed for hydrocarbons by pumping air or nitrogen through the tube.
Liquid sensing cable; buried beneath or adjacent to a pipeline. Specific cable types are chosen to reflect changes in electrical properties by contact with hydrocarbon liquid.
Acoustic sensor; since any leak generates a sound, acoustic sensors can be attached or positioned close to a pipeline. Acoustic sensors can also be used as aids to human external surveys, or within 'intelligent pigs' or 'smart balls' during routine internal surveys.
Vapor sensor; hydrocarbon gas sensors are used as 'electronic noses' at different locations along a pipeline or used as hand-held probes during a routine pipeline survey.
Infrared camera; infrared imaging is used to detect hydrocarbon vapor above a pipeline either by permanently mounted cameras or mobile cameras that are hand-held, mounted on road vehicles, or airborne via drones or aircraft.

The main internally based methods include:

- Volume balance
- Rate of pressure/flow change
- Real time transient model

- Statistical analysis
- Negative pressure wave

This paper will explain the above five methods as they are most the most commonly used. The high cost and the risk of a line strike make it impractical to retrofit fiber optic leak detection on existing pipelines. However, this paper will discuss fiber optic leak detection as it is frequently considered for new pipelines because it is cheaper to lay the fiber.

EVALUATING LEAK DETECTION SYSTEMS

Per API 1155, the two most important performance parameters in evaluating "an algorithmic monitoring tool" are reliability and sensitivity.

"Reliability is defined as a measure of the ability of a leak detection system to render accurate decisions about the possible existence of a leak on the pipeline, while operating within an envelope established by the leak detection system design. It follows that the reliability is directly related to the probability of detecting a leak, given that the leak does in fact exist, and the probability of incorrectly declaring a leak, given that no leak has occurred. A system is more reliable if it consistently detects actual leaks without generating incorrect declarations"[1].

If the LDS generates significantly more than 2 or 3 false alarms per year, controllers will lose confidence in the system.

API 1155 defines "sensitivity" as a composite measure of the size of a leak that a system is capable of detecting and the time required for the system to issue an alarm if a leak of that size should occur.

Sensitivity and reliability trade off. Setting the sensitivity to aggressively reduces the reliability of a leak detection system.

VOLUME BALANCE

Volume balance leak detection is commonly used because of its simplicity and direct correlation with leaks. If flow meters are available at all inlets and outlets of a pipeline, their measurement data are sent to a Supervisory Control and Data Acquisition (SCADA) system at regular sample intervals. Depending on the availability of other measurements the volume balance is calculated in two common forms:

Simple volume balance

the total inlet flow is subtracted from the total outlet flow at each SCADA sample with no pipeline inventory compensation for temperature or pressure.

Modified or corrected volume balance

the simple volume balance is compensated for pipeline inventory change based on the fluid properties, pressure, and temperature along the pipeline.

The volume balance method can be applied to all gas, liquid, and multiphase pipelines where flow meters are available. It can be implemented within a SCADA system or in a stand-alone computer.

The performance of volume balance depends on the quality of the instrumentation system and whether effective inventory compensation is implemented. It is expected that:

- Large leaks can be detected within minutes, medium leaks in hours, and small leaks (such as 1%) can take 24 hours or longer to alarm
- It cannot provide leak location estimates
- It is prone to false alarms during transient operations

RATE-OF-CHANGE MONITORING

Rate of change monitoring of pressure and flow is also a common method used in leak detection. Changes of pressure and flow over a defined time interval are compared with their respective threshold values. A leak alarm is generated if two or more of the thresholds are exceeded (e.g. inlet flow increase and inlet pressure decrease). The rate of change method can be applied to all gas, liquid, and multiphase pipelines where flow and pressure measurements are available. It can be implemented within a SCADA system or in a stand-alone computer.

Shut-in Leak Detection

Pressure rate-of-change monitoring is used in shut-in leak testing. Shut-in leak testing should not be confused with hydrostatic testing, which is a means of verifying the quality of facility construction. For shut-in leak testing, the pipeline is stopped and shut-in under pressure. There is no need to pressurize the pipeline to the MAWP. The pressure in the shut-in segment is monitored for a period to see if the rate of pressure change is greater than that caused by the product cooling. This is a useful technique for detecting leaks that are too small to be detected when the pipeline is running.

REAL-TIME TRANSIENT MODEL (RTTM)

The Real Time Transient Model is the most complex internal method used in leak detection. Hydraulic models are configured to simulate a pipeline by solving three partial differential equations based on the conservation of mass, momentum, and energy. The configuration includes:

- Physical pipeline parameters such as diameter, length, wall thickness, internal roughness, pump/compressor, and valve curves
- Fluid properties such as composition, density, and viscosity

The simulation software uses some measurement data as boundary conditions to compute flow, pressure, and temperature along the pipeline. It also calculates pipeline inventory (line pack) and other variables such as fluid velocity. While the implementation of the RTTM method may vary from one company to another, the basic principle is the same; comparing measured data with its corresponding model-calculated values. If the difference is greater than a pre-configured threshold for one or more variables, then a leak alarm is generated.
The RTTM method can be applied to gas, liquid, and multi-phase pipelines if flow, pressure, and temperature measurements are available. Due to the intensive computation requirement, it is implemented in a stand-alone computer. It is expected that:

- The RTTM method can detect medium and large leaks within minutes.
- Its leak location estimates are not accurate but can provide a good indication of the leaking section.
- It requires many online measurements; such as ambient temperature and fluid density/viscosity at strategic locations.
- It is time consuming and costly to support, and therefore is mainly used by large pipeline companies with in-house hydraulic experts.

STATISTICAL ANALYSIS

Different levels of statistical analysis can be applied to leak detection. At one end, simple low-pass filtering is applied to flow or pressure data to reduce the noise level before deciding if an anomaly has occurred. The more comprehensive method compares the probability of a leak with the probability of no-leak.

Two main commercially available systems are:

Pressure Point Analysis (PPA)
the Student-t statistics are used to determine if the average pressure in a pipeline has changed significantly. If the average pressure has decreased with a level of confidence, then a leak alarm is generated. The PPA is an old technology; it is only suitable for pipelines with steady operating conditions

Statistical Volume Balance (SVB)
the Sequential Probability Ratio Test (SPRT) is applied to the pipeline inventory compensated volume balance. The statistical volume balance works effectively for all pipelines, including gathering networks with multiple injection points. By calculating the ratio of the probability of a leak over the probability of no-leak, the system decides if the corrected volume balance has increased with a predetermined probability (e.g. 99%). The statistical analysis method can be applied to gas, liquid, and multiphase pipelines. Usually implemented in a stand-alone computer, the statistical volume balance system is one of the statistical analysis methods referred to in API publications [2 & 3]. It uses the corrected volume balance in conjunction with SPRT to provide reliable leak detection.

The SPRT is a hypothesis testing method used to decide between a leak (H1) and no-leak (H0) scenario [3 & 4] . The data used for the SPRT is the inventory compensated volume balance. The SPRT calculates the ratio of the probability of a leak over the probability of no-leak and decides if the corrected volume balance has increased with a predetermined probability, e.g. 99%.

A leak will normally cause the pipeline pressure to decrease and introduce a discrepancy between the receipt and delivery flow rate. This SVB system is designed to recognize these patterns; leak determination is based on probability calculations at regular sample intervals. Although operational changes cause the flow and pressure in a pipeline to fluctuate, statistically the total volume entering and leaving a network must be balanced by the inventory variation inside the network, unless there is a leak. The combination of SPRT with pattern recognition provides the SVB system with a very high level of system reliability, i.e. minimum spurious alarms.

The volume balance principle determines under leak free operations that the difference between the ingress and egress flow rate should be equal to the inventory variation in a pipeline.
One key feature of the SVB is its learning capability, e.g. operational changes introduced after the installation are used to further tune the system automatically, and gradual instrument drift is incorporated for eliminating false alarms. Since no transient model is used, variations in fluid properties, e.g. composition change and viscosity variations, do not present a problem to the SVB system.

One of the main advantages of the SVB over simple volume balance is that it does not generate leak alarms if the volume balance shoots up for 10 seconds or so and then recovers.

It is expected that:

- The statistical volume balance method can detect small, medium, and large leaks within minutes
- Its leak location error can be around 1 km using SCADA data and less than 1 km with fast scanned data from RTU's
- It has a low false alarm rate
- It works with different fluid types and does not require viscosity and density measurements

NEGATIVE PRESSURE WAVE

When a leak occurs in a pipeline, the pressure drops at the release location. This negative pressure wave propagates out from the location of the release in both directions and can be sensed by pressure meters at the ends or along the pipeline. The detection and confirmation of the negative pressure form the basis of this technology.
With the significant improvement in pressure sensors and communication infrastructure in recent years, the new generation of negative pressure wave technology samples pressure data at high frequencies (e.g. 60 Hz) and sends them to the central server for analysis. Comprehensive algorithms are used to
detect small leaks while minimizing false alarms due to operational changes.

The negative pressure wave method can be applied to both gas and liquid pipelines. Usually it is implemented in a stand-alone computer. It is expected that:

- The negative pressure wave method can detect small to large leaks within a few minutes
- It can provide very accurate leak locations (e.g. 100 meters)
- Its leak size estimates are not accurate if no flow meter is used
- False alarms may occur if pressure patterns from operational changes are like the patterns of leaks
- It is event driven, if a leak is missed at the time when it occurs, it may remain undetected

FIBER OPTIC LEAK DETECTION

Fiber optic cables can be used for leak detection, as variations in physical properties such as temperature or strain change the characteristics of light transmission (scattering) locally in the fiber. This scattering damps the light in the quartz glass fibers at the location of an external physical effect, providing the location of the disturbance along the optical fiber. The two most common detection methods used are Distributed Acoustic or Vibration Sensing (DAS/DVS) and Distributed Temperature Sensing (DTS). Distributed Strain Sensing (DSS) is also used to detect a small strain on the fiber or ground heave created by a large leak. The different methods respond differently to a leak event, depending on the soil type, cable offset and ground conditions and the same leak will take a different time for each method to generate an alarm.

Distributed Acoustic Sensing (DAS) or Distributed Vibration Sensing (DVS)
The system pumps coherent laser energy pulses into the optical fibers within the cable laid alongside the pipeline and analyzes the naturally occurring Rayleigh backscatter. The system calculates the location of a leak by measuring the time delay between emission of the laser pulse and the detection of the reflection; this technique can also be combined with the DTS. Audibility decreases with the increasing distance from a leak.

Distributed Temperature Sensing (DTS)
Products such as crude oil, brine, and heating systems usually cause local warming close to the pipeline when they leak. Leaks from a gas pipeline cause local cooling in the ground close to the gas leak; this is the Joule-Thomson effect. The threadlike geometry and low propagation loss characteristics of optical fibers allow them to monitor a pipeline over long distances (10-50 km segments, depending on the technique). Distributed sensing techniques can provide an uninterrupted measurement of the fiber temperature as a function of distance.

Detecting a leak by monitoring temperature changes along a pipeline requires special processing to discriminate an actual leak from environmental temperature fluctuations. Leak detection is only possible through analysis of temperature deviations with respect to a baseline profile (that may evolve slowly over time). The system monitors a fiber optic cable installed along the length of the pipeline. If the product spilled from a leak reaches the cable and changes the temperature of the cable, the reflection of the laser beam pulse is altered signaling a leak.
Fiber work in theory for liquid, gas, and multiphase pipelines and can discriminate between multiple leaks that occur at the same time. Fiber optic leak detection systems are expensive to install on new pipelines and almost impossible to retrofit to existing pipelines. It is difficult to prove the performance of fiber optic leak detection systems, as it is difficult to test the system in the field where actual product loss must occur on an operating pipeline. Furthermore, there is a risk that the spill path of a leak can miss the fiber optic cable, causing the system to miss the leak. There has been more controlled third-party testing of fiber optic systems that seems to confirm that environmental conditions can cause a high false alarm rate in fiber optic systems, so it can be difficult to confirm a leak. If the product spill is at ambient temperature the DTS can also miss the event.

An accurate estimation of leak size is important for leak response, regulatory requirements, and damage estimation. Currently fiber optic systems cannot provide this information. While this technology can be used for the detection of third party intrusion, it cannot detect product theft from a pipeline once
the theft pipeline and equipment are installed, as no product is spilled. Finally, if the cable is cut then the system will not function.

CONCLUSION

Method	Volume Balance	Rate-of-change	RTTM	Statistical Volume Balance	Negative Pressure	Fiber Optic
Application requirements	Measurement of flow; SCADA and communication	Measurement of pressure; SCADA and communication	Measurement of ambient temp., density, gas composition in addition to flow, pressure, temp., SCADA & communication	Measurement of flow 7 pressure; SCADA and communication	Measurement of pressure. Dedicated data acquisition equipment & communication	Installation of cable and proprietary devices along pipeline
Applicable pipelines	Gas, liquid, & multiphase.	Gas, liquid, & multiphase.	Gas, liquid, & multiphase.	Gas, liquid, & multiphase.	Gas, liquid, & multiphase.	Gas, liquid, & multiphase,

	Onshore and onshore	Onshore and onshore	Onshore and onshore	Onshore and onshore	Onshore and onshore	mostly onshore
Reliability		Low; false alarms during transients	Medium; depending on model performance	High; designed to minimize false alarms	Medium to high; depending on tuning	Medium, depending on environmental factors & leak effect
Sensitivity	Low	Medium to high; detecting small leaks during shut - in	Medium; due to difficulty in maintaining high accuracy models	Medium	High; detecting small leaks and thefts	High
Robustness	Medium; loss of function if flow meters fail	High: rate of pressure change works if flow meters fail and vice versa	Medium; loss of function due to missing data or slack flow	High; still detects leaks even if some instruments fail	Medium; loss of function if pressure sensors are not available	Low; may not detect leaks if cable is cut or hole is not close to cable
Location Accuracy	No location available	No location available	Medium	Medium	High	High
Calculate leak size	Yes	No	Yes	Yes	Yes; accurate only after leak calibration tests	No

TABLE 1. Summary of Internal Leak Detection Methods

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