Implementing a Reliable Leak Detection System on a Crude Oil Pipeline

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1. Introduction

Pipeline leak detection or integrity monitoring (PIM) systems have been applied to various operational pipelines. While most of the systems can meet the requirements for detecting leaks within a specified time period, they generate false alarms during normal pipeline operating conditions (API 1995, Mears 1993). Such false alarms reduce the confidence of pipeline operators in these systems and increase their maintenance costs.

The operational experience of the statistical pipeline leak detection system in Shell (Zhang 1993, Zhang 1997) has demonstrated that the system can detect leaks quickly and it does not give nuisance alarms. This statistical system is trade marked as ATMOS PIPE by REL Instrumentation Limited.

To overcome the difficulties of running a dynamic model-based leak detection system, Shell UK Limited has decided to have ATMOS PIPE installed for its crude oil pipeline. After giving some background of the pipeline (Section 2), the implementation of the system will be discussed in Section 3. Section 4 describes the principle of ATMOS PIPE and conclusions are given in Section 5.

2. Pipeline Description

The pipeline is 23 Kilometres in length including chainage and has an average internal diameter of 24”. Variations in diameter occur as the wall thickness changes with geographical location.

Most sections of the pipeline are underground with one section in a tunnel under locks and three sections above ground (**Figure 1**). The pipeline is not insulated and it runs from a tank farm to a refinery.

The pipeline is designed for bi-directional operation and all plant I/O is bi-directional. Crude oil is pumped in either direction in batches. The length of a batch varies between 4 and 20 hours depending on the delivery available. Between the batch transfers, sometimes there are long periods of shut-in when the pipeline is filled with the last batch of crude. Four pumps are used at the inlet and they are started in sequence.

The crude density changes significantly from heavy Arabic crude to the light North Sea oil. In order to facilitate the heavy crude pumping, the oil is heated to reduce viscous friction or it is mixed with lighter crude.

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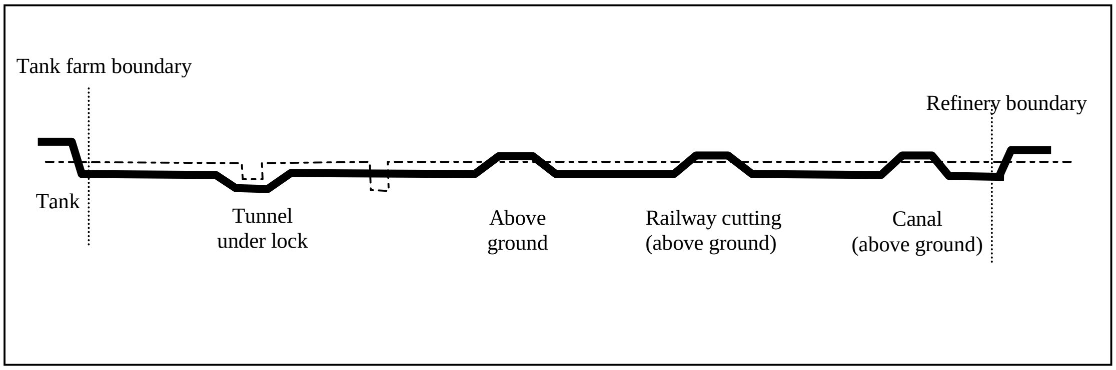


FIGURE 1 A SCHEMATIC DIAGRAM OF THE PIPELINE PROFILE

The following measurements are available at the inlet and outlet of the pipeline:

- Volumetric flow,
- Pressure,
- Temperature and
- Density.

A valve open/close indicator is also provided together with a flow direction indicator at each end.

The field data are collected by dual DEC MicroVAX Computers, through a number of Remote Terminal Units (RTU) and a Microwave communication system. Since the instrumentation system was set up for the application of a dynamic model-based system to pipeline integrity monitoring (PIM) in 1991, the data were collected at 2 second intervals. Over the period 1995 and 1996, Shell experienced a lot of operational problems with the existing PIM system. For example, frequent false alarms were generated during pump start/stop and other transient periods. The VAX Computer also crashed sometimes.

After trouble shooting with the existing PIM for several months, no satisfactory result has been achieved. Therefore Shell decided to have an additional PIM system installed and ATMOS PIPE was chosen in 1997.

3. Implementation of ATMOS PIPE

3.1 System Installation

As shown in **Figure 2**, ATMOS PIPE can be installed in a Personal Computer (PC), which communicates with the existing VAX machine. Since the instrumentation system was already in place, the only additional hardware required was a PC and the cost to Shell was minimal.

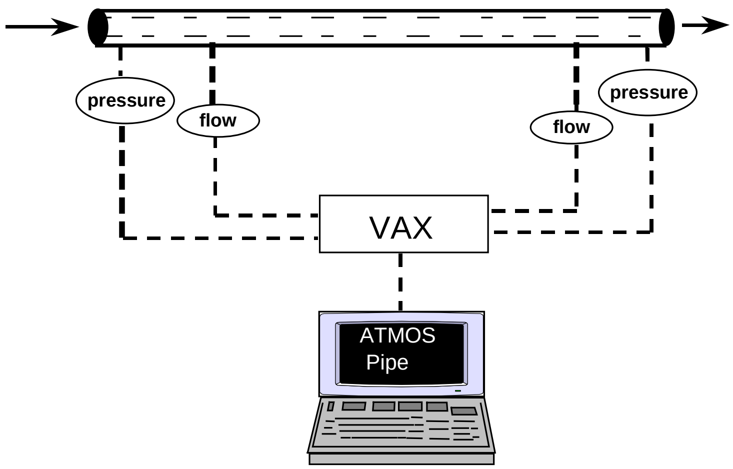


FIGURE 2 INSTALLATION REQUIREMENTS

ATMOS PIPE was installed without any disruption to the pipeline operation or instrumentation system. A software interface was designed to allow ATMOS to read data from the VAX computer. Although data was available at 2-second intervals, a scan rate of 5 seconds was chosen for ATMOS. It was not necessary to sample at the faster rate since the pipeline dynamics were slow.

Figure 3 shows the layout of the system. Since the existing equipment was already a few years old and it did not have any spare capacity for additional trending or alarm, new facilities would be provided together with ATMOS PIPE.

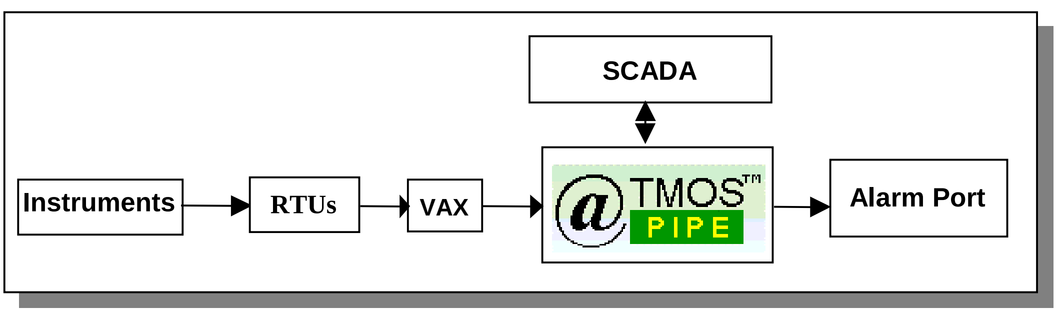


FIGURE 3 THE INTERFACE BETWEEN ATMOS AND OTHER SYSTEMS

ATMOS PIPE runs in a PC with Windows NT operating system and a SCADA system and a digital card have been installed in the same PC. The SCADA is used for trends and user interface and the digital card for generating audible alarms in the control room.

In trying to reduce the cost to the client and install ATMOS within the existing instrumentation environment, ATMOS had to interface with three separate systems:

- VAX computer,
- PC SCADA and
- Alarm port.

These interfaces were written based on the information provided by the individual suppliers. Significant project time has been consumed in making them work due to the following reasons:

1. Both the SCADA and the digital card suppliers have recently changed from Windows 3.1 to Windlows NT. The products were experiencing teething problems.
2. The SCADA software was not robust and it had quite a few outstanding bugs.
3. The software supplied for the digital card was not the correct version.
4. The VAX computer was loaded heavily, hence the communication between the PC and the VAX takes longer than expected.

Note that interfacing with different software and equipment is a common practice in the oil and gas industry as most of them were installed for a long working life and upgrading frequently is costly and unnecessary. Unfortunately the continuous change in the PC and software does make it difficult for system integrators to bring all the data together. The time and effort involved for such integration are often underestimated.

3.2 Parameter Tuning

To achieve a reliable and sensitive leak detection system, the statistical parameters are tuned based on normal operational data over a one year period. The tuning criteria used are as follows:

4. ATMOS will detect leaks of given sizes within the specified time limits.
5. No false alarm should be generated during the one year operation period.

The main tuning parameters include:

- Filter length and threshold values for data validation,
- Leak sizes to be detected and the corresponding variance values,
- Conditions for detecting pipeline transients automatically and setting the operating mode to “steady state”, “medium transient” and “large transient”.

Since the system is designed and tuned for this particular pipeline, it learns about its pipeline operation and instrument performance specifically. No assumption has been made about the pipeline and once installed the system continues to learn about the pipeline e.g. an increase in the friction. This on-line learning capability is very important as pipeline operation always changes and instrument drift could occur over a long time period.

The data validation function of ATMOS is an essential part of the system because in the real world the data collected by the instrumentation system is rarely perfect. For example, **Figure 4** and **Figure 5** show the inlet and outlet flow measurements over a period of

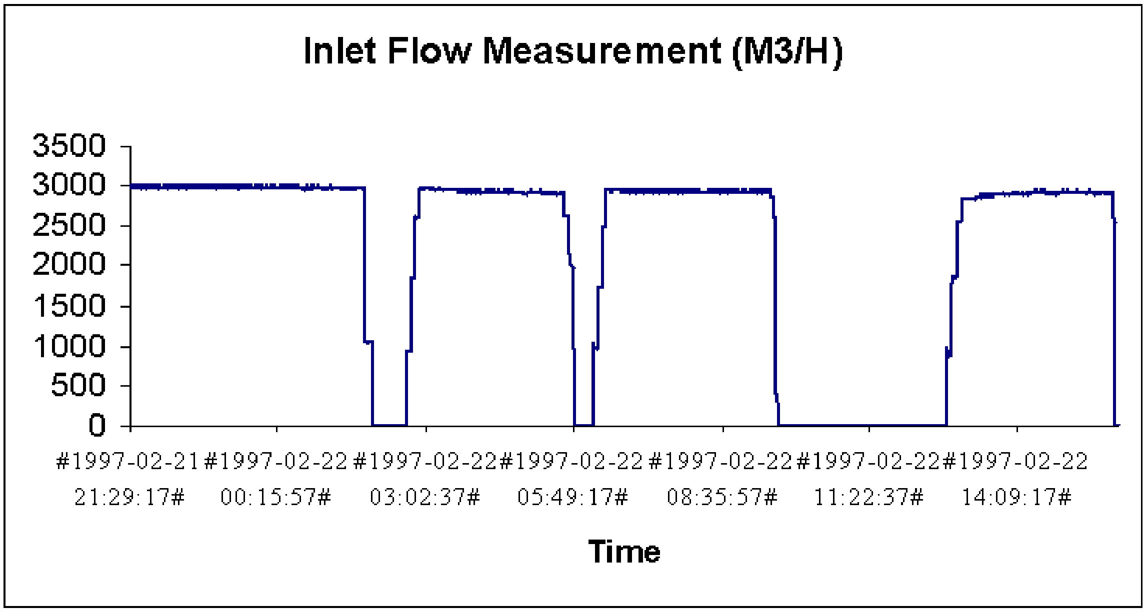


FIGURE 4 INLET FLOW CHANGES AS THE PUMPS ARE SWITCHED ON AND OFF

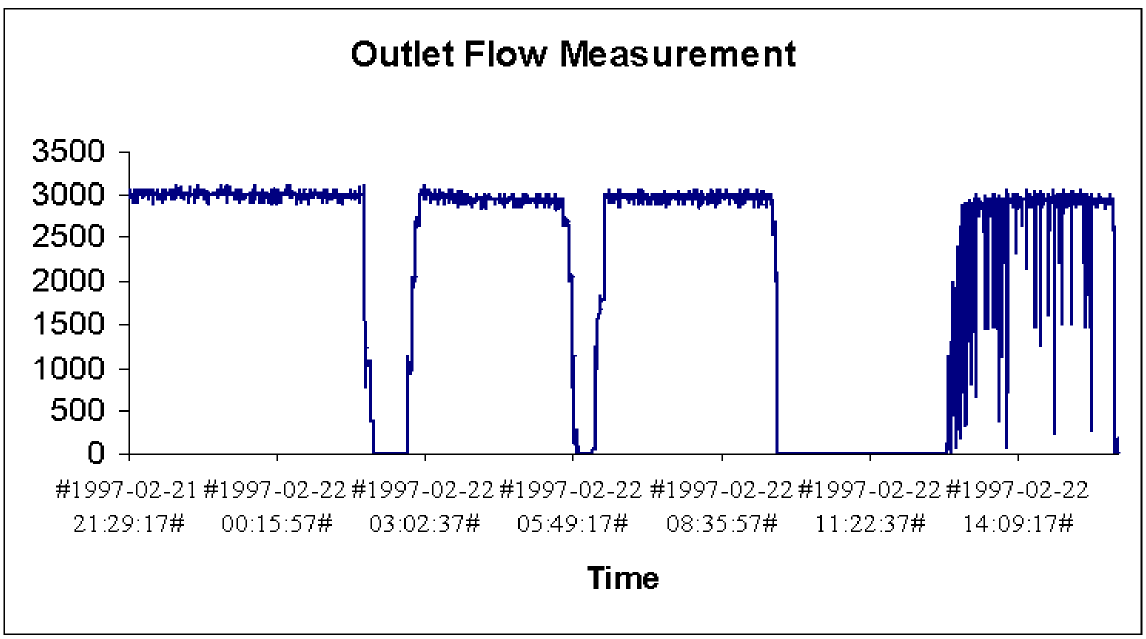


FIGURE 5 OUTLET FLOW FOLLOWS INLET FLOW CHANGES WITH MORE NOISES

about 17 hours. Towards the end of this data collection period, the outlet flow readings become erratic. Such behaviour has been observed frequently during this period. After reporting this data fault to the client, further investigations have been carried out and the client found out that the electronics inside the outlet flow meter was not changed after the inlet flow meter electronics was updated.

In general typical data faults detected are:

- out of range data,
- excessively noisy data,
- outliers (sudden increase in the rate of change),
- frozen data (no change at all for a certain time period)
- inconsistent data (one measurement is within a different window from the others).

When ATMOS identifies any of the above data faults, it will inform the operators of the fault type so that corrective actions can be taken. In the meantime, it continues the monitoring of the pipeline. However the leak detection response time is expected to increase as the system will be running in the “degraded” mode. For this crude oil pipeline, the expected detection time for sizes between 1% and 50% are given in **Table 1**.

TABLE 1 THE AVERAGE LEAK DETECTION TIME ON THE CRUDE OIL LINE

Leak size	Average detection time
1%	7 min
2%	5 min
5%	3 min
10%	2 min
20%	2 min
30%	2 min
50%	2 min

3.3 Batch Tracking

In addition to leak detection, a batch tracking function has been implemented for this pipeline. In order to discriminate different batches the crude average density has been used (**Figure 6**). The operator is provided at each scan with an automatic batch serial number, a log of the times of departure and estimated arrival, estimation of the crude volume delivered, calculation of the average density, estimation of the batch velocity and the current batch position within the pipeline. This information is displayed on a pipeline mimic window using a set of colour displays and a table displaying the numerical values (**Figure 7**).

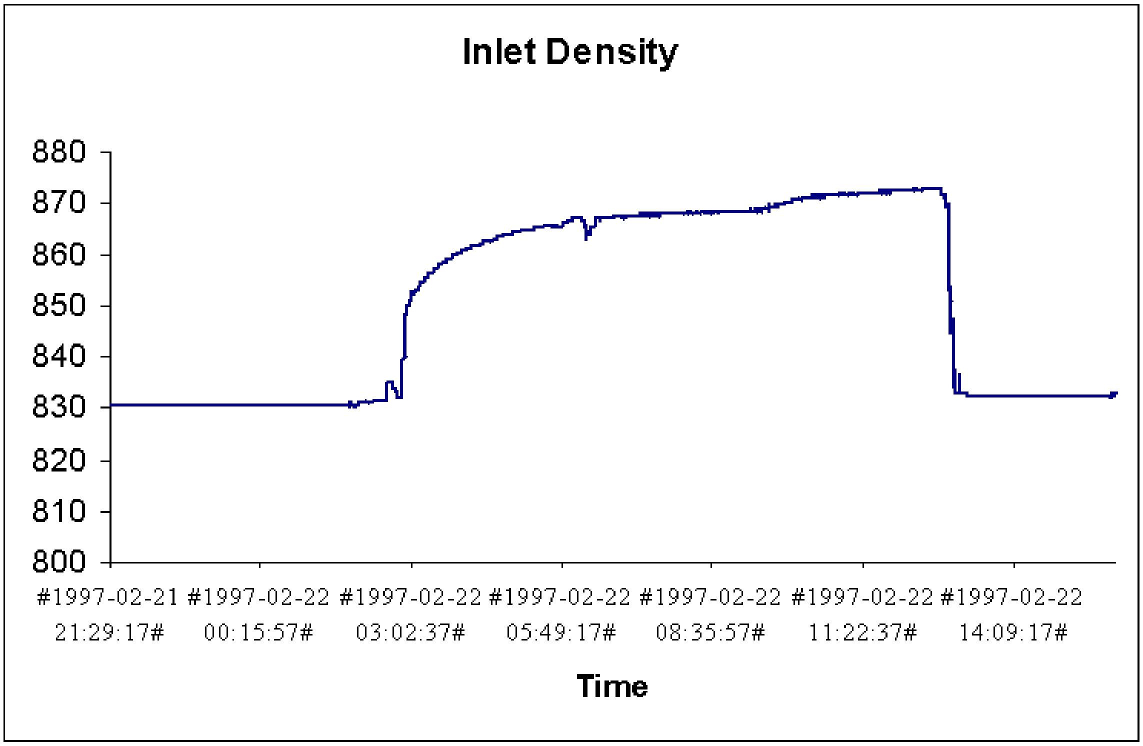
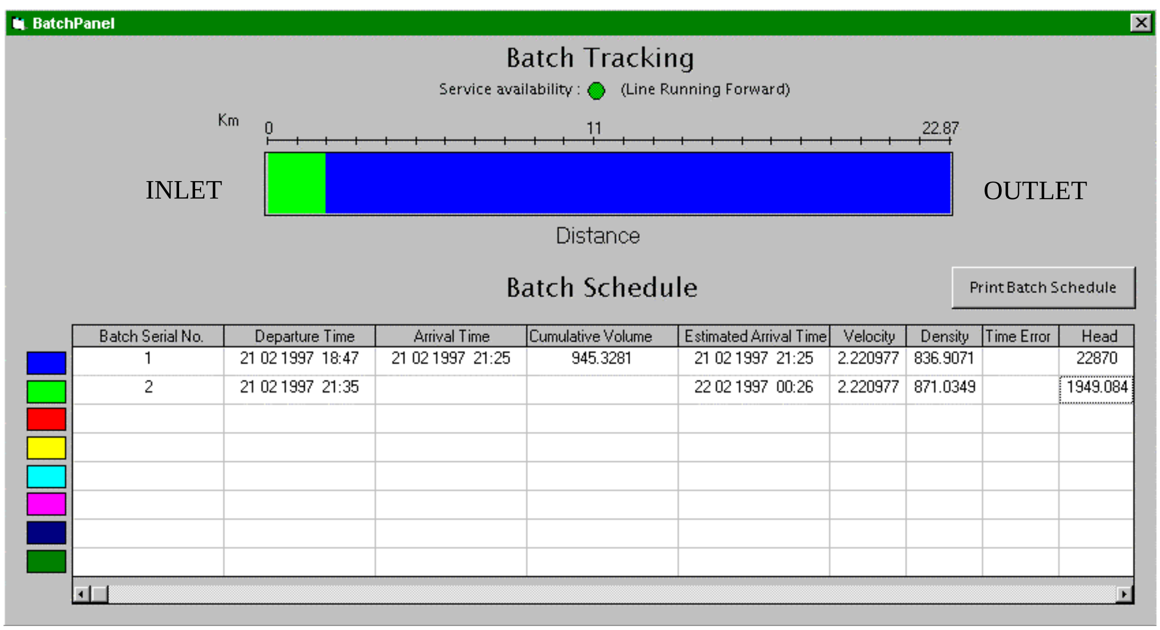


FIGURE 6 DENSITY CHANGES AS DIFFERENT BATCHES OF CRUDE ARE TRANSPORTED



Batch Serial No.	Departure Time	Arrival Time	Cumulative Volume	Estimated Arrival Time	Velocity	Density	Time Error	Head
1	21 02 1997 18:47	21 02 1997 21:25	945.3281	21 02 1997 21:25	2.220977	836.9071		22870
2	21 02 1997 21:35			22 02 1997 00:26	2.220977	871.0349		1949.084

FIGURE 7 AN EXAMPLE OF BATCH TRACKING

Hardcopy and logging facilities are provided. The algorithm used is a state transition machine whose initial entry stage is a full system flush. Operational conditions are taken into account to make the system more robust. Problems encountered included temperature variations between inlet and outlet (which affected density) and the width of the interface region between batches which seems to increase as it approaches the outlet, causing different gradients in the outlet density readings.

3.4 System Performance Statistics

One added value of ATMOS PIPE is that it stores all the information it gathers and processes. For operator and client information, the following data are provided in the Executive Summary which is available both on line and off-line (using the event log file):

- Operational status (steady state, small and large transient),
- Line status (stopped, run forward, run reverse),
- Data faults detected,
- Alarm status (leak warnings, leak alarms),
- Estimated pipeline resistance and
- Average flow difference after pressure correction.

Such information can be valuable to operators as a report on the performance of the pipeline, the instrumentation system and the loss monitoring system (**Figure 8**).

4. Description of ATMOS Pipe

4.1 Introduction

ATMOS PIPE is a Trade Mark of the statistical pipeline integrity management system developed by **Shell** (Zhang 1993, Zhang 1997). It applies advanced statistical techniques to flow, pressure and temperature measurements of a pipeline. Variations generated by operational changes are registered and thus reliable system performance can be achieved through tuning of statistical parameters.

ATMOS PIPE does not solve partial differential equations to calculate flow or pressure in a pipeline but it detects changes in the relationship between flow and pressure using measurement data available. Therefore no error is introduced by ATMOS PIPE itself and the computational requirement of the system is low.

As the system monitors a pipeline continuously it learns about continual changes in the line and in the flow, pressure and temperature instruments. As long as the instruments continue to function correctly, variations in fluid properties e.g. composition change, will not present a problem to ATMOS PIPE. This is a major advantage of ATMOS PIPE.

ATMOS PIPE has been developed by Shell following several years of research and field tests in pipeline leak detection. After its initial development, field tests have been performed on liquid propylene, ethylene gas and natural gas pipelines. During all of the tests, controlled pipeline leaks were created at different locations and the responses of the system were monitored closely. The minimum leak created was 0.5% and the maximum leak 55%. All leaks created during the field tests were detected and leak size and location estimates were given.

The continuous monitoring of the above pipelines under leak-free operations showed that the system was truly reliable as no false alarm was generated. Having tested the system successfully, Shell decided to commercialise the system through REL Instrumentation Limited.

In the following sections, the system design is discussed.

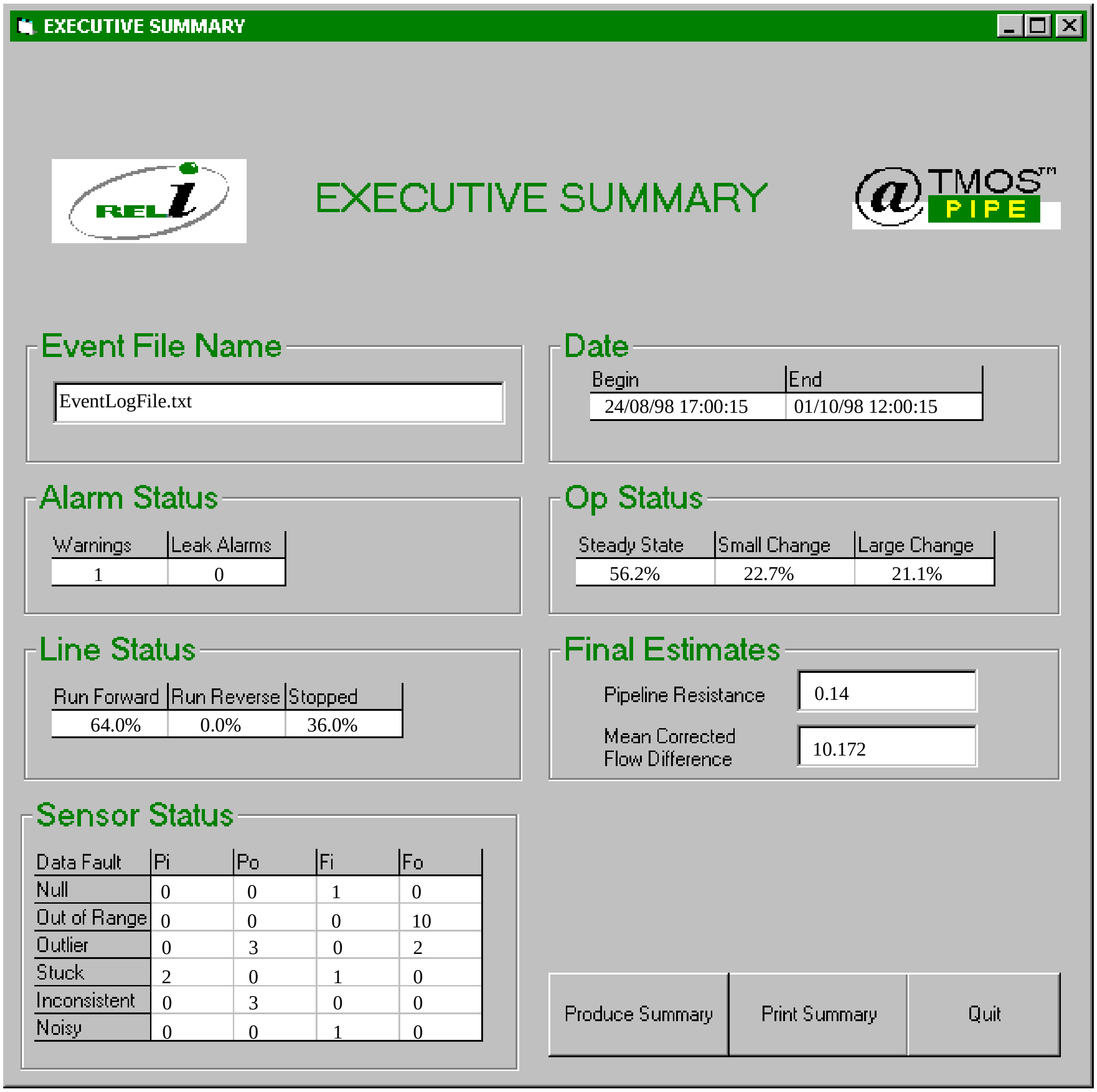


FIGURE 8 AN EXAMPLE OF THE SYSTEM PERFORMANCE STATISTICS

4.2 The Leak Detection Algorithm

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 rate.

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:

$$\tau(t) = \sum_{1}^{M} Q_i(t) - \sum_{1}^{N} Q_o(t) - \sum_{1}^{L} \Delta Q_j(t) \qquad (1)$$

where $\tau(t)$ is called the corrected flow difference term at time t. In practice $\tau(t)$ usually fluctuates around a non-zero value due both 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 types in the network 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 hypotheses, e.g.

H_0: $\tau(t)$ is gaussian with mean m and variance σ^2

H_1: $\tau(t)$ is gaussian with mean m+Δm 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 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:

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

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

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.

4.3 Factors Affecting ATMOS Pipe Performance

Note that the quality of field instruments for flow, pressure, temperature measurements is very important for pipeline integrity monitoring. According to the definitions given by the Scientific Apparatus Makers Association Standard, instrument accuracy determines the maximum measurement error, repeatability represents the consistency of measurement results and resolution determines the minimum change an instrument can sense. For pipeline monitoring the above three qualities are of varying importance for ATMOS PIPE:

- Instrument resolution determines the minimum leak detectable by any system based on field measurements. If the resolution of flow and pressure meters is 0.1%, for example, it is impossible to use these meters to detect a leak smaller than 0.1%.

- Instrument repeatability is critical in determining leak detection reliability. If it is required to detect a leak of a magnitude equal to or smaller than the instrument repeatability, then false alarms will be generated.

- Since ATMOS PIPE detects relative changes in the mean value of the corrected flow difference term, known instrument errors are accepted as 'normal' discrepancy between the instruments assuming no leak is present when the system is first installed. Therefore it is possible for ATMOS PIPE to detect a leak smaller than the instrument errors. Previous field tests have shown that ATMOS PIPE detected a leak of 0.5% while the flow accuracy was 1%.

Note that SCADA (Supervisory Control And Data Acquisition) systems 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 16 bit AD converters.

5. Conclusions

The application of ATMOS PIPE to the crude oil pipeline illustrates that it can detect leaks quickly while remaining reliable during normal operating conditions. Reverse flow, batch start and stop, changes in the crude grade and pump on/off switches have presented no problem to ATMOS.

Since ATMOS PIPE has been installed within the existing instrumentation and data collection system, the only cost incurred is for the software design and a Personal Computer. However interfacing with different systems has proven to be a time consuming exercise because the SCADA system and digital card specified by the client were having teething problems after upgrading to Windows NT Operating System. Where possible, REL Instrumentation Limited strongly recommends the use of mature systems particularly as computer hardware and software changes take place so quickly that they are not always tested fully before their release to end users.

Acknowledgement

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