

Designing a Cost Effective and Reliable Pipeline Leak Detection System

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ATMOS PIPE is a statistical pipeline leak detection system, incorporating advanced pattern recognition functions. Real time applications and field tests show that it is cost effective and has a very low false alarm rate. Leaks with sizes from 0.5% to 55% were detected on liquid propylene, ethylene gas, natural gas and natural gas liquid (NGL) pipelines. In this paper, the performance of the system is reported after the comparison of different leak detection methods.

INTRODUCTION

With increasing public awareness and concern for the environment, recent pipeline leak incidents have shown that the cost to a company can be far more than the downtime and clean up expenses. As more stringent statutory regulations are introduced in the developed countries, cost effective and reliable leak detection systems are in demand.

In this paper various pipeline leak detection methodologies are reviewed. These include biological, hardware-based and software-based methods. Each method has its advantages and disadvantages. To compare the performance of these methods, seven key attributes are defined: **leak sensitivity, location estimate capability, operational change, availability, false alarm rate, maintenance requirement** and **cost**. Unfortunately none of the existing methodologies can offer good performance for all the attributes. A common problem for most of these methods is high false alarm rate, i.e. generating a leak alarm when the pipeline is under normal operation. False alarms are undesirable because

- they generate extra work for operational personnel,
- they reduce the confidence operators have in a system,
- a real leak may be overlooked.

Therefore it is essential to design a cost effective and reliable leak detection system. Such a system has been developed by Shell after intensive research and field tests over several years. The system applies advanced statistical techniques and its trademark is ATMOS PIPE. Examples of real time applications and field tests are presented in this paper.

REVIEW OF LEAK DETECTION METHODS

Different leak detection methods are applied to monitor the integrity of a pipeline (Bose 1993, Carlson 1993, Turner 1991). Broadly speaking they can be classified into three categories (**Figure 1**):

1. Biological methods – Experienced personnel or trained dogs can detect and locate a leak by visual inspection, odour or sound.

2. Hardware-based methods – Different hardware devices are used to assist the detection and localisation of a leak. Typical devices used include acoustic sensors and gas detectors, negative pressure detectors and infrared thermography.
3. Software-based methods – Various computer software packages are used to detect leaks in a pipeline. The complexity and reliability of these packages vary significantly. Examples of these methods are flow/pressure change detection and mass/volume balance, dynamic model-based system and Pressure Point Analysis.

In the following sections, a brief description of the above methods will be given followed by a comparison of their key attributes.

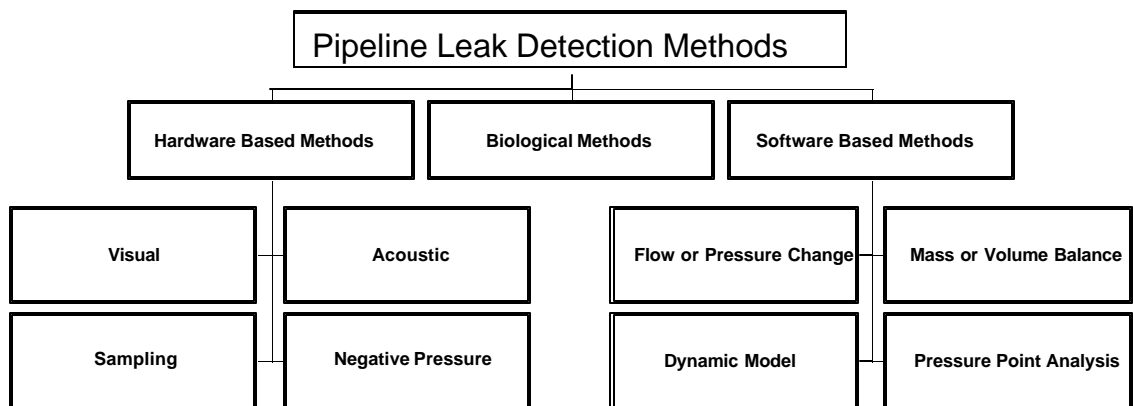


Figure 1 Review of Leak Detection Methods

Biological Methods

A traditional leak detection method is to use experienced personnel who walk along a pipeline, looking for unusual patterns near the pipeline, smelling substances which could be released from the pipeline or listening to noises generated by product escaping from a pipeline hole. The results of such leak detection methods depend on individuals' experience and whether a leak develops before or after the inspection.

An additional leak detection method is to use trained dogs which are sensitive to the smell of substances released from a leak.

Hardware-Based Methods

The hardware-based methods can be divided into four types according to the principles on which the devices are designed:

- Visual devices
- Acoustic devices
- Gas sampling devices
- Pressure wave detectors

Visual devices

Some leaks can be detected through the identification of temperature changes in the immediate surroundings. Infrared thermography was used to detect hot water leaks as the surrounding

temperature increases after a leak develops (Weil 1993). This method can be used from moving vehicles, helicopters or portable systems and is able to cover several miles or hundreds of miles of pipeline per day.

The recent development of advanced wide area temperature sensors makes the temperature profile technique more practical. Temperature sensors such as multi-sensor electrical cable and optical time domain reflectometry using fibre optic cables are used to detect changes of temperature in the neighbourhood of a leak (Turner 1991).

Ground penetrating radar (GPR) uses a radar transmitter and receiver to accurately pinpoint buried pipeline leaks without digging. The leaking substances can be 'seen' at the source by the radar via the changes in the surrounding soil's electrical parameters. A 'colorgraphic' data format then displays the leak (Graf 1990, Hennigar 1993).

Acoustic devices

When a leak occurs, noise will be generated as the fluid escapes from the pipeline. The wave of the noise propagates with a speed determined by the physical properties of the fluid in the pipeline. The acoustic detectors detect these waves and consequently the leaks (Hough 1988, Klein 1993, Kurmer 1993, Turner 1991).

Due to the limitation of the detection range, it is usually necessary to install many sensors along the line. These sensors detect acoustic signals in the pipeline and discriminate leak sounds from other sounds generated by normal operational changes.

Sampling devices

If the product inside a pipeline is highly volatile, a vapour monitoring system can be used to detect the level of hydrocarbon vapour in the pipeline surroundings. This is usually done through gas sampling (Sperl 1991).

The sampling can be done by carrying the device along a pipeline or using a sensor tube buried in parallel to the pipeline. The response time of the detection system is usually from several hours to days. For application to offshore pipelines, a hydrocarbon detector can be used with a ROV (remotely operated vehicle) with swimming and sea bed crawling capacity. Pipeline leaks result in hydrocarbon anomalies in surrounding sediments and sea water, which can then be detected by the hydrocarbon detector.

Negative pressure

When a leak occurs a rarefaction wave is produced in the pipeline contents. The wave propagates both upstream and downstream from the leak site. The wave travels with speed equal to the speed of sound in the pipeline contents. Pressure transducers can be used to measure pressure gradient with respect to time (Turner 1991). Usually two sensors are used for each pipeline segment to help discriminate between noise and externally caused pressure drops.

Software-Based Methods

Software-based methods use flow, pressure, temperature and other data provided by a SCADA (Supervisory Control And Data Acquisition) system (Bose 1993, Turner 1991), they can be divided into four types:

- Flow or pressure change
- Mass or volume balance
- Dynamic model based system
- Pressure Point Analysis

Flow or pressure change

This technique relies on the assumption that a high rate of change of flow or pressure at the inlet or outlet indicates the occurrence of a leak. If the flow or pressure rate of change is higher than a predefined figure within a specific time period, then a leak alarm is generated (Mears 1993).

Mass or volume balance

If the difference between an upstream and down stream flow measurement changes by more than an established tolerance, a leak alarm will be generated. This method allows the detection of a leak which does not necessarily generate a high rate of change in pressure or flow. The methods can be based on flow difference only which would generate a simple mass or volume balance scheme or on flow difference compensated by pressure/temperature changes and inventory fluctuations in a pipeline (Liou 1993, Parry 1992).

Dynamic model based system

In its various forms this technique attempts to mathematically model the fluid flow within a pipeline. Leaks are detected based on discrepancies between calculated and measured values (Griebenow 1988, Hamande 1995, Liou 1994, Mears 1993).

The equations used to model the fluid flow are:

- Conservation of mass
- Conservation of momentum
- Conservation of energy
- Equation of state for the fluid.

The partial differential equations are solved by a variety of computational techniques, depending on the choices of suppliers. The alternative methods currently in use in commercial software packages include:

- Finite difference
- Finite element
- Method of characteristics
- Frequency response/spatial discretisation.

The method requires flow, pressure, temperature measurements at the inlet and outlet of a pipeline, ideally also pressure/temperature measurements at several points along the pipeline.

Pressure Point Analysis (PPA)

This method is based on the assumption that if a leak occurs in a pipeline, the pressure in the line drops. Using simple statistical analysis of the pressure measurements, a decrease in the mean value of a pressure measurement is detected. If the decrease is more than a predefined level, then a leak alarm is generated.

Comparison of Key Attributes of Different Methods

Each leak detection method has its advantages and disadvantages. To compare the performance of different methods, it is necessary to define the key attributes of a leak detection system:

1. **Leak sensitivity** — Can small leaks be detected?
2. **Location estimate capability** — Is location estimate given?
3. **Operational change** — Can the method work if pipeline experiences operational changes e.g. throughput change, pigging?
4. **Availability** — Can the method monitor a pipeline continuously i.e. 24 hours a day?
5. **False alarm rate** — Frequency of leak alarms generated during leak-free operations.
6. **Maintenance requirement** — Level of technical expertise required to maintain the system.
7. **Cost** — Capital expenditure (CAPEX) and on going operating costs (OPEX).

Based on these definitions, **Table 1** shows the comparison of the above methods.

Table 1 The Key Attributes of Leak Detection Techniques #

Method	Leak sensitivity	Location estimate	Operational change	Availability	False alarm	Maintenance requirement	Cost
biological	YES	YES	YES	NO	LOW	MEDIUM	HIGH
visual	YES	YES	YES	NO	MEDIUM	MEDIUM	HIGH
acoustic	YES	YES	NO	YES	HIGH	MEDIUM	MEDIUM
sampling	YES	YES	YES	NO	LOW	MEDIUM	HIGH
negative pressure	YES	YES	NO	YES	HIGH	MEDIUM	MEDIUM
flow change	NO	NO	NO	YES	HIGH	LOW	LOW
mass balance	NO	NO	NO	YES	HIGH	LOW	LOW
dynamic model	YES	YES	YES	YES	HIGH	HIGH	HIGH
PPA	YES	NO	NO	YES	HIGH	MEDIUM	MEDIUM

The attributes are rated as follows:

YES – good

LOW – good

NO – not good

MEDIUM – average

HIGH – not good

Note that the above attributes are common features of the leak detection methods. In practice the performance of each method varies considerably depending on the vendors, pipeline operating conditions and quality of the hardware/instrumentation system available.

Examination of **Table 1** shows that there is no method which is rated “good” for all the attributes. In particular **false alarm** appears to be a common problem for all the techniques except the biological and sampling methods, which cannot monitor a pipeline continuously.

Comparison of the four software based methods show that

- Flow change, mass or volume balance and Pressure Point Analysis methods are easy to maintain and inexpensive to install but they cannot estimate leak location and are not suitable for pipelines with operational changes.
- Dynamic model-based method works during operational changes and can provide location estimate but it requires a high level of expertise to maintain and is expensive to install.

To overcome the deficiencies of the above systems, research and development have been carried out to design a reliable and cost effective leak detection system. The result of this development work is a statistical pipeline leak detection system — ATMOS PIPE

ATMOS PIPE TECHNOLOGY

ATMOS PIPE is a statistical pipeline leak detection system, incorporating advanced pattern recognition functions. It has been developed at Shell applying advanced statistical techniques to flow and pressure measurements of a pipeline. Variations generated by operational changes are registered and a leak alarm is generated only when a unique pattern of changes in flow and pressure exists (Zhang, 1993).

This statistical method does not use mathematical models to calculate flow or pressure in a pipeline but it detects changes in the relationship between flow and pressure using measurement data available. As the system monitors a pipeline continuously it learns about continual changes in the line and flow/pressure instruments.

An optimum sequential analysis technique (Sequential Probability Ratio Test) is applied to detect changes in the overall behaviour of the inlet and outlet flow and pressure. It works based on the observation that although the control and operation may vary from one pipeline to another, the relationship between the pipeline pressure and flow will always change after a leak develops in a pipeline. For example a leak could cause the pipeline pressure to decrease and introduce a discrepancy between the inlet and outlet flow-rate. This leak detection system is designed to detect such changes i.e. pattern recognition.

Field tests and real-time applications show that ATMOS PIPE is superior to the above methods. Some examples of the field tests are given below.

Liquefied Propylene Pipeline

Two 4" diameter, 37 kilometre long liquefied propylene pipelines (line A and B) run in parallel through a hilly area. The initial leak detection system was implemented in 1991 for line A only. In the summer of 1992 due to pipeline maintenance and pigging, line B was commissioned to transport propylene as well. Investigations showed that the system designed for line A was readily applicable to line B. Therefore with little effort the system was tailored to monitor either or both of the lines, including switching from one line to the other. Such flexibility has proven to be a major advantage of the system, compared with the conventional model-based systems. Significant time and money were saved by applying the Shell system to these pipelines.

Pipeline operational changes take place continuously as a result of upstream plant variations. As shown in **Figure 2** and **Figure 3**, both the inlet and outlet flow fluctuate significantly and the difference between them is non-zero. However no false alarm is generated by such operational changes or discrepancy between the instruments. Over the past 5 years of operation, a number of changes have

been introduced in both the plant and pipeline operation e.g. throughput increase by maximising the upstream plant production, pigging, but the system has been running satisfactorily without any modification or false alarm.

Leaks with sizes from 0.5% to 9.3% were generated during field tests. The tests show that as the leak size increases, both the detection time and localisation error decrease exponentially (**Figure 4** and **Figure 5**).

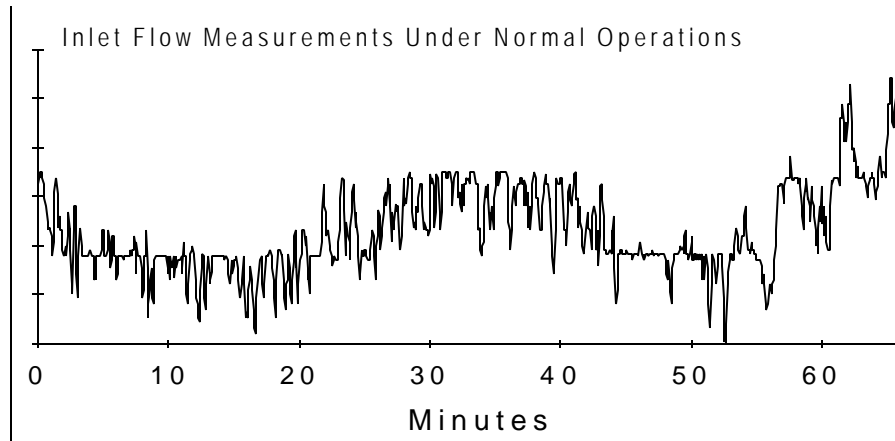


FIGURE 2 - AN EXAMPLE OF INLET FLOW MEASUREMENT UNDER NORMAL PIPELINE OPERATIONS

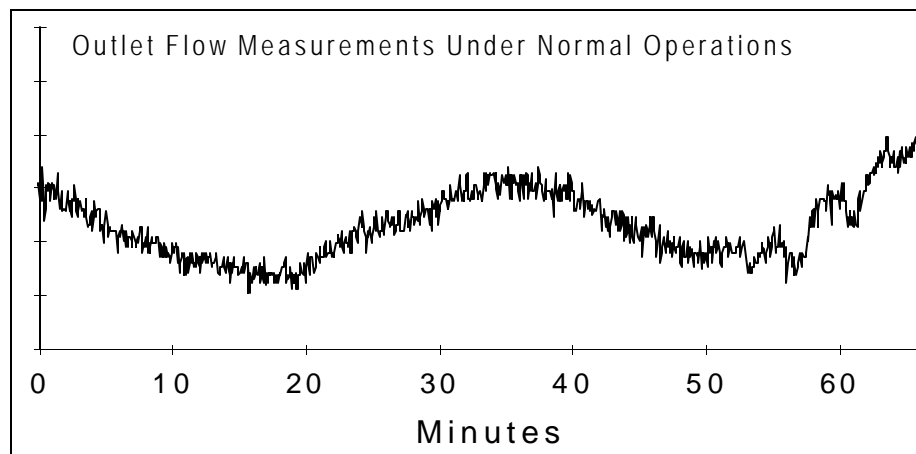


FIGURE 3 - THE OUTLET FLOW MEASUREMENT CORRESPONDING TO THE INLET FLOW IN FIGURE 2

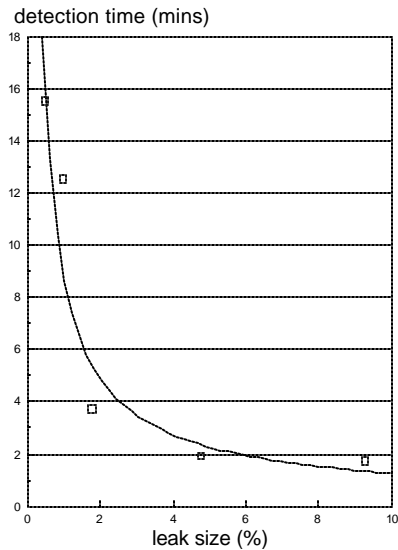


FIGURE 4 - LEAK DETECTION TIME AGAINST LEAK SIZE FOR PROPYLENE PIPELINES

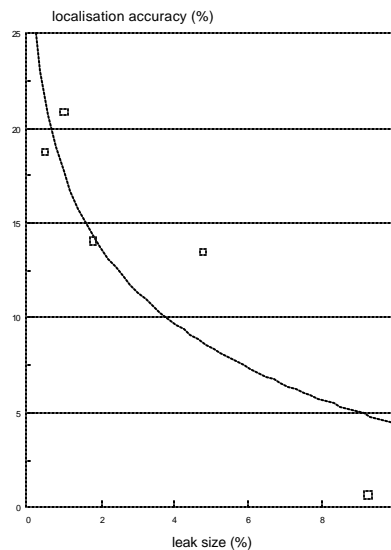


FIGURE 5 - LOCALISATION ACCURACY AGAINST LEAK SIZE FOR PROPYLENE PIPELINES

Low Pressure Ethylene Pipeline Grid

The leak detection system was installed on the low pressure ethylene pipeline grid with diameters of 6”/8” and a total length of 40 kilometres. It was the first time the system was applied to a pipeline network. There are two possible suppliers to the pipeline and ethylene can be taken out of the line at two delivery points.

A number of controlled leaks have been generated on purpose to test the system since its installation. The minimum leak generated was 3% of the total throughput in the pipeline and was detected in 3 hours.

Note that this application was carried out without updating the old instrumentation system and the only additional equipment was a personal computer. Flow and pressure meters were available at the supply and delivery points but they were of poor quality. For example, the resolution of the pressure meter at supply 1 was 0.5 bar (**Figure 6**). Such low resolution did decrease the sensitivity of the system and hence leaks lower than 3% were not created during the tests.

Frequent operational changes took place in the pipeline and usually there was no ‘steady state’ operation. As an example, **Figure 6** and **Figure 7** show the flow and pressure measurements over an 18 hour period. No false alarm is generated during such operating conditions.

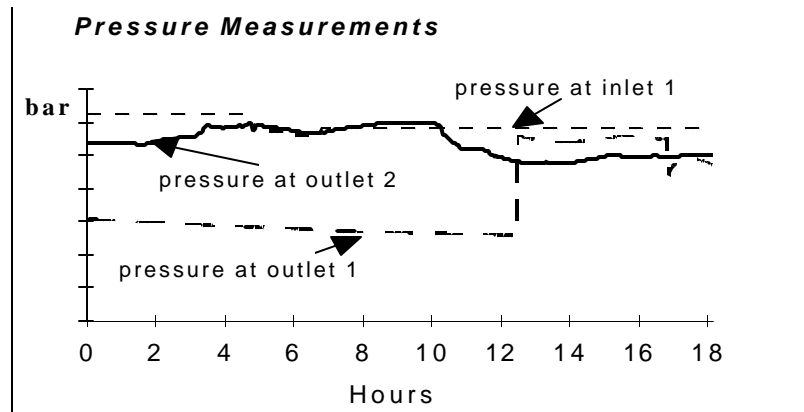


Figure 6 Pressure measurements during normal pipeline OPERATING CONDITIONS

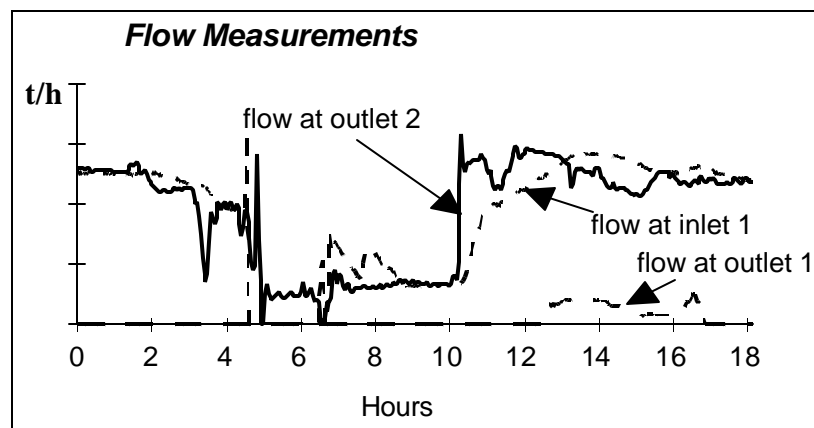


FIGURE 7 FLOW MEASUREMENTS DURING NORMAL PIPELINE OPERATING CONDITIONS

Sour Gas Pipeline

The system implemented on the sour gas pipeline was intended for field tests only. The total pipeline length is 73 km and the line diameter is 18". In addition to the pressure and flow measurements at the inlet and outlet of the pipeline, pressure measurements are available at the five valve stations along the pipeline.

During the field tests, ten leaks were generated at two locations: 45 and 60 km from the inlet. The minimum leak generated was 0.7% of the throughput and the maximum detection time was two hours. The system was successful in detecting all the leaks and the leak size estimate was satisfactory. The field tests illustrate that only marginal changes occur in the detection time as the leak location changes from 45 to 60 kilometre.

Natural Gas Liquid Pipeline

A study was carried out for a natural gas liquid pipeline. The pipeline is 220 kilometre long with a diameter of 22 inches. In total, 107 days of pipeline operating data were collected including flow and pressure at the inlet, outlet and pressure at 21 valve stations along the line. During the data collection period, ten leaks were generated with sizes ranged from 0.5 to 1.7 kg/s. The leaks were generated at different sites: inlet end, outlet end and middle of the line.

From the collected data, it can be seen that the pipeline experiences a lot of operational changes. **Figure 8** illustrates that although the flow has changed by more than 20% between 18:00 and 21:00 hour, the corrected mass imbalance term has a relatively constant mean as a result of the inventory change corrections.

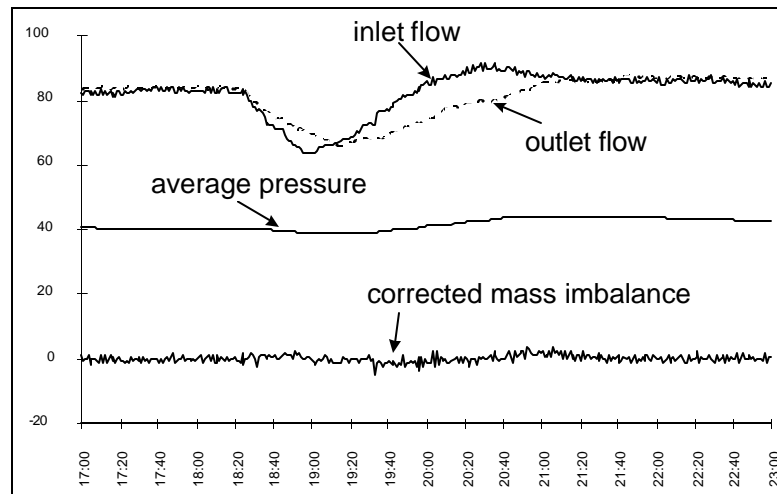


FIGURE 8 - THE CORRECTED MASS IMBALANCE DERIVED FROM FLOW AND PRESSURE MEASUREMENTS

The test of ATMOS PIPE on the 107 days' data demonstrates that the system can detect leaks greater than 1.6 kg/s without generating false alarms. The main conclusions of the study are:

1. The same leak detection results have been achieved with or without any intermediate measurements between the inlet and the outlet. Significant reduction in capital investment and maintenance costs is expected by reducing the number of instruments required.
2. It is not realistic to detect leaks lower than 1 kg/s without false alarms, due to the relatively low repeatability of the existing instruments.
3. It is more cost effective to install high quality flow and pressure instruments at the inlet and outlet only than having poor quality instruments at all valve stations as well as at the inlet and outlet.

CONCLUSIONS

Statutory regulation demands that automated leak detection systems are installed for new and upgraded pipelines. To design a cost effective system, it is necessary to improve the performance of existing techniques. Intensive research and development at Shell have produced a novel statistical leak detection system, which is marketed as ATMOS PIPE. Operational experience and a number of field tests illustrate that this new technology is cost efficient in terms of capital investment (CAPEX) and operating costs (OPEX), it is reliable to run and requires a low level of expertise for maintenance.

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