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DEVELOPMENT OF PIPELINE LEAK DETECTION TECHNOLOGIES

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ABSTRACT

New development continues in pipeline leak detection technologies in order to meet the increasing demand of the oil, gas, chemical and water industry. After a review of the available technologies, this paper discusses the advances made in two key technologies: statistical volume balance and negative pressure wave.

Some application examples in brine, multi-product and crude oil pipelines are presented to demonstrate the improvement in leak detection sensitivity and location accuracy.

INTRODUCTION

Pipeline leaks and product thefts have increased in recent years, causing more human fatalities, environmental catastrophe and property damage. While leak detection systems cannot reduce the probability of a leak, the optimal implementation of an advanced technology can reduce the consequence of the leak significantly.

To provide maximum support to pipeline operating companies, an ideal leak/theft detection system should

- Detect leaks down to 0.0001% (1 Part Per Million)
- Pinpoint leak location within 1 meter
- Generate zero false alarms
- Have auto-tune capability
- Retrofit to existing pipelines
- Work under transient, slack & shut-in conditions
- Be economical to install and maintain.

The reality of the current available technologies is somewhat different from this ideal system. However, continuous research and development is narrowing the gap.

There are many types of leak detection technologies in the market. Largely they can be divided into two groups [1]:

- Externally based methods that operate on the non-algorithmic principle of physical detection of an escaping commodity.

- 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. and infer a commodity release by computation.

Figure 1 summarizes the common types of external and internal methods. A brief description of each of these methods is given below.

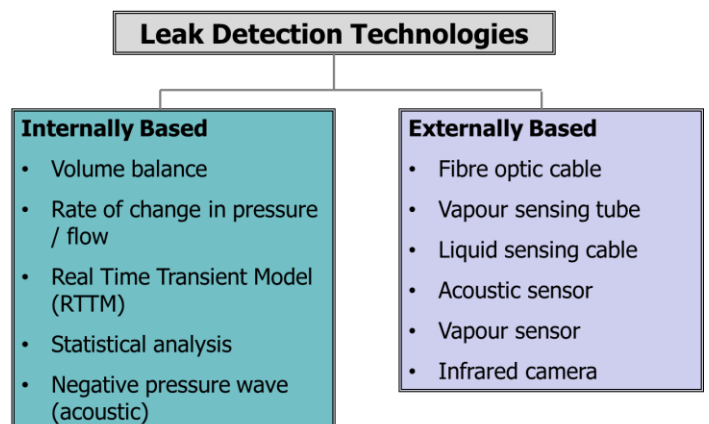


Figure 1 Summary of Leak Detection Technologies

Externally based methods:

Fibre optic cable – fibre optic cables laid alongside a pipeline can be used to detect leaks in four different ways: distributed temperature sensing, distributed acoustic (or vibration) sensing, distributed strain sensing and distributed chemical sensing.

Vapour 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 – Leaks generate sound. Acoustic sensors attached to and potentially tapped into a pipeline, positioned close to a pipeline, can be used as aids to human external surveys or within “intelligent pigs” or “smart balls” during routine internal surveys.

Vapour sensor – hydrocarbon gas sensors are used as “electronic noses” at different locations along a pipeline or used as hand carried probes during a routine survey.

Infrared camera – infrared imaging is used to detect hydrocarbon vapour above a pipeline either by permanently mounted cameras or mobile cameras that are handheld, mounted on road vehicles or airborne.

Internally based methods:

Volume balance – the measurement imbalance between the incoming and outgoing volume is calculated over different time periods, this imbalance can be compared with a predetermined alarm threshold with or without inventory compensation.

Rate of change in pressure/flow – rate of change in pressure and flow are compared to the values under normal operating conditions to infer possible commodity release.

Real time transient model – a pipeline specific hydraulic model is configured and run online based on boundary conditions provided by field instruments at supply, delivery points and pump/compressor stations. Typical field inputs include flow-rate, pressure, temperature, liquid density or gas composition. Leak alarms are generated by comparing measured values with model calculated ones.

Statistical analysis – by applying statistical analysis to different signals from a pipeline, commodity release is inferred. Typical field data used include flow, pressure and temperature.

Negative pressure wave – the pressure wave generated by a leak travels upstream and downstream of the leak location, a commodity release is inferred by analyzing the pressure data sampled at high rate.

The pros and cons of external systems are shown in Table 1. External systems are expensive, difficult to retrofit, difficult to extend or modify and need very careful installation. In the market today, they have a very limited track record compared to internal systems. Testing of some of these systems is challenging as actual fluid spillage or gas release is required.

World-wide, internal systems are installed much more regularly than external systems and they can be applied to many more pipelines. The pros and cons of internal systems are listed in Table 2 based on the method of detection that they use. It is interesting to note that the DOT Leak Detection Study – DTPH56-11-D-000001 that reported on US pipeline leaks in the period between January 1, 2010 and July 7, 2012 found that many of the pipelines in the study had no CPM leak detection systems (LDS) or used very basic LDS [3]. It is likely that with a better leak detection system, these leaks could have been detected much sooner.

Table 1 External Leak Detection System Characteristics

Pros	Cons
<ul style="list-style-type: none"> Accurate leak location (one meter error with some methods) Fast detection time with certain leaks 	<ul style="list-style-type: none"> Expensive Difficult to retrofit Difficult to expand and modify as the pipeline changes Some are routine monitoring only Limited track record High false alarm rates

Table 2 Internal Leak Detection System Characteristics

Leak Detection Method	Pros	Cons
Volume balance	<ul style="list-style-type: none"> Inexpensive Easy to implement 	<ul style="list-style-type: none"> Low performance Many false alarms Effectively switches off during transients
Rate of Change in Pressure/Flow	<ul style="list-style-type: none"> Inexpensive Easy to implement 	<ul style="list-style-type: none"> Many false alarms Low performance if false alarms are reduced Effectively switches off during transients Onset detection only
RTTM	<ul style="list-style-type: none"> Computes linepack and pressure profile Performs other functions such as batch tracking 	<ul style="list-style-type: none"> Requires accurate flow meters and other measurements Expensive to maintain Many false alarms
Statistical Analysis	<ul style="list-style-type: none"> High sensitivity No special hardware required 	<ul style="list-style-type: none"> Slower to detect small leaks than negative pressure wave systems Leak location accuracy not as good as systems with dedicated hardware
Negative pressure/rarefaction wave (acoustic)	<ul style="list-style-type: none"> High sensitivity Fast leak detection High leak location accuracy 	<ul style="list-style-type: none"> More false alarms than statistical systems Requires dedicated leak detection hardware Onset detection mostly

As shown in Table 1 and Table 2, there is a big gap between the available technologies and the ideal leak detection system. To narrow the gap, continuous research and development has been carried out in the following three technologies:

- Statistical analysis
- Negative pressure wave and
- Real Time Transient Model.

In the following two sections the improvements made in the statistical analysis and negative pressure wave technologies will be discussed.

STATISTICAL VOLUME BALANCE

The internally based technologies are more widely used in the pipeline industry as they provide continuous monitoring of the pipelines. The faster detection of leaks will help reduce the consequences of pipeline leaks. This section will describe the statistical volume balance technology and the performance improvement made in recent years.

The statistical volume balance is one of the statistical analysis methods as referred to in API 1130 [4]. It uses the corrected volume balance in conjunction with sophisticated statistical techniques to provide reliable leak detection and leak location. It has been successfully applied to more than 600 pipelines world-wide with various fluids, pipeline dimensions and operating transients.

The engine to this statistical volume balance technology is the Sequential Probability Ratio Test (SPRT): a hypothesis testing method used to decide between a leak and no-leak scenario. The data used for the sequential probability ratio test is the inventory compensated volume balance. By calculating the ratio of the probability of a leak over the probability of no-leak, it decides if the corrected volume balance has increased with a predetermined probability e.g. 99%.

To cover the full range of operating conditions, flow and pressure analysis is carried out to determine if the pipeline is running, shut-in or stopped and if it is under “steady state”, “small transient” or “large transient” operations. Different detection time is applied to each of these operations in order to minimize false alarms.

Usually accurate leak size estimates are provided by correcting the average corrected volume balance with metering errors. Two leak location options are available based on Time Of Flight (TOF) and pressure interpolation method respectively. Least Squares algorithm is applied to the pressure interpolation method to minimize the location error.

The above statistical volume balance system has been applied to more than 600 pipelines successfully including:

- Crude Oil: heavy, medium and light
- Multi-product: gasoline, diesel and jet fuel
- Natural Gas
- Ethylene: high and low pressure
- Condensate
- Diluent

- LPG
- Methanol
- Chlorine
- Ammonia
- Carbon Monoxide
- Hydrogen and
- Slurry.

The pipeline diameter ranges from 0.5” to 80” and length from 2 KM to 2100 KM. The elevation profile changes from 2100 meters below to 3000 meters above sea level. The operating conditions include steady state, transient, slack flow and shut in with both batched and single product in a pipeline. Most of the pipelines run pigs on a regular basis. Figure 2 shows the layout of a crude oil pipeline in Germany where the statistical system has been operational since 2002 [2].

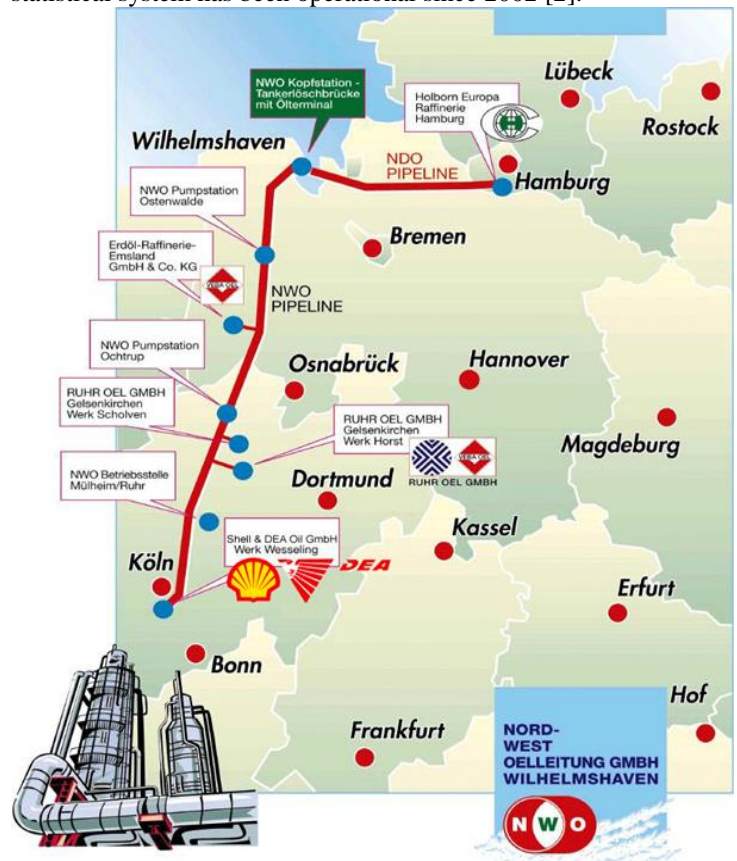


Figure 2 The Layout of NWO and NDO Pipelines

The crude oil pipeline pumps more than 400 types of crude oil with a wide range of batch sizes and properties. Table 3 summarizes the crude oil properties.

Table 3 Crude Oil Properties of the NWO Pipeline

	Density (kg/m3)	Viscosity ((cSt@10°C))	Batch Volume (m ³)
Minimum	798	2.8	93
Maximum	925	309	111,245

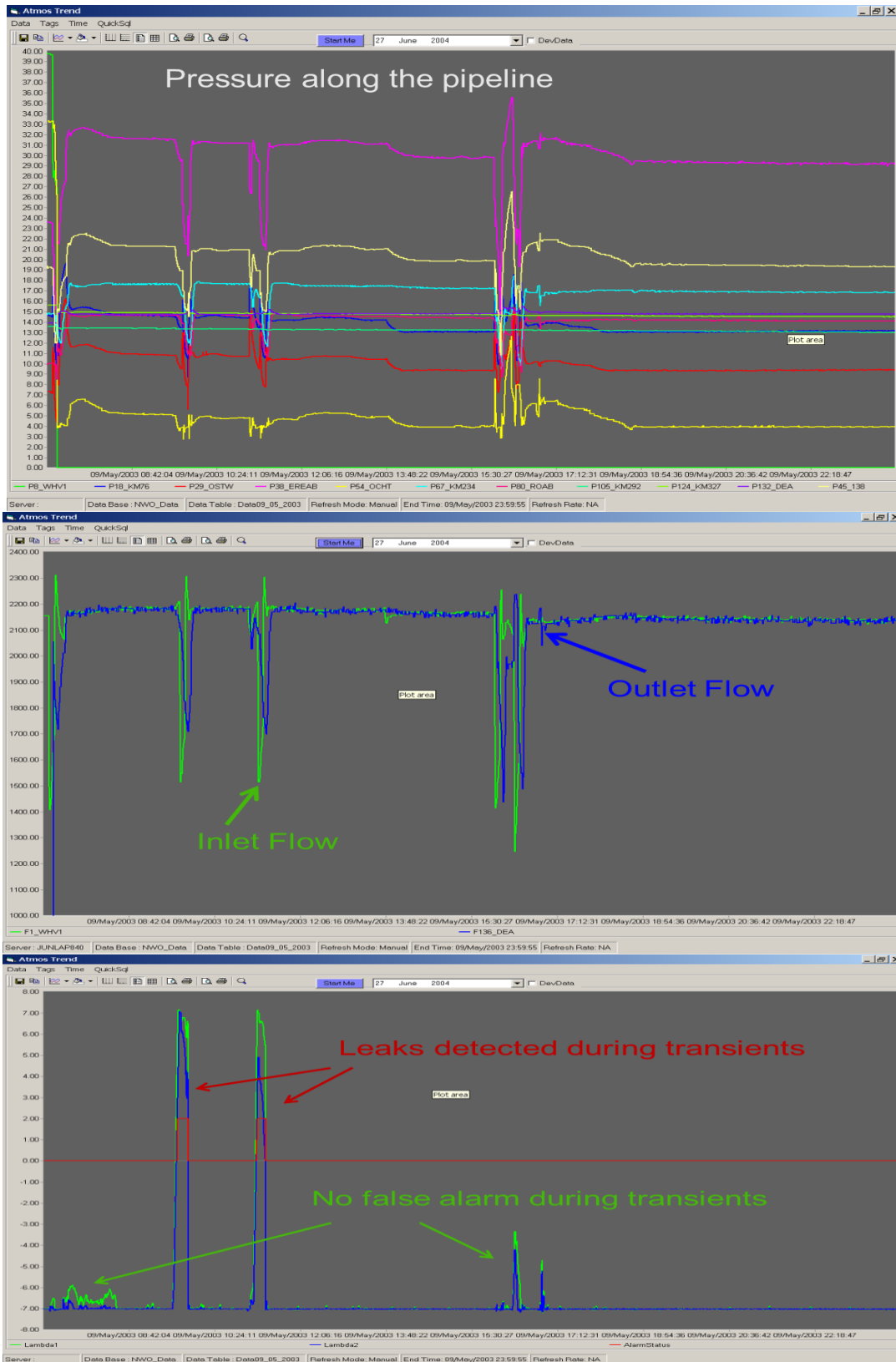


Figure 3 Pressure and flow measurements over a 15 hour period with the statistical leak detection system results, clearly distinguishing between normal transients and leaks.

The statistical volume balance system has replaced a RTTM leak detection system on the NOW/NDO pipeline because of the following main reasons:

- Its unique ability of detecting leaks under transient conditions. As shown in Figure 3, the statistical volume balance system detected two transient leaks while it did not generate any false alarm when the pipeline experienced severe transients due to pump switch over. More than 64 controlled leaks had been detected successfully prior to the approval of the system by TUV in compliance with the applicable rules and standards in Germany, especially the TRbF 301 and TRFL (Technical Rules for Inflammable Substances).
- Its low false alarm level under all operating conditions: transients, crude oil batch changes with different properties, start up, shut down, delivery location switches, temperature variations, running to shut in operations.
- It copes with slack flow effectively. When the pipeline shuts down the pressure is reduced sufficiently to cause vapour pocket at the high points. The statistical system is able to cover the start-up and shut down of the pipeline without false alarms.
- Its cost effective maintenance over the years.

One of the main challenges in flow based leak detection systems is the availability of accurate flow meters. Sometimes a pipeline operating company still needs to detect a 0.5% leak even when their flow meters have an accuracy of, say 1%. In order to narrow the gap between the clients' expectation and the performance of existing technologies, continuous research and development has been carried out. Figure 4 shows an example of the flow meter discrepancy changes as the flow-rate increases from 500 m³/h to 2000 m³/h on a 27 KM long brine pipeline. The maximum discrepancy between the inlet and outlet flow meter is 3.5% (from -45 to 25 m³/h). However the client wanted to detect leaks of 0.25%.



Figure 4 An example of the flow meter discrepancy change from -45 to 25 m³/h

With improved meter error handling capability and advanced data processing, it has proven possible for the statistical volume balance method to detect leaks down to 0.25% on this liquid pipeline and reduce the leak detection time significantly without increasing the false alarm level. Figure 5 illustrates the leak alarm of the statistical system before and after the advanced data processing. It is clear that the noise level of the corrected flow difference has been reduced significantly after more advanced data processing. Table 4 compares the detection time before and after the improvement.

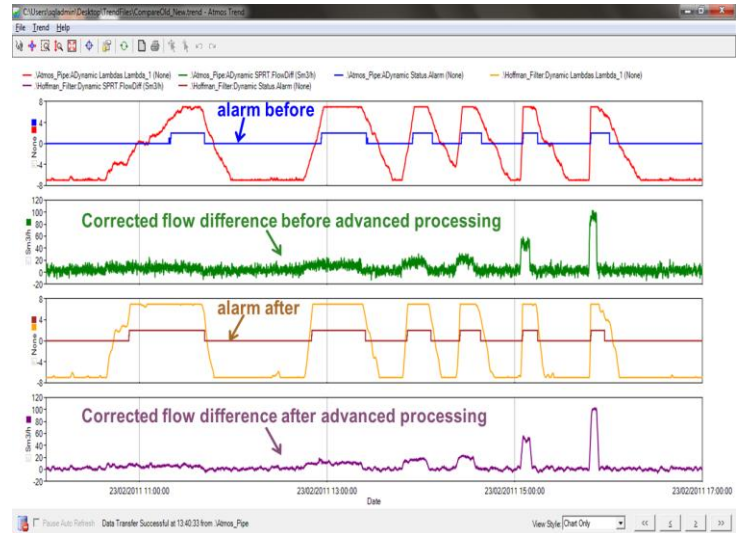


Figure 5 The improved leak detection performance after more advanced data processing

Table 4 Improvement in Detection Time after More Advanced Data Processing

Leak size (% of flow-rate)	Detection Time Before min:sec	Detection Time After min:sec
0.25%	41:19	5:34
0.5%	11:14	4:09
0.75%	6:39	2:55
1.25%	3:34	2:35
2.5%	2:14	1:50
5%	1:15	1:15

In addition, leak location accuracy has been improved for leaks greater than 1%.

NEGATIVE PRESSURE/RAREFACTION 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. Note that this technology is also (incorrectly) referred to as “acoustic” method.

As the initial pressure drop caused by a leak is short lived, it is necessary to sample the pressure data quickly e.g. 60 times per second. Thus dedicated data acquisition hardware is usually required.

Although the first negative pressure wave system was available since the early 1980’s, it has not been widely applied due to the high false alarm rate caused by the old algorithm developed based on the bandwidth and hardware limitations. Recently a new system was developed capitalizing in the significantly improved pressure sensor technology, communication infra-structure and computer power. This system samples pressure data at high frequencies, e.g. 60 Hz, and send them all to the central server for thorough analysis. The algorithms filter out noises, arrange the analogue pressure data into a detailed 3-dimensional map that allows the system to clearly differentiate true leak/theft events from the pressure changes caused by transient operations. This system has been subjected to hundreds of tests with both leaks and thefts, including one facilitated by PRCI (Pipeline Research Council International) [5]. Some very impressive results have been generated in both gas and liquid pipelines.

The response time is in minutes only limited by the propagation time of the pressure wave to the sensors and algorithm processing time. This is typically governed by the speed of sound in the pipeline and the distance between two consecutive pressures sensors. The leak event is a “one-shot” event – i.e. if the event is missed for any reason, some post leak analysis method would be used to detect the leak at a later stage. Such post leak processing has been incorporated in this new system including the use of low cost flow meters. This applies also to existing leaks that cannot be detected by the conventional negative pressure wave method. Leak location can be very accurate – within a few hundred meters. However leak size is usually inferred from the observed pressure drop with limited accuracy unless flow meters are available.

Since the pressure wave decays as it propagates along the pipeline, the sensitivity and location accuracy depend on the distance between pressure sensors. On a multi-product pipeline, the new system has detected a theft of less than 0.5% in a segment of 220 KM length without intermediate pressure sensors. The tests carried out on a 42” natural gas pipeline have demonstrated that it can detect leaks down to 0.3% and the pressure wave is detectable after 140 KM (87 Miles). The decay of the pressure wave in the gas line is much smaller than expected.

Although most installations are on liquid pipelines, the technology is equally applicable to gas pipelines. Some tests have been carried out on multi-phase pipelines and the performance depends on the flow regime, signal to noise ratio, gas liquid fraction and elevation profile.

Unlike traditional negative pressure wave technologies, the new technology examines all aspects of the negative pressure wave front and its propagation through the entire pipeline length. Three comprehensive algorithms filter out noise, arrange the analogue pressure data into a detailed 3-dimensional map that allows the system to differentiate true leak/theft events from the pressure changes caused by transient operation.

Figure 6 summarizes the 3-step process of the new technology. In the first step the pressure signals are filtered to remove noise. In the second step all the analogue pressure data are collected at the central processor and combined into a dynamic 3-dimensional picture of the moving pressure wave front. In the third step the algorithms identify and differentiate the leaks taking into consideration the entire pressure distribution along the pipeline and its dynamic evolution in time.

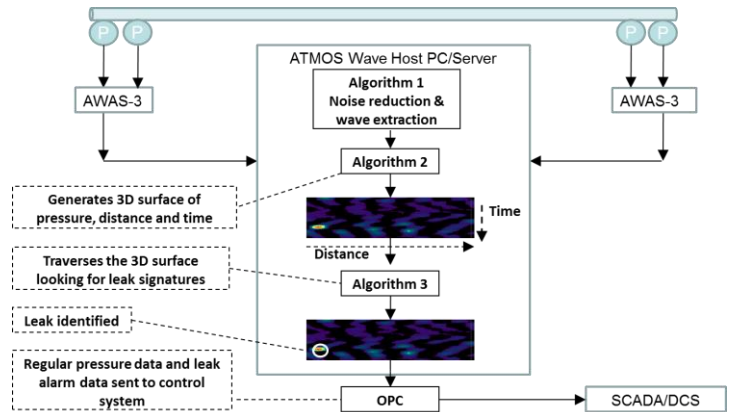
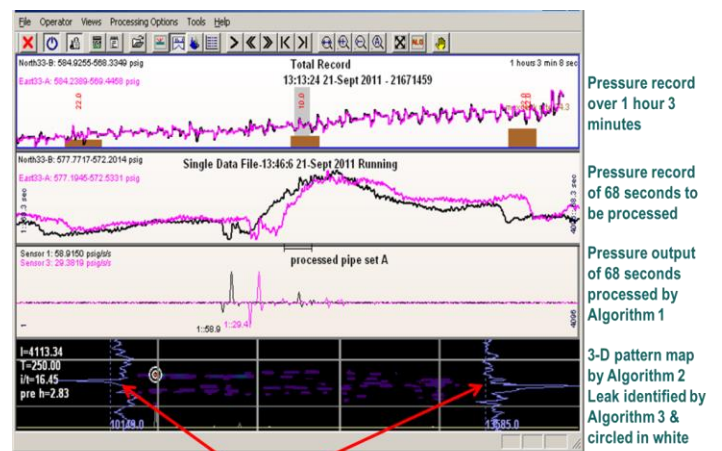


Figure 6 – The Three Step Process of the New System

Figure 7 gives an example of how this new technology identifies a leak from transient pressure data.



Wave direction identification confirms a leak

Figure 7 An Example of Leak Detection in a Pipeline where the Pressure Changes Continuously due to Transient Operations

To demonstrate the ability of the new pressure wave technology in covering long distances between two consecutive pressure sensors, an example of a 48” crude oil pipeline is shown in Figure 8. This shows a distance of 234.5 KM between the pressure sensors. As shown in Figure 9, the pressure at the inlet (PT1302-04) and outlet (PT1301-02) responded to a 1% leak clearly and a leak alarm was generated with an accurate location estimate.

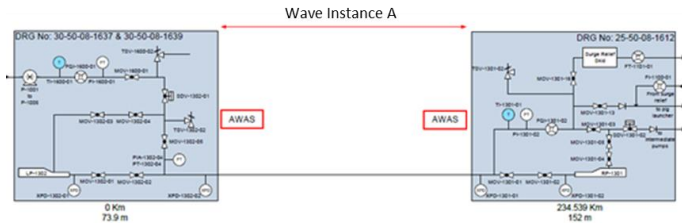


Figure 8 The schematic diagram showing a 48”, 234.5 KM crude oil pipeline monitored as one segment



Figure 9 Leak test results showing the clear pressure responses to two leaks in the 234.5 KM segment

The new negative pressure wave leak detection system has the following key features compared with the traditional technologies:

- Low false alarm rate compared to other negative pressure systems
- Detection of the opening and closing of theft valves (important feature for pipeline theft detection)
- Based on “off the shelf” high performance pressure sensors available in the market place from reputable manufacturers that are more robust and easier to replace than proprietary sensors
- The pressure sensors can also be used for process control and the acquired pressure values can be relayed to the SCADA/DCS

- Leak detection under all operating conditions including shut in and hydrostatic tests
- It can work over a much longer segment between two consecutive pressure sensors.

COMBINING LEAK DETECTION SYSTEMS

The DOT Leak Detection Study report [3] suggests that the reliability will be improved by a combination of technologies – utilizing redundant independent LDS. This option is available for several systems. For Example, significant improvement has been achieved by the deployment of the negative/rarefaction wave leak detection system to compliment the statistical system. For gas networks, the model-based LDS can be used with the statistical volume balance effectively. Other methods such as fiber optic cables are also useful to accelerate the detection time and increase the sensitivity provided by the highly reliable statistical volume balance system.

The DOT report [3] also states that LDS are engineered systems. This means that precisely the same technology, applied to two different pipelines, can have very different results. This reinforces the need to have a team of professional and experienced engineers who understand pipeline operations and having the knowledge to recommend the best solution for each pipeline.

CONCLUSIONS

Although there are many different technologies, none of them meets the requirements of an ideal leak detection system. As shown in this paper, improvements have been made in both the statistical analysis and negative pressure wave technologies. However further research and development will be required to continue reducing the gap between the ideal system and the available technologies.

ACKNOWLEDGMENTS

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NOMENCLATURE

- DCS – distributed control system
- SCADA – supervisory control and data acquisition

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