Abstract

This paper outlines the Esso experience of leak detection within its own organization. It will detail the historical methods, the systems available and the testing of suitable systems which were short listed for use on their own and operated on pipeline networks around the country. The paper is divided into two parts, part one being the Esso perspective, and part two being the technical solution currently being engineered for installation during this year. The criterion used is that a leak should be detected within a predetermined time with minimum false alarms.

1. Introduction

Esso Petroleum Company Limited operates a network of jet oil and multi-product pipelines in the UK. As shown in Figure 1, these pipelines run cross the country with a total length of 1,200 kilometres.

Figure 1 Esso Operated Pipelines (Red lines represent Esso owned pipelines, blue lines indicate pipelines owned by Mainline Pipeline Company but operated by Esso).
Historically Esso has always invested in pipeline leak detection because of the following reasons:

- Integrity monitoring is one of the conditions of our construction authorisation on several lines.
- The quicker we can detect a leak, the sooner we can limit the environmental damage.
- To deploy emergency services and repair crews effectively within the shortest time possible.
- Safeguard the Public as soon as possible.

As the computer technology has developed rapidly over the past few years, Esso has been seeking a more effective leak detection system for their pipelines. The next section will outline the historical methods used, followed by a description of the selection process for a suitable system (Section 3). Section 4 describes the principle of the ATMOS Pipe statistical leak detection system and its field test results are summarised in Section 5. Section 6 concludes the paper by summarising the performance of the implemented system on the jet oil pipeline.

2. Historical Methods

Historically Esso has made the best use of SCADA Control Systems so that all data are generally stored and are readily available for the operators to control the pipelines. Typical instrumentation on the pipelines includes:

- Flow, pressure, temperature and density meters at all the supply and delivery points.
- Pressure and temperature meters on both the suction and discharge sides of a pump.
- DRA (Drag Reducing Agent) injection flow meters.
- Pig launching and receiving signals.
- Valve open/close, pump start/stop status signals.

The above field signals are sent to a FIX SCADA system via Allen Bradley PLCs at 5 second intervals. The following four types of leak detection methods were used:

1. Line balance;
2. Line break;
3. Operator amendable alarms;

2.1 Line Balance

The line balance method is based on volumetric flow difference calculations. Given that the instrument error is negligible, the total volume of products pumped into a pipeline should be equal to the volume taken out of it, if no leakage exists. However due to frequent pump stop/start and control valve manipulations, the volumetric flow difference is seldom zero. Under transient operating conditions, the line pack can increase or decrease resulting in a non-zero difference between the inlet and outlet flow. Figure 2 and Figure 3 illustrate the packing and unpacking of a pipeline respectively.

To avoid false alarms, the line balance programme is inhibited during transient operating conditions. For most of the pipelines, this means that the line balance method is not used for over 60% of the time.
To detect leaks of different sizes under steady-state operating conditions, the line balance programme is split into three time intervals:

1. 5 minutes for a leak volume of 10 m$^3$ i.e. a leak of 120 m$^3$/hour is detected in 5 minutes.
2. 60 minutes for a leak volume of 5 m$^3$ i.e. a leak of 5 m$^3$/hour is detected in one hour.
3. 24 hours for a leak volume of 2 m$^3$ i.e. a leak of 0.08 m$^3$/hour is detected in 24 hours.

- Pipeline pressure increases
- Inlet flow is greater than outlet flow
- Flow difference is greater than zero.

**Figure 2 Packing of a Pipeline**

- Pipeline pressure decreases
- Inlet flow is less than outlet flow
- Flow difference is less than zero.

**Figure 3 Unpacking of a Pipeline**

Note that the above detection limits vary according to the pipeline diameter and volume. The performance of the line balance programme depends also on the metering accuracy. For all the product pipelines, on-line meter calibrations are carried out whenever the product changes e.g. from jet to petrol. Our operational experience shows that even with the on-line calibrations, the flow meter accuracy achievable is around 0.15%. Therefore it is difficult for the line balance programme to alarm the 2 m$^3$ i.e. 0.08 m$^3$/hour leak, without false alarms.

### 2.2 Line Break

The line break method is designed to detect catastrophic incidents caused mainly by third party activities. It monitors the flow and pressure at the inlets and outlets of a pipeline closely. Alarms are generated when the flow and pressure change by more than the threshold levels. The programme is run in the SCADA system.

Two distinctive sets of changes are monitored depending on whether the leak is close to the pipeline inlet or outlet. **Figure 4** shows the changes caused by a large leak at location A and B respectively.

If a leak occurs close to the pipeline inlet e.g. location A, the inlet flow increases while the inlet pressure decreases. If a leak occurs close to the pipeline outlet e.g. location B, both the
outlet flow and pressure will decrease. If the changes in the flow and pressure exceed their alarm thresholds, then a leak alarm is generated. If a leak occurs in the middle of the pipeline, a combination of the above changes in flow and pressure will occur.

![Figure 4 Alarm of Leaks at Location A or B](image)

Note that the above changes caused by a leak could be masked by the reaction of the pipeline control system. Therefore the line break method is not suitable for detecting small leaks.

### 2.3 Operator Amendable Alarms

This method works in steady state operating conditions or when the pipeline is in shut in (static with zero flow). Basically the flow and pressure readings received from the instrumentation system are trended; if they change by more than the upper or lower limits then alarms are generated. The upper and lower limits can be adjusted by the operators as the pipeline operating condition varies. **Figure 5** shows the principle of this method.

![Figure 5 Operator Amendable Alarms](image)
2.4 Manual Line Balance
As a back up to the SCADA based leak detection systems, operators used to take hourly readings of flow and calculate the differences between the inlets and outlets manually. Although this method seems to be tedious, it does draw the operators’ attention to the line balance variations.

3. Selection of an Advanced System
For steady state operating conditions, the above four leak detection methods work quite adequately. However the following disadvantages have been identified with the existing systems:
- No effective leak detection during transient operating conditions, that is over 60% of the time for some pipelines.
- The detection time for medium to small leaks is very long.
- No leak location estimate is given although the Line Break method does indicate which half of the pipeline a leak is in.
- Operators have to diagnose if an alarm is caused by a leak or operational changes.

To improve the integrity monitoring of the pipelines, Esso has decided to select a more advanced leak detection system that will meet the following criteria:
- Minimal false alarms
- Detection of all but the smallest leaks (below instrument repeatability)
- Reasonable detection time
- Acceptable location accuracy
- Robust software
- Solid implementer with track record
- High confidence factor
- Acceptable costs
- Vendor willing to undertake real-time field trials.

With the above criteria, a comprehensive market survey and assessment of the leak detection technologies were conducted between 1998 and 2000. The assessment process consists of three main stages:
1. Verbal discussions with various vendors.
2. Site visits to existing client installations.
3. Field tests on the jet oil line and Fawley White Oil network system, for selected vendors who are willing to participate.

The field tests include both normal pipeline operations and leak trials. Leaks at different locations were introduced by the use of road tankers and prefabricated orifice plates. Four orifice diameters are included: 2.5 mm, 3.1 mm, 6.35 mm (¼ inch) and 12.7 mm (½ inch). Figure 6 shows the set up for the leak trials.

![Figure 6 Set up for the Leak Trials](image-url)
To make the field tests as realistic as possible, the leak detection systems and their vendors were totally blind to the field activities. Information supplied to the vendors is limited to:

a. Pipeline Lengths  
b. Topography  
c. Pipeline wall thickness  
d. Pipeline configuration  
e. Instrument readings of:  
   Flow, Pressure, Temperature, Density  
f. Digital Information:  
   Valve Status, Pump Status  

For the Jet oil pipeline, the vendors were given a set of flow, pressure, temperature and density data for a period of three weeks. In total seven leaks were included, one of which was generated during shut-in and another one during pipeline start up.

For the Fawley White Oil Network system, the leak detection systems were installed on site and the field tests were conducted real-time.

From the above selection process, Esso has chosen ATMOS Pipe for real-time installations on all of Esso operated pipelines as shown in Figure 1 above.

4. Principle of ATMOS Pipe

ATMOS Pipe is a statistical pipeline leak detection system developed by Shell. It applies advanced statistical techniques to flow imbalance and pressure readings of a pipeline. Variations generated by operational changes are registered and distinguished from changes generated by a leak.

ATMOS Pipe™ is unique as it applies three CPM (Computational Pipeline Monitoring, API 1130) methods simultaneously:
- 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 ATMOS Pipe reliable yet sensitive in detecting leaks.

Since the principal design criterion for ATMOS Pipe is **Minimum False Alarms**, a leak alarm is generated only after systematic checks that pipeline flow and pressure changes do conform to the patterns of a leak.

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 measurements 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 Pipe with a very high level of system reliability i.e. minimum spurious alarms.

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:

\[ \tau(t) = \sum_{i=1}^{M} Q_i(t) - \sum_{o=1}^{N} Q_o(t) - \sum_{j=1}^{L} \Delta Q_j(t) \]  

where \( \tau(t) \) is called the corrected flow 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 signal \( \tau(t) \) 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 is used to decide between the leak-free and leak-present hypotheses, e.g.

- **H⁰**: \( \tau(t) \) is gaussian with mean \( m \) and variance \( \sigma^2 \)
- **H¹**: \( \tau(t) \) is gaussian with mean \( m + \Delta m \) and variance \( \sigma^2 \)

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

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

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

The SPRT for testing hypothesis \( H¹ \) against \( H⁰ \) is transformed to the calculation of the following cumulative sum:

\[ \lambda(t) = \lambda(t-1) + \frac{\Delta m}{\sigma^2} (\tau(t) - m - \frac{\Delta m}{2}) \]  

By comparing the on-line calculated value \( \lambda(t) \) (Lambda) with a preset threshold value, a leak alarm can be generated.
The above scheme is implemented using operational data provided by the client, in order to optimise the performance of the leak detection system. Parameter tuning is carried out both during the design stage and after the initial installation. Typically it takes about four hours for ATMOS Pipe to be commissioned if a pipeline is operational and instrument data are available for the design of the system. For newly constructed pipelines, it takes two weeks to commission ATMOS Pipe after the pipeline and the instrumentation system become operational.

One key feature of ATMOS PIPE is that it has 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 hydraulic models are used, variations in fluid properties e.g. composition change, viscosity variations, do not present a problem to ATMOS Pipe.

5. Field Test Results

The first set of tests were carried out on the 10”, 106 KM long jet oil pipeline between Fawley and West London (Heathrow Airport). The second set of tests were carried out on the 10”/12”, 225 Km long multi-product pipeline network from Fawley to West London, Gatwick and Purfleet. The results are summarised in the following two sections.

5.1 Jet Oil Pipeline

The Jet Fuel Pipeline runs from Fawley to West London Terminal. Flow, pressure, temperature and density measurements are available at Fawley and West London. Esso provided two sets of data: leak-free data (11 days) and leak data (5 days). The first set was used to tune the leak detection system to guarantee that no false alarm was raised. The second set was used to test if ATMOS PIPE could actually detect the unknown leaks, and provide estimates of the size and location.

The 'blind' tests detected seven leaks of different sizes and locations. In particular, a leak appeared to have started during shut-in and another when the pipeline was started up. As shown in Table 1, six of the leaks were detected within a few minutes and the transient leak was detected in 23 minutes.

<table>
<thead>
<tr>
<th>Date</th>
<th>Estimated Time when the leak started</th>
<th>Time when a leak was detected</th>
<th>Detection Time</th>
<th>Estimated Leak Size</th>
<th>Estimated Leak Location @</th>
</tr>
</thead>
<tbody>
<tr>
<td>13/10/98</td>
<td>7:59 hour</td>
<td>8:05 hour</td>
<td>6 minutes</td>
<td>9.6 m/h</td>
<td>16.2 km</td>
</tr>
<tr>
<td>13/10/98</td>
<td>12:26 hour</td>
<td>12:49 hour</td>
<td>#23 minutes</td>
<td>11.4 m/h</td>
<td>50.8 km</td>
</tr>
<tr>
<td>14/10/98</td>
<td>7:22 hour</td>
<td>7:25 hour</td>
<td>3 minutes</td>
<td>18.5 m/h</td>
<td>7.7 km</td>
</tr>
<tr>
<td>14/10/98</td>
<td>9:47 hour</td>
<td>9:52 hour</td>
<td>5 minutes</td>
<td>10.2 m/h</td>
<td>3.5 km</td>
</tr>
<tr>
<td>14/10/98*</td>
<td>*12:48 hour</td>
<td>*12:50 hour</td>
<td>*2 minutes</td>
<td>*18.6 m/h</td>
<td>*19.2 km</td>
</tr>
<tr>
<td>15/10/98</td>
<td>7:06 hour</td>
<td>7:11 hour</td>
<td>5 minutes</td>
<td>9.9 m/h</td>
<td>11.9 km</td>
</tr>
<tr>
<td>15/10/98</td>
<td>10:40 hour</td>
<td>10:43 hour</td>
<td>3 minutes</td>
<td>13.6 m/h</td>
<td>45.4 km</td>
</tr>
</tbody>
</table>

@ Leak location is shown in kilometres from the pressure meter at the inlet.
* Leak during pipeline shut-in conditions.
# Leak during pipeline start up.
Note that the above performance has been improved since 1998, in particular the leak location accuracy.

5.2 Fawley White Oil Network

Figure 7 shows the Fawley White Oil Network. The pipeline is used to transfer oil products and consists of the following main segments:

- A 12”, 50 KM section from Fawley to Alton with supply to BP Hamble at 3.5 KM from Fawley,
- A 12”, 51 KM section from Alton to West London,
- A 10”, 114 KM section from Alton to Purfleet with supply to Gatwick at 55.8 KM from Alton.

In total 18 leaks were generated at different locations and with the following orifice sizes: 2.5 mm, 3.1 mm, 6.35 mm (1/4 inch), 12.7 mm (1/2 inch).

The main purpose of the real-time trial is to assess the capability of the leak detection system and test the limits of the instrumentation system. Since ATMOS Pipe was designed for leak tests, only limited engineering time has been available for this project. Prior to the test, Esso made about 17 days data available to RELi.

During the in-house tuning period, ATMOS Pipe was configured to run through all the available operational data so that it would not give any false alarm. The data used for tuning are as follows:

2. 29 October 2000 to 31 October 2000.
3. 6 November 2000 to 13 November 2000.

On Friday the 1\textsuperscript{st} December 2000, ATMOS Pipe was installed on site. Leak tests were then conducted between Monday the 4\textsuperscript{th} and Friday the 8\textsuperscript{th} December 2000. In total eighteen controlled leaks were generated over this five day period. The leaks are categorised as follows:

- Seven leaks during normal steady-state operation (+/-10\% change).
- Four leaks during transient operating conditions, some during pipeline start up when flow changed from 0 to full scale.
- Seven leaks during shut-in operation (no flow).

The following results have been achieved from these tests:

1. The smallest leaks detected were 2 m\textsuperscript{3}/h (0.2\% of the flow meter range). This took 12 minutes during transient shut-in condition.
2. A 3 m\textsuperscript{3}/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 for a shut-in leak of 24 m\textsuperscript{3}/h.
4. The largest leak generated was 29 m\textsuperscript{3}/h (2.9\% of flow meter range). This leak was accompanied by transient operating conditions and it took 5 minutes for ATMOS to alarm the leak.
5. The leak rate estimates were very accurate compared with the volume of product collected by Esso.
6. All leaks detected were located within the correct segments e.g. Hamble to Alton.

Figure 8: Display of Flow against Time during the leak trial on 4\textsuperscript{th} December. The position in time (14:02:27) of the leak is shown by the white line at the centre of the graph.
Figure 9: Display of Pressure against Time during the leak trial on 4th December. The position in time (14:02:27) of the leak is shown by the white line at the centre of the graph.

Figure 10: Corresponding Lambda Values against Time showing the calculation of the probability 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.

Figure 8, 9 and 10 show the flow, pressure and Lambda values during the field tests on the 4th December. Note that no leak alarm was generated between 13:00 and 13:30 hours when significant transients occurred but a leak of 10 m3/h (1% of the flow meter range) was detected in 4 minutes at 14:06 hours.
6. Conclusions

Esso has had a long history in pipeline leak detection. The traditional methods used were implemented within the SCADA system and they worked well under steady-state operating conditions. Due to the transient nature of some multi-product and batch operated pipelines, these methods had to be inhibited for over 60% of the time. To select a more advanced leak detection system, comprehensive market research and assessment have been conducted. Before the final selection was made, field tests were carried out on the Jet oil and White oil pipelines. Based on the assessment and field test results, ATMOS Pipe has been selected for final installation.

The implementation project was initiated in December 2001. The first real-time system was installed on the jet oil pipeline on the 19th April 2002 and no false alarm has been generated to date. The system has now been installed for the whole network as shown in Figure 1 and more than 15 further leak tests have been carried out successfully.

Through the leak detection project, both Esso and ATMOS have learnt a lot about the effect of routine maintenance has on the leak detection system. For example when a flow meter is proved on-line, a small amount of product is used to fill the prover loop and ATMOS generates a leak alarm. To prevent such self-induced alarms, Esso has now introduced a maintenance switch that informs ATMOS that maintenance work is being carried out. With the effective team work between Esso and ATMOS, it is now feasible to shut down the pipelines automatically when a leak alarm is generated.

References:
5. X. J. Zhang, 2001, “Real Time Pipeline Leak Detection on Shell’s North Western Ethylene Pipeline”, 2001 Spring meeting at the Ethylene producers conference in Houston, AICHE.