

DESCRIPTION OF ATMOS PIPE LEAK DETECTION SYSTEM

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TABLE OF CONTENTS

1	INTRODUCTION	2
2	DATA VALIDATION	2
3	DESCRIPTION OF LEAK DETECTION SYSTEM.....	3
3.1	LEAK DETECTION UNDER LOW AND NORMAL FLOWING CONDITIONS	3
3.2	LEAK DETECTION UNDER TRANSIENT & SLACK FLOWING CONDITIONS	6
3.3	MATHEMATICAL DESCRIPTION OF LEAK DETECTION UNDER LOW, SLACK, NORMAL AND TRANSIENT FLOWING CONDITIONS	9
3.4	DESCRIPTION OF STATIC LEAK DETECTION.....	10
4	INSTRUMENTATION REQUIREMENTS FOR LEAK DETECTION	11
5	PERFORMANCE EXPECTATIONS	12
6	TRAINING.....	16
7	TESTING	16

1 INTRODUCTION

ATMOS pipe, is a pipeline leak detection software developed by Shell to reduce false alarms while maintaining sensitivity and accuracy. ATMOS is successfully used by SHELL, BP-AMOCO, ESSO, DOW and the UK Ministry of Defence among others. ATMOS pipe is a statistical based leak detection software that has been applied to oil, gas, chemical and product pipelines successfully. It is also one of the most tested leak detection systems in the world, and has detected more than 100 leaks during leak trials.

ATMOS pipe works in a Personal Computer, it gets flow and pressure data from the field instruments via PLC (Programmable Logic Controller), RTU (Remote Terminal Unit), SCADA (Supervisory Control And Data Acquisition) or DCS (Distributed Control) system. Once installed it monitors a pipeline continuously and will generate a leak alarm whenever a leak develops. ATMOS does not generate false alarms and remain operational during transients, it is the most reliable system in the market.

The track record of ATMOS PIPE on the crude oil, jet oil, natural gas, propylene and ethylene pipelines has shown that it continues to monitor the pipelines under all kinds of operating conditions. Reverse flow, intermediate pump start/stop, flow stoppage, pipeline restart and throughput increase have all been experienced by ATMOS PIPE and no loss of function has ever occurred.

A detailed description of the system is given in the following sections.

2 DATA VALIDATION

Pipeline data will be acquired from the SCADA system at regular sample intervals e.g. 10 seconds. Before applying the data for leak detection, ATMOS will check whether these data are valid. Typical instrument faults will be detected, for example, outlier, frozen point and out of transmitter range.

Should a data be found “invalid”, it will be replaced by the most recent “good” measurement or calculated using redundancy provided by other measurement data. In the meantime, an instrument fault alarm will be displayed to inform the operators of the fault type and the faulty instrument tag number. **No false leak alarm will be generated due to the instrument failures.**

Note that not all instrument faults can be detected. However ATMOS PIPE can learn about errors generated by instrument inaccuracies and remove these errors in the software algorithms.

3 DESCRIPTION OF LEAK DETECTION SYSTEM

3.1 LEAK DETECTION UNDER LOW AND NORMAL FLOWING CONDITIONS

AtmosPipe™ is unique as it applies three leak detection methods simultaneously (**Figure 3.1**):

- Modified volume balance
- Pressure and flow monitoring
- Statistical analysis.

The use of the above methods, combined with a comprehensive data validation procedure and a rigorous decision making mechanism, makes AtmosPipe™ the most reliable yet sensitive leak detection system in the world.

Since the modified volume balance is used for statistical calculations, the system performance does not depend on the actual flow-rate in the pipeline. The repeatability of the flow meters will determine the minimum leak detectable without false alarms during both low and normal flowing conditions.

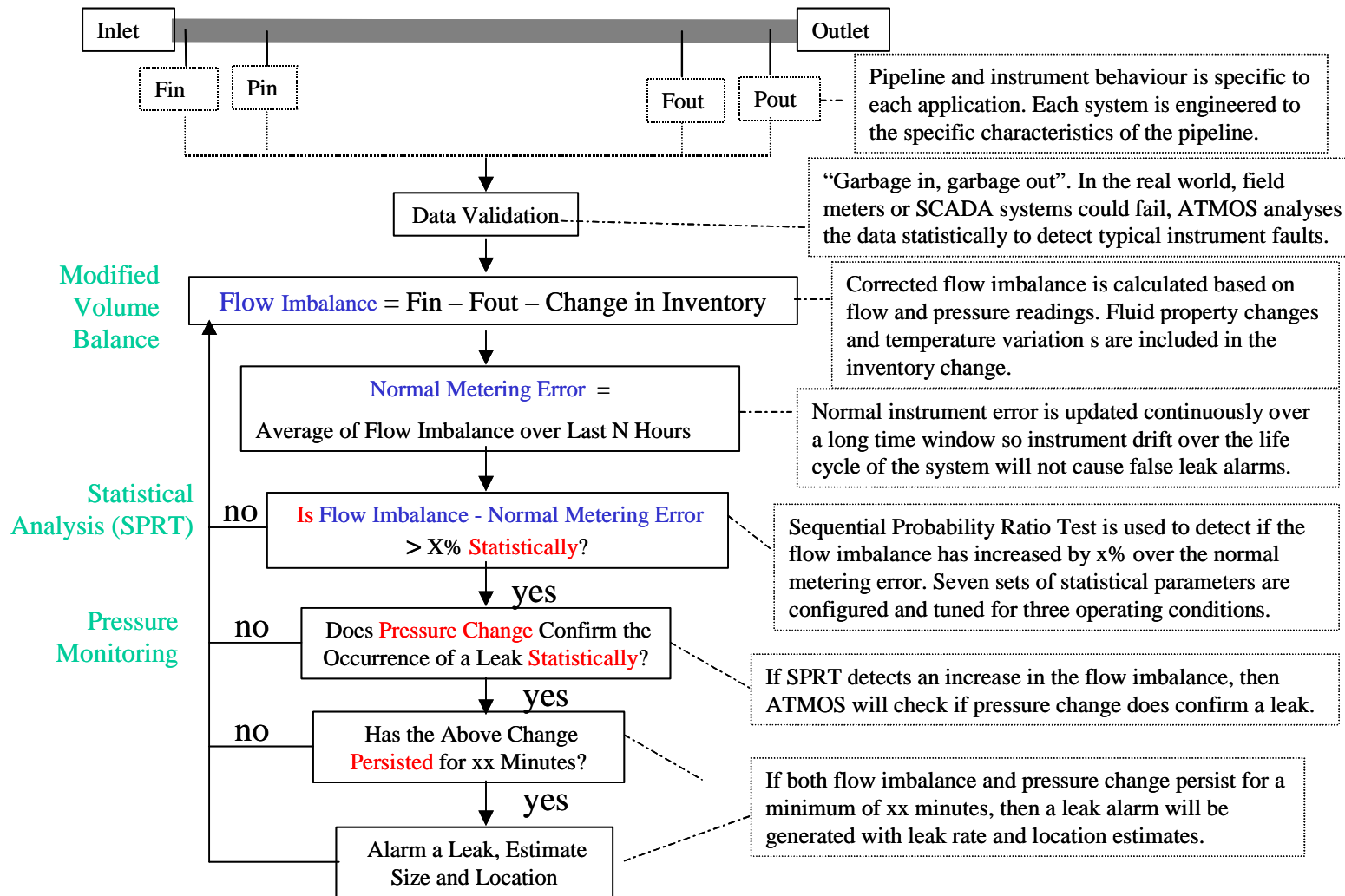


Figure 3.1: Why AtmosPipe™ is more sensitive, yet generates far less false alarms

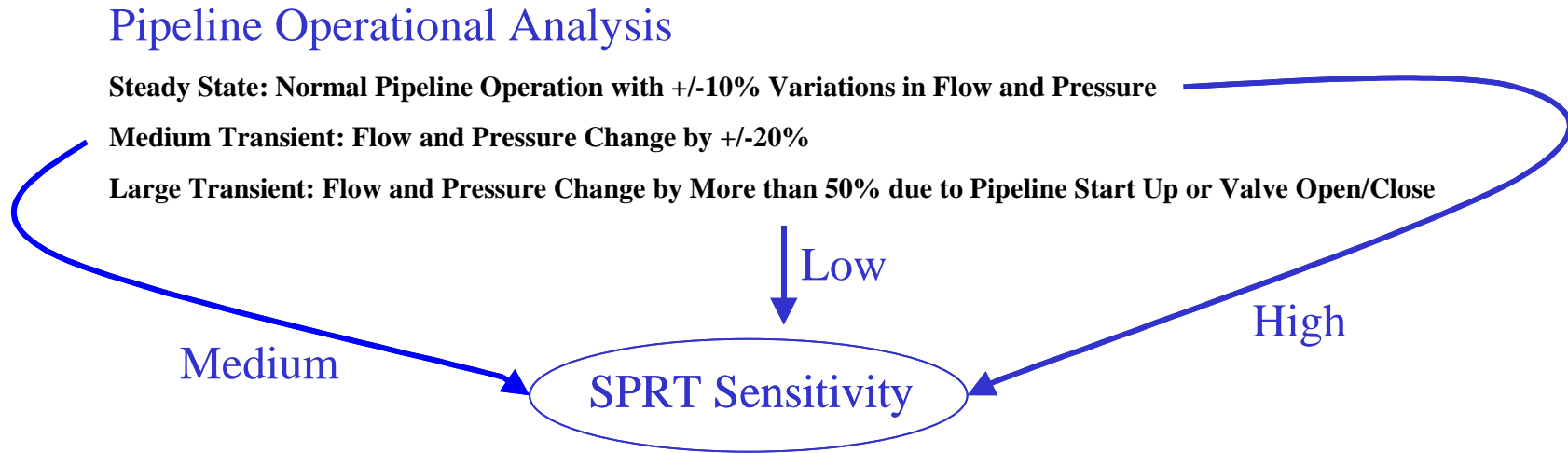


Figure 3.2: Automatic Tuning of System Sensitivity to Pipeline Operating Conditions

3.2 LEAK DETECTION UNDER TRANSIENT & SLACK FLOWING CONDITIONS

Figure 3.2 shows how ATMOS PIPE adapts itself to pipeline operating conditions. The statistical parameters will be tuned so that **no false alarm** is generated when pumps stop/start and valves open/close. Since the system is de-sensitised during transient (non-steady state) operating conditions, it takes longer for a leak to be detected if it occurs during transient conditions. However the system sensitivity will be increased automatically as soon as the pipeline returns to normal operating conditions.

If a leak occurs where there is **slack flow**, initially the effect of the leak may be masked by vapour formation and the pressure upstream and downstream of the leak would not decrease as much as in a normal flow situation. However the loss of containment will eventually be reflected by the flow imbalance between the flow meters immediately upstream and downstream of the leak. Therefore the leak will be detected by ATMOS Pipe in the same way as under normal flow conditions although the detection time may be a couple of minutes longer.

The system above proved to be successful in eliminating false alarms during transients while monitoring pipelines for leaks effectively. Figure 3.3 and 3.4 shows pressure and flow measurements of a pump start up in a 36” crude oil pipeline. Figure 3.5 shows the corresponding ATMOS response and absence of leak alarms during this transient event.

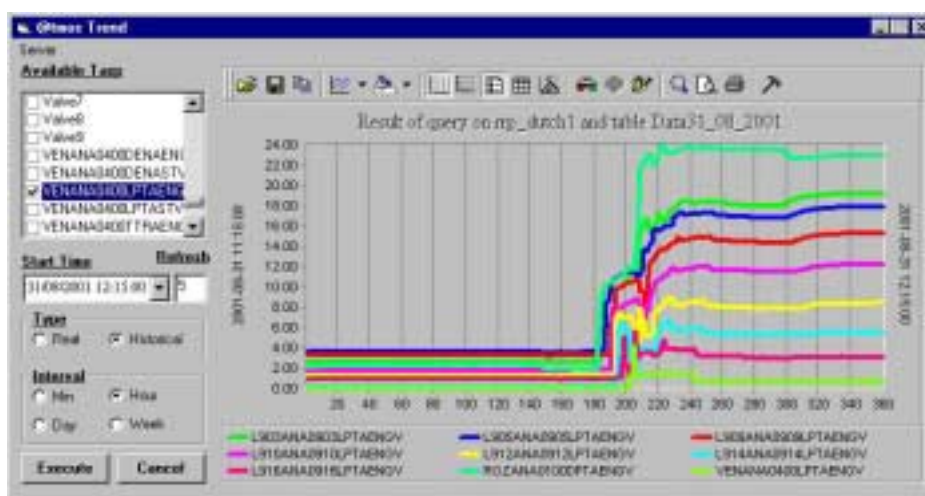


Figure 3.3: Pressure readings during a pump start-up on a 36” crude oil pipeline.

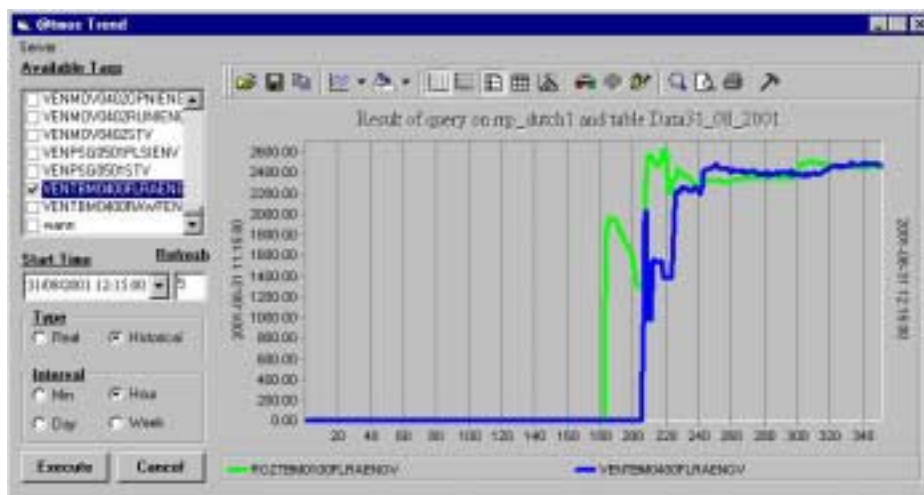


Figure 3.4: Associated flow meter readings during the pump start-up as shown in Figure 3.3

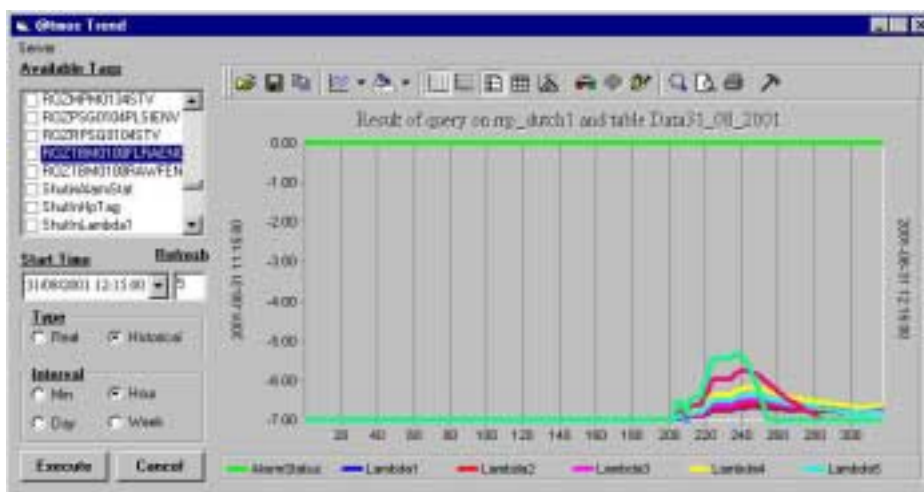


Figure 3.5: Associated statistical parameters (Lambda's) and Alarm Status during the PUMP START-UP as shown in Figure 3.3 and 3.4. The variation in Lambda's values shows ATMOS IS MONITORING for leaks continuously while the constant zero value of the Alarm Status shows the ABSENCE OF FALSE ALARMS.

Figures 3.6 and 3.7 show further evidence of ATMOS in distinguishing transients from leaks. At 14:02 hours ATMOS detected a leak after severe transients during tests on a multi-product line.



Figure 3.6 : Display of Flow x Time values during a leak trial. **The position in time (14:02:27) of the leak is shown by the white line at the centre of the graph.**

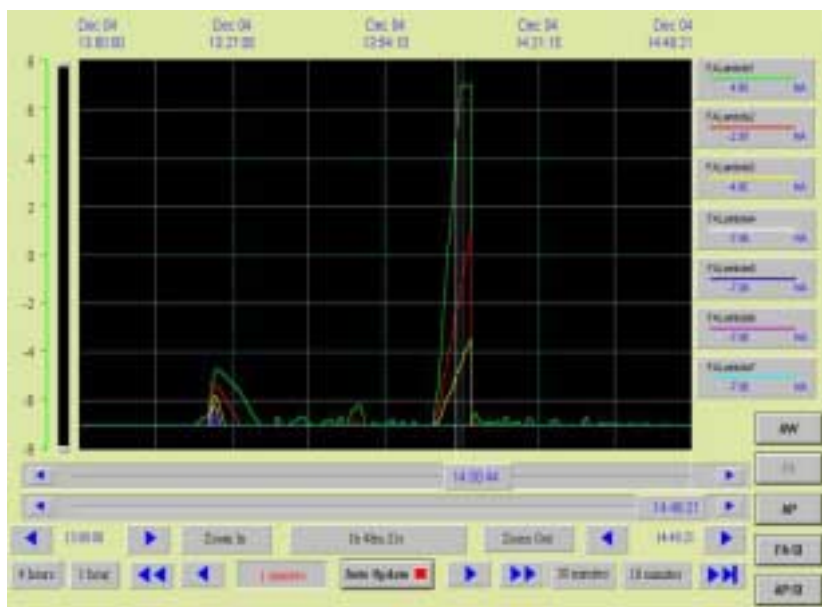


Figure 3.7: Corresponding Lambdas x Time display showing the calculation of the probability of the existence of a leak during the transient (Negative Lambda and therefore **no Alarm during the transient**). During the leak event the Lambda values show a steep rise to positive values triggering a **Leak Alarm** at time 14:06:44.

3.3 MATHEMATICAL DESCRIPTION OF LEAK DETECTION UNDER LOW, SLACK, NORMAL AND TRANSIENT FLOWING CONDITIONS

ATMOS PIPE applies statistical techniques to detect changes in the overall behaviour of flow and pressure at the ingress and egress points. 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 ingress and egress flow-rate. The leak detection system is designed to detect such changes i.e. pattern recognition.

Leak determination is based on probability calculations at regular sample intervals. The basic principle used for the probability calculations is mass conservation and hypothesis testing: leak against no-leak. Although the flow and pressure in a pipeline fluctuate due to operational changes, statistically the total mass entering and leaving a network must be balanced by the inventory variation inside the network. Such a balance cannot be maintained if a leak occurs in a network. The deviation from the established balance is detected by an optimal statistical test method - Sequential Probability Ratio Test (SPRT).

The combination of the probability calculations and pattern recognition provides ATMOS with a very high level of system reliability i.e. minimum spurious alarm.

Under leak-free operations, the mass balance principle determines that the difference between the ingress and egress flow-rate should be equal to the inventory variation in a pipeline. Therefore the following term is calculated:

$$\tau(t) = \sum_1^M Q_i(t) - \sum_1^N Q_o(t) - \sum_1^L \Delta Q_j(t) \quad (1)$$

where $\tau(t)$ is called the corrected mass imbalance term at time t . In practice $\tau(t)$ usually fluctuates around a non-zero value due to the inherent differences in the instruments and fluid compressibility.

$Q_i(t)$ represents the flow measurement at the ingress points and $Q_o(t)$ at the egress points. M is the number of ingress points, N the number of egress points and L is the number of pipeline sections.

$\Delta Q_j(t)$ is a correction term for the inventory variation over the sample period of $t-1$ to t . $\Delta Q_j(t)$ is a function of pressure and temperature in the pipeline, different product properties in the pipeline will introduce changes in the inventory calculations. The mean value of the above process $\tau(t)$ remains unchanged unless a leak develops in a pipeline or an instrument error occurs. The distinction between these two failure modes has to be made by further analysis, e.g. instrument change pattern identification. ATMOS PIPE can identify typical instrument faults thus informing operators of possible faulty instruments.

To detect leaks efficiently with a low false alarm rate, SPRT will be used to decide between the leak-free and leak-present hypothesis, e.g.

$$H_0: \tau(t) \text{ is gaussian with mean } m \text{ and variance } \sigma^2$$

H_1 : $\tau(t)$ is gaussian with mean $m+\Delta m$ and variance σ^2

where m represents the mean value of $\tau(t)$ under normal (leak-free) operations and Δm is a parameter determined by the leak size to be detected. To take into account of instrument drifts over time, m is tuned slowly using measurements available during a no leak alarm period. The value σ^2 depends on the fluctuations of the flow and pressure signals in a pipeline. For changing operating conditions in the pipeline, different values of σ^2 will be used. Usually three operating modes are identified automatically in a pipeline:

- Steady state operation, operating status = 0,
- Medium operational change, operating status = 1,
- Large operational change, operating status = 2.

After a large operational change, it will take longer for ATMOS to detect a leak than during steady state operations. The choice of the different σ^2 values is determined to achieve maximum system reliability, without loss of leak detection functionality.

The SPRT for testing hypothesis H_1 against H_0 is transformed to the calculation of the following cumulative sum:

$$\lambda(t) = \lambda(t-1) + \frac{\Delta m}{\sigma^2} \left(\tau(t) - m - \frac{\Delta m}{2} \right) \quad (2)$$

By comparing the on-line calculated value $\lambda(t)$ with a pre-set threshold value, a leak alarm can be generated.

The above scheme will be implemented using operational data provided by the Client, in order to optimise the performance of the system. Parameter tuning will be carried out both during the design stage and after the initial installation.

After a leak is detected, the leak rate is estimated by subtracting the on-line updated value m from the average value of $\tau(t)$ shown in equation (1).

One key feature of ATMOS PIPE is that it has learning capability, e.g. operational changes introduced after the installation will be used to further tune the system and gradual instrument drift is incorporated for eliminating false alarms. The reliability of the system will improve after it has the opportunity to experience different operational changes: start up, shut down, valve opening.

3.4 DESCRIPTION OF STATIC LEAK DETECTION

The principle of leak detection during static operations (the pipeline is shut-in) is similar to that used for dynamic leak detection. The main differences in the static leak detection algorithm are:

- The corrected flow difference term shown in equation (1) is reduced to the following form:

$$\tau(t) = -\Delta Q_j(t) \quad (3)$$

Since each pipeline section will be monitored individually, the above term $\Delta Q_i(t)$ is calculated based on the pressure readings at both ends of the blocked section. Temperature measurements will be used to check whether a reduction in the section pressure is caused by temperature changes in the product (pattern recognition). The relationship between the pressure and temperature during the static conditions will be tuned both during the design stage and after the initial installation.

- After a pipeline is first shut-in, the line pressure decreases quickly as a result of cooling. To avoid spurious alarms, the operational status immediately after the pipeline shut-in will correspond to the large operational change i.e. status = 2 and the corresponding statistical parameter σ^2 value is large. This period is expected to last for approximately one hour.
- The SPRT algorithm will be used to detect pressure drop in the pipeline. Tuning of the statistical parameters will ensure that temperature fluctuations between day and night will not introduce leak alarms.

Changes in temperature between winter and summer will have no effect on the SPRT algorithm as the mean value m is learnt on-line and any slow change will be incorporated automatically.

4 INSTRUMENTATION REQUIREMENTS FOR LEAK DETECTION

Table 4.1 shows typical instrumentation used by ATMOS Pipe to work on most pipelines. At minimum instrumentation level, ATMOS requires that Flow and Pressure meters are installed at all pipeline inlets and outlets.

Table 4.1 Available Instruments Along the Pipeline

	Inlet	Outlet
Pump/Compressor Station	Press, Temp	Press, Temp
Block Valve	Press	-----
Pressure Reduction Station	Press	Press
Pig Launcher/Receiver	Pig Signal (launching and receiving)	

It is assumed that the above field meter signals are sent to a SCADA system at regular sample intervals e.g. 10 seconds.

The recommended instrumentation accuracy and repeatability are given in Table 4.2 although better quality meters will improve the leak detection performance. The overall meter repeatability will determine the minimum leak size detectable without false alarms and meter accuracy will affect the leak location estimates.

Table 4.2 Recommended Instrument Specifications

Instrument	Accuracy	Repeatability
Pressure	0.1%	0.1%
Flow	1%	0.5%
Temperature	1° C	0.5° C

As a statistical system, ATMOS PIPE handles measurement noise effectively and no performance degradation is expected from instrument noise (see **Section 3.3** above).

Note that SCADA and telecommunication system can reduce measurement resolutions if the Analogue to Digital (AD) converters are not selected properly. To maintain a high resolution level, it is recommended to use 12 bit or higher AD converters.

5 PERFORMANCE EXPECTATIONS

ATMOS PIPE is one of the most tested leak detection systems in the world. Unlike a system developed by a software company, ATMOS PIPE was born in **Shell** whose extensive pipeline facility made it possible for different leak tests to be carried out. For example, field tests and real-time applications can be found on the following operational pipelines:

- One 36” diameter, 177 kilometre long crude oil pipeline,
- One 10” diameter, 102 kilometre long jet oil pipeline,
- One 10” diameter, 413 kilometre long ethylene pipeline with an intermediate pump station,
- One 4” diameter, 37 kilometre long liquid propylene pipeline,
- One 6”/8” diameter, 40 kilometre long ethylene gas pipeline,
- One 16” diameter jet fuel distribution network with multiple inlets and outlets.
- One 6” diameter, 33 kilometre long carbon monoxide pipeline network with multiple outlets.

During all the field tests, controlled leaks were created at different locations along the pipelines. These tests were carried out in Shell UK and Shell Netherlands respectively and leaks of sizes ranging from **0.5% to 50%** were all detected by the system.

As demonstrated on the **415 Km** long North West Ethylene Pipeline (NWEP) at **Shell**, ATMOS PIPE has detected a leak of 8 t/h **within 15 minutes** on the 25th March 1998 when a field test was carried out. These tests have shown that ATMOS PIPE is **superior to** the conventional leak detection systems in terms of reliability, leak detection time and maintenance costs.

In April 2000, ATMOS PIPE has detected the following leaks:

- 4% of the throughput in four minutes
- 1% of the throughput in nine minutes

in a 36" and 177 KM long crude oil pipeline in **Rotterdam Rijn Pijpleiding** in the Netherlands. All these leaks were located accurately.

In December 2000, **Esso Petroleum Company Limited** tested ATMOS PIPE on their West London Multi-product Pipeline Network by the generation of 18 controlled leaks. The pipeline network is used to transfer oil products to Heathrow, Gatwick airports and two other customers. It consists of three main segments of varying diameters and has a total length of 218 Kilometres.

The following results have been achieved to the satisfaction of Esso:

1. The smallest leaks detected were 2 m³/h (0.2% of the flow meter range). This took 12 minutes during transient shut-in condition.
2. A 3 m³/h (0.3% of the flow meter range) leak was detected in 61 minutes during transient operating conditions when flow and pressure were varying.
3. The shortest detection time was **1 minute** that was for a shut-in leak of 24 m³/h.

Between June and July 2001, Plantation Pipe Line Company in Atlanta, USA has tested ATMOS Pipe on their 18", 126 mile long product pipeline. The following controlled leaks have been detected by ATMOS Pipe:

1. A 3% leak in 40 minutes following a transient.
2. A 1.7% leak in 60 minutes.
3. A 0.5% leak in 70 minutes.

The 0.5% leak was below Plantation's threshold limit and they were delighted to witness the sensitivity of ATMOS Pipe.

All these tests confirm the excellent track record of ATMOS PIPE, its reputation of being one of the most reliable and sensitive system for real-time pipeline leak detection.

Figure 5.1 shows the leak detection time against leak size during the field test in the 37 km long propylene pipeline. Note that the leak detection time decreases exponentially as the leak size increases.

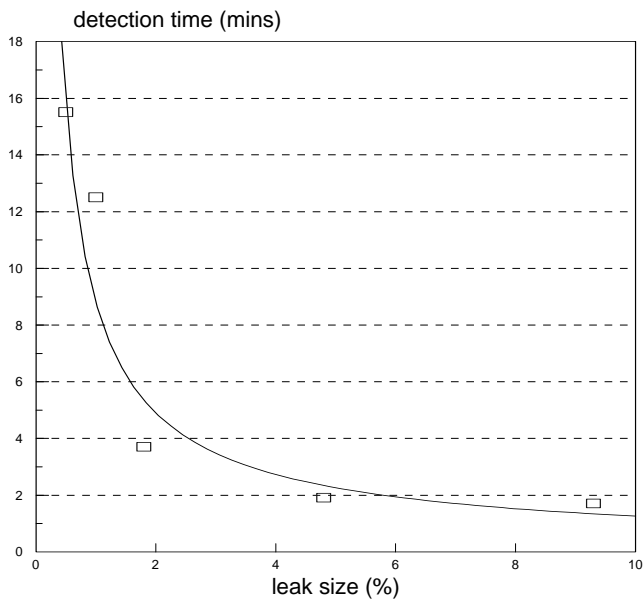


Figure 5.1 - Leak detection time against leak size for a Propylene pipeline

Given the instrumentation system listed in **Table 4.1** and **Table 4.2**, the Typical Performance Expectations of ATMOS Pipe for a crude oil line are shown in **Table 5.1**.

Table 5.1 - Typical Leak Detection Performance for a crude oil pipeline

Performance Metric	SPECIFIC PERFORMANCE CRITERIA	Operating Condition
Sensitivity	Minimum detectable leak rate not to exceed <u>0.5%</u> .	Steady State
	Minimum response time not to exceed <u>2 Minutes</u> .*	Steady State
	Response time not to exceed <u>2 Min</u> for <u>50%</u> leak rate.	Steady State
	Response time not to exceed <u>5 Min</u> for <u>20%</u> leak rate.	Steady State
	Response time not to exceed <u>10 Min</u> for <u>10%</u> leak rate.	Steady State
	Response time not to exceed <u>20 Min</u> for <u>5%</u> leak rate.	Steady State
	Response time not to exceed <u>40 Min</u> for <u>2%</u> leak rate.	Steady State
	Response time not to exceed <u>60 Min</u> for <u>1%</u> leak rate.	Steady State
Reliability	Incorrect leak declarations not to exceed <u>2</u> per year [@] .	Overall
	Incorrect leak declarations not to exceed <u>2</u> per year [@] .	Transient
	Incorrect leak declarations not to exceed <u>0</u> per year [@] .	Steady State
	Incorrect leak declarations not to exceed <u>0</u> per year [@] .	Start up
	Incorrect leak declarations not to exceed <u>0</u> per year [@] .	Shutdown
Robustness	No loss of function due to <u>2</u> pressure outages [#] .	Overall
	No loss of function due to <u>2</u> temperature outages [#] .	Overall
	No loss of function due to <u>0</u> flow measurement outages.	Overall
	No loss of function due to pump state change.	Overall
	No loss of function due to valve state change.	Overall
	Start up stabilisation period not to exceed <u>0</u> minutes ^{\$} .	Overall
Accuracy	Leak location error not to exceed <u>10%</u> of the section length between pressure meters, for leaks greater than <u>20%</u> .	Steady state
	Leak location error not to exceed <u>20%</u> of section length between pressure meters, for leaks greater than <u>10%</u> .	Steady state
	Leak location error not to exceed <u>30%</u> of section length between pressure meters, for leaks greater than <u>5%</u> .	Steady state
	Leak rate error not to exceed <u>1%</u> .	Steady state

Notes :

- * The minimum detection time is determined by the speed of sound in crude and the distance between two pressure meters. The system also allows the statistical factor to confirm a leak before the alarm.
- @ This figure can be achieved only if the instrumentation system has the same or better reliability.
- # Leak detection will be available even if all pressure and temperature meters at block valves are not working.
- \$ In the case of power failure, leak detection will resume as soon as the PC is powered up again.

6 TRAINING

Training courses will be provided for different personnel including operators, engineers and system manager. **Table 6.1** summarises these courses.

Table 6.1 Training Courses for Different Personnel

Course Type	Contents	Skills Required	Duration	Equipment
Two Engineers	Design principle, ATMOS interface, System start/stop, Key parameters, Maintenance, Configuration	Pipeline Operations, Computer Literate, Familiar with Windows Operating System, Basic Statistics	One day	Overhead Projector Computer
Two Operators	Design principle, ATMOS interface, Alarm diagnosis and acknowledgement	Pipeline Operations	One day	Overhead Projector PCS

7 TESTING

The following testing will be carried out during the execution of the project:

- ◇ Interface with SCADA system

It is expected that the interface will be done using OPC protocol. ATMOS Pipe will be OPC Client and SCADA OPC Server. The interface test will test the communication of data between the two systems: pipeline data from SCADA to ATMOS and leak detection results from ATMOS to SCADA.

- ◇ Factory Acceptance Test

The functionality of ATMOS will be tested fully including data validation, leak detection, size and location estimation. Operational data from a similar pipeline will be used for the FAT including leak data.

- ◇ Site Acceptance Test

Site Acceptance Test can be performed after the leak detection system is tuned and commissioned by one of the following methods:

- release of product from pump or valve stations by the use of road tankers or flaring if gas pipelines.
- manipulation of flow and pressure meter readings in the SCADA system to simulate a leak.
- changing ATMOS from real-time to test mode so that historical data with leak test can be re-run.

It is not necessary to perform site tests regularly as the responsiveness of the leak detection system can be observed from the statistical factors that are updated at every sample.