Abstract

With the global expansion of unconventional gas plays and increased consumer demand, greater pipeline capacity to transport natural gas to market is a necessity. Old pipelines are being repurposed and new pipelines are being built. Regulators and watchdog groups are increasingly scrutinizing the safety and risk of these developments.

Leak detection, particularly computational leak detection, is a crucial component of a pipeliner’s risk mitigation. The major concerns in a leak detection system include robustness, leak sensitivity, and location accuracy.

- Robustness is primarily determined by the maximum variation expected in the system during normal running as a consequence of changing operations and instrument noise.
- Leak sensitivity is typically determined by the scale of flow and pressure deviations observed in a leak scenario compared to normal operation.
- Location accuracy depends on methodology.

In this paper we examine the effectiveness of gas pipeline leak detection by simulating several typical configurations. We estimate the maximum variation observed in normal running. We evaluate the pressure and flow deviations that occur when various leaks are imposed. Finally the accuracy of leak location from a transient computational pipeline model is examined.

The results will assist pipeliners, regulators, and concerned parties to develop realistic expectations about the efficacy of meter-driven leak detection systems in natural gas pipelines.

Introduction

We focus here on the usefulness of computational leak detection and location using RTTM with the aim of demonstrating high performance on gas transmissions lines. For a survey of other leak detection methods, see [3]. [10] is a recent introduction to the hydraulic effect of leaks on a pipeline. The basic method for leak location used here is unchanged since [1]. For a discussion of selecting a leak detection method appropriate to your situation, see [11].

Pipeline Definitions

In this paper we model several different pipeline configurations. We impose leaks and analyze output. The pipelines are all natural gas lines, although our results should be generalizable to any gas-phase fluid with similar compressibility.

The gas composition used is (by mol) 95% C1 (methane), 4% C2 (ethane) and 1% CO2 (carbon dioxide).

The pipelines are conceptually newly built or refurbished, with high-quality instrumentation and data acquisition, as noted below. Pipeline schematics are given in the Figures below.

We do not address pipeline networks here. However, provided sufficient instrumentation on the network to model flow through the interconnections, a network is reducible to a
number of straight pipe segments and can be reached used the same techniques. See also [4] for a discussion of modeling techniques for generic networks without instrumentation at interconnections.

**Pipeline #1**

Pipeline #1 is a 5 mi long flat elevation pipeline with a 4 inch internal diameter and a 0.5 inch wall thickness. The supply is assumed to have an infinite gas resource feeding the line at a constant pressure 200 psig, into a 250 hp compressor limited to 1775 psig discharge pressure. The flow rate at the delivery varies on daily schedule.

A normal daily delivery flow schedule is

- 6 MMSCFD, 7 hours and 45 minutes
- shut 15 minutes
- 4 MMSCFD, 7 hours and 45 minutes
- shut 15 minutes
- 2 MMSCFD, 7 hours and 45 minutes
- shut 15 minutes

This is intended to model a shift schedule with different levels of productivity, with short breaks between shifts, as is typical operations in an inter-plant pipeline.

In a one-week simulation, there is an 8 hour unexpected shutdown at the start of day 3 when the compressor trips. The leak imposition time was chosen to be 2 hours after the compressor is restarted and normal flow patterns are resumed.

The upstream supply can supply at a high rate, and operates to keep the upstream pressure within a high and low range. As the pipeline is short with very little linepack to store or draw on, upstream pressure is essentially fixed except during the low flow period of “third shift”.

This pipeline is instrumented with pressure, temperature and flow at the upstream and downstream. Inlet temperature varies between 70F and 360 F depending on flow rate and compressor activity. Ambient temperature is 59.6 F.

**Pipeline #2**

Pipeline #2 is a 160 mile transmission line with two supplies and five deliveries, 24 inch OD with 0.5 inch wall thickness. The elevation profile is non-flat, but varies over a range of 370 feet, upstream generally higher than downstream.

The primary supply is at the head of the line, with a secondary supply at a booster station 10 miles downstream. There is an additional compressor at milepost 85. The compressor stations divide the pipeline into three segments.

The primary delivery is at the end of the line, with secondary deliveries at milepost 25, 95, and 110, and a delivery to power the compressor at milepost 85.

The pipeline has continuously varying activity, with deliveries ramping up and down. The activity cycle is perhaps not very “real world”, but it does effectively keep the pipeline in transient state that is consistent with this sort of transmission line.

Flow measurements are available at all supplies and deliveries. Pressure measurement is available at all supplies, deliveries, and suction and discharge of compressors. Temperature measurement is available at supplies, the terminal delivery, and suction and discharge of compressors, but not at midline deliveries. Inlet temperature is 80 F. Ambient temperature is 60 F.

**Pipeline #3**

Pipeline #3 is a long undersea transmission line, 320 miles long, 48in OD, 1 in WT. The first 45 miles and the last 15 miles are on land. Elevation ranges from sea level to 600 ft below sea level, typical for a pipeline on the continental shelf.

The pipeline operates continually, with negligible variation in flow. While pipelines such as this are intended to operate at near steady state for as long as possible, this is not the practical result. The two largest sources of variation from steady operation are instrument and equipment maintenance (including that which affects either the supply of gas or the capacity of recipient to accept delivery) and weather and current changes that affect the thermal environment of the submerged pipe.

The only instrumentation available is flow, pressure, and temperature at the supply and delivery. The large distance between instruments on this pipeline and the slow speed of sound in gas mean that the signal from undersea events can take ten to fifteen minutes to register on instruments. Inlet temperature is 100 F. Ambient temperature depends on depth and varies from 80 F onshore, rapidly decreasing to 40 F on the sea floor.

See [8] for discussion of underwater gas pipelines deriving from a well source rather than a transmission line such as this.

**METHODODOLOGY**

We use a three-step approach to analyze the leak detection sensitivity of these pipelines.

First, we use a commercial offline design and modeling tool, PipelineStudio, to build the pipeline and operating scenarios.
In addition to simulating normal operations, we add one or more leak cases for each pipeline. Leaks are simulated as flow through pipe holes of specified size, with leak rates therefore depending on local pipeline conditions. (Leak rates were stable with the exception of one case on pipeline #2.) The model includes thermal effects, both internal and with heat transfer to the ground. The pipeline wall heat transfer coefficient is set to 2 BTU/h.in2.F.

Second, output from this model was modified using a SCADA simulation utility (SSU) to approximate typical noise and uncertainty in measurements.

Third, we use a commercial real-time transient model and leak detection tool, PipelineManager. The RTTM uses the simulated pressure and temperature measurements to drive a hydraulic model, which assumes that no leak is present. The results of the hydraulic model are compared to the simulated flow measurements to determine a leak signal, in the industry-standard for computational leak detection methodology. The leak signal is herein called the volume balance, defined as the difference between the measured flow balance and the modeled packing rate. [9] and [10] illustrate the differences expected between measured values during a leak and the output of a model that assumes no leak, the heart of RTTM-based leak detection.

The two hydraulic engines are similar in methodology, but are independent. This is particularly significant in heat exchange with the environment, where the simulation engine uses a single heat transfer coefficient while the leak detection engine uses a concentric thermal shell model. This is by choice, as the simulation engine can also use a concentric thermal shell model. The choice was made to increase the dissimilarity of the hydraulic engines. Both engines use independent implementations of the BWRS equation of state to model the natural gas used here. The independence of the hydraulic engines provides a useful systematic check on the method to ensure that the input does not assume the output. In fact, a real-world source of inaccuracy in a model is uncertainty about its configuration, such as the physical dimensions of the pipeline, ground thermal characteristics, and fluid properties. We do not have that here, where the pipeline is precisely defined in both models, but the inaccuracy resulting from different models can serve as a proxy for the inaccuracy introduced by real-world uncertainty.

As noted above, we do not address pipeline networks here, but the RTTM and leak detection techniques are generalizable to networks, although leak location techniques in networks are a more complicated issue and a worthwhile subject for future research.

**Instrument Emulation**

The trend data from the offline simulation is further processed using a SCADA simulation utility, or SSU.

This utility permit the addition of instrument shifts, drifts and excursions to the trend data, as well as the addition of simulation noise and general precision error from the analogue to digital conversion process.

Instruments have random noise applied of:

- 0.15% of current value for pressures
- 1% of current value for flows
- 0.1 degree for temperatures

No drift is applied to instruments. On a timescale longer than the simulations herein, some drift could be expected in instruments. The effect of pressure and temperature drift on a RTTM can be compensated by automatic tuning, but drift in flowmeters is generally passed directly through to the leak signal.

Instrument data acquisition is assumed to be modern, with no resolution limitations due to analog-to-digital conversion or bandwidth restrictions. No deadband is applied to instrument measurements. These effects, if present, will generally increase short-term noise in the volume balance without much effect on long-term ultimate sensitivity. [4] The data scan period is 12 seconds. This, again, assumes a modern data acquisition environment; compare to [6], which reports on sensitivity using a 120 second scan period.

Inside the RTTM, to compensate for instrument noise, a Bessel filter with a 150s cutoff period is applied to the instrument value.

**Leak Alarming**

A leak alarm is raised when the volume balance exceeds a threshold for a certain amount of time (a persistence requirement). Leak detection thresholds are generally dynamic in response to changing conditions on the pipeline, but were set to constant values here.

Thresholds were set to 125% of the 99% confidence value for the volume balance during normal operations. Table 1 lists the 99% confidence values and discusses their calculation.

In leaks, the calculated volume balance is not constant (indeed, the size of the leak itself depends on operations and conditions and can vary over the lifetime of the leak). Since a leak alarm is cleared when the volume balance drops below the threshold, it is possible for leak alarms to be raised and
cleared. The leak results noted below are only for those alarms that are raised and remain raised for the duration of the leak.

**RESULTS**

See Table 2 below for a summary of results.

**Pipeline #1**

The pump trip, which occurred 10 hours before the leaks are imposed, causes a brief false alarm.

Figures 1-3 below illustrate normal operations on this pipeline. Transitions between modes of operation are notably abrupt. Figures 4-7 and 8-10 illustrate the two leak scenarios.

**Case 1a**

A leak was simulated as a 0.25in hole in the pipeline at milepost 2.5.

A leak alarm was declared at +00:03:24. The leak size fluctuated between 0.6 MMSCFD and 1.5 MMSCFD depending on pressure in the pipeline through the course of the day. The leak size averaged 1 MMSCFD. This represents a leak between 12% and 25% of flow. The leak was located at milepost 3.0.

**Case 1b**

A leak was simulated as a 0.1in hole in the pipeline at milepost 2.5. The imbalance size varied between 0.15 and 0.45 MMSCFD, averaging 0.25. This represents a leak between 2.5% and 7.5% of flow. The leak was located at milepost 3.1.

This leak was declared at +00:50:00.

**Pipeline #2**

A 6-day baseline case was used as the basis for six leak cases, one large and one small for each segment of the pipeline. In each case, the leak was imposed at the beginning of the sixth day.

Figures 11-16 illustrate some of the normal operations on this pipeline. The complete 6-day baseline is available for review on request.

Figures 17-19, 22-26, and 31-35 illustrate the three large leaks. Figures 20-21, 27-30, and 36 illustrate the three small leaks.

**Case 2b**

A leak was simulated as a 1in hole in the pipeline at milepost 120. The leak size was 31 MMSCFD, approximately 10% of flow.

A leak alarm was declared at +00:14:00, with size 31.7 MMSCFD at milepost 124.

**Case 2c**

A leak was simulated as a 0.3in hole in the pipeline at milepost 120. The leak size was 2.9 MMSCFD, approximately 1% of flow.

A leak alarm was declared at +03:50:00, with size 2.8 MMSCFD at milepost 132. There were preceding leak alarms, but the alarms cleared because the leak size was at the threshold, whereas the listed alarm was permanent.

**Case 2d**

A leak was simulated as a 1in hole in the pipeline at milepost 5. The leak size was 22 MMSCFD, dropping to 16 MMSCFD later in the scenario, approximately 5-7% of flow. The size of the leak decreases because the secondary supply is downstream, and when the secondary supply increases later in the scenario, there is less pressure drop on the segment.

A leak alarm was declared at +00:10:00, with size 21.5 MMSCFD (later dropping to 15.9) at milepost 4.3.

**Case 2e**

A leak was simulated as a 0.4in hole in the pipeline at milepost 5. The leak size was 3.5 MMSCFD, approximately 1% of flow.

A leak alarm was declared at +02:40:00, with size 3.2 MMSCFD at milepost 4.1, dropping to 3.4. There were preceding leak alarms, but the alarms cleared because the leak size was at the threshold, whereas the listed alarm was permanent.

**Case 2f**

A leak was simulated as a 1in hole in the pipeline at milepost 55. The leak size was 29 MMSCFD, approximately 10% of flow.

A leak alarm was declared at +00:22:00, with size 29.2 MMSCFD at milepost 54.5.
Case 2g

A leak was simulated as a 0.3in hole in the pipeline at milepost 55. The leak size was 2.6 MMSCFD, approximately 1% of flow.

A leak alarm was declared at +03:50:00, with size 2.4 MMSCFD. The location was unstable, with bimodal values of 58.1 and 22.

Pipeline #3

The pipeline was simulated during a long period of steady operation. Because the simulation reported here does not include any effects of variable flow, it underestimates the variability of the volume balance, so that the thresholds used here are too small from a practical perspective. Detection times are thus likely optimistic. However, from the figures, note that leaks pass the optimistic thresholds while the leak rate is still rising. Thus, higher thresholds would have a limited delaying effect on leak alarming.

Three leaks were simulated during periods of steady operation. Two were at the location where the pipe enters the water, mileposts 45 and 305, and one deep underwater at milepost 175. Each leak was simulated as a 2in hole, and then again as a 0.5 in hole.

Figures 37-40 illustrate normal operations on this pipeline. Figures 41-44, 45-48, and 49-52 illustrate the near-shore, undersea, and far-shore leak scenarios.

Case 3A

A leak was simulated as a 2 in hole in the pipeline at milepost 45, at the shore where the pipeline goes undersea. The leak size increases over many hours, eventually rising to approximately 155 MMSCFD, or about 8.5% of flow.

From this location, the leak signal reaches the head of the line after about four minutes.

The leak alarm was issued at +00:17:00 when the leak had reached a size of approximately 20 MMSCFD. The location was unstable, with bimodal values of 155 and 200.

The leak was re-simulated as a 0.5in hole. The leak alarm was issued at +03:10:00. Leak size eventually reached approximately 10 MMSCFD, or about 0.5% of flow.

Case 3B

A leak was simulated as a 2 in hole in the pipeline at milepost 175, at the midway point of the underwater segment. The leak size increases over many hours, eventually rising to approximately 135 MMSCFD, or about 7.5% of flow.

Note that the water pressure at -600 ft is approximately 300 psi, which is well below pipeline pressure. Thus, this leak does not risk seawater ingress, although its flowrate is undoubtedly overestimated by the simulator, though this amounts to no more than a small correction in the size of the hole.

From this location, the leak signal reaches the tail of the line after about 12 minutes.

The leak alarm was issued at +01:13:00 when the leak had reached a size of approximately 20 MMSCFD. The location was unstable, with bimodal values of 155 and 200.

The leak was re-simulated as a 0.5in hole. The leak alarm was issued at +03:10:00. Leak size eventually reached approximately 10 MMSCFD, or about 0.5% of flow.

Case 3C

A leak was simulated as a 2 in hole in the pipeline at milepost 305, at the point where the pipeline comes ashore. The leak size increases over many hours, eventually rising to approximately 87 MMSCFD, or about 4.8% of flow.

From this location, the leak signal reaches the tail of the line after about one minute.

The leak alarm was issued at +00:10:00 when the leak had reached a size of approximately 20 MMSCFD. The location was unstable, with bimodal values of 255 and 317.

The leak was re-simulated as a 0.5in hole. The leak alarm was issued at +02:00:00. Leak size eventually reached approximately 7 MMSCFD, or about 0.4% of flow.

Analysis

Table 1 is illuminating. Gas pipeline systems are slow to respond to leaks due to compressibility and speed-of-sound issues. The elastic linepack of a gas pipeline means that a leak may not have significant effect on measured flows for long periods of time. Calculated flow is highly sensitive to microscopic changes in pressures and characteristically demonstrates large swings in the short term as a response to instrument noise.

However, the 99% confidence numbers in Table 1 show noise in calculated flows readily averages out to correct values, with the result that you can accurately model linepack changes. Thus, the standard computational leak detection approach of
comparing measured flow to modeled linepack changes retains efficacy.

Pipeline #1 is short with variable flow, and hence shows a gas pipeline with little linepack to buffer flow changes. Pressure changes due to a leak that are subtle on other systems are more visible here.

Pipeline #2 has continually variable operations, and hence shows a gas pipeline in continuous transient state, with linepack increasing and decreasing.

Pipeline #3 has enormous distance between instrumentation, and hence shows both the speed-of-sound effect profoundly and stark dependence on the accuracy of the linepack model.

Yet in all three pipelines, great sensitivity (as a function of flow) can be attained. Even considering real-world sources of noise not fairly represented here, leak sensitivity is comparable to that attained on pipelines transporting non-compressible fluids [1]. Compare to [6].

Leak Location

We provide some leak location results for the leak scenarios discussed herein. It is well-known that computational pipeline modeling leak location techniques are limited in accuracy and sensitive to the size of the leak and the distribution of instrumentation. [7] Nonetheless, some of the simulated leaks were well-located.

It is worth discussing the cases where location is bimodal. Leaks are localized to pipeline legs by finding the largest point imbalance in the pipeline, and then assigning the leak to the adjacent leg that has the largest imbalance at its other end. When more than one leg adjacent to a point has a significant imbalance at its other end, which leg gets assigned the leak can fluctuate, which results in bimodal leak location. This problem is more likely to occur for smaller leaks and for leaks that are further from instrumentation, as seen in the cases above.

CONCLUSIONS

Computational pipeline modeling, conventional and industry-standard, provides sensitive and robust leak detection to natural gas pipelines with modern, but real-world instrumentation, and should be deployed as part of any natural gas pipeline risk mitigation plan.

REFERENCES

3. Geiger, Gerhard and Thomas Werner (University of Applied Sciences Gelsenkirchen), and Dragos Matko, (University of Ljubljana); “Leak Detection And Locating - A Survey”; 0301 PSIG Conference Paper – 2003
5. Hauge, Espen and Ole Morten Aamo (Norwegian University of Science and Technology), and John-Morten Godhaavn (StatoilHydro ASA); “Model-Based Monitoring and Leak Detection in Oil and Gas Pipelines”; 114218-PA SPE Journal Paper – 2009

ACKNOWLEDGEMENTS

The authors wish to acknowledge the financial and professional support of Energy Solutions International. We would like to thank Dr. Jon Barley for his guidance and Dr. Dick Spiers for his commentary on early drafts of this paper. Without the logistical support of Patricia Granados, we would not be at this conference to present this research. Dr. Morrow wishes to acknowledge the personal, and occasionally literal, support of his fiancée Dawn Roberts, who made having a broken foot bearable. Mr. Dickerson wishes to acknowledge his wife Emma Smith, who makes all that travel worthwhile.
TABLES

Table 1 – 99% Volume Balance Confidence

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Typical Flow (MMSCFD)</th>
<th>Averaging Period</th>
<th>99% Confidence Volume Balance (Positive) (MMSCFD) (%)</th>
<th>99% Confidence Volume Balance (Absolute) (MMSCFD) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>6, 4, or 2</td>
<td>1 Min</td>
<td>0.299 (7.5%)</td>
<td>0.418 (10%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Min</td>
<td>0.206 (5.1%)</td>
<td>0.283 (7.1%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Min</td>
<td>0.145 (3.6%)</td>
<td>0.148 (3.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Hour</td>
<td>0.022 (0.55%)</td>
<td>0.062 (1.5%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Hour</td>
<td>0.020 (0.50%)</td>
<td>0.039 (0.97%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Hour</td>
<td>0.005 (0.12%)</td>
<td>0.022 (0.55%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 Hour</td>
<td>0.007 (0.17%)</td>
<td>0.007 (0.17%)</td>
</tr>
<tr>
<td>#2</td>
<td>340</td>
<td>2 Min</td>
<td>19.7 (5.8%)</td>
<td>22.0 (6.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Min</td>
<td>7.30 (2.1%)</td>
<td>8.09 (2.4%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Min</td>
<td>3.50 (1.0%)</td>
<td>3.99 (1.2%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Hour</td>
<td>2.11 (0.62%)</td>
<td>2.12 (0.62%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Hour</td>
<td>1.26 (0.37%)</td>
<td>1.31 (0.39%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Hour</td>
<td>0.890 (0.26%)</td>
<td>0.890 (0.26%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 Hour</td>
<td>0.284 (0.08%)</td>
<td>0.365 (0.11%)</td>
</tr>
<tr>
<td>#3</td>
<td>1810</td>
<td>1 Min</td>
<td>50.0 (2.8%)</td>
<td>54.7 (3.0%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Min</td>
<td>13.2 (0.73%)</td>
<td>13.9 (0.77%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 Min</td>
<td>6.52 (0.36%)</td>
<td>6.80 (0.38%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 Hour</td>
<td>2.93 (0.16%)</td>
<td>2.93 (0.16%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>4 Hour</td>
<td>2.10 (0.12%)</td>
<td>2.10 (0.12%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>8 Hour</td>
<td>1.59 (0.09%)</td>
<td>1.59 (0.09%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>24 Hour</td>
<td>1.09 (0.06%)</td>
<td>1.09 (0.06%)</td>
</tr>
</tbody>
</table>

The numbers in this table were taken from baseline, normal operations runs for the given pipelines as discussed above. The volume balance as a function of time was tabulated. The 99% confidence level is the number which is greater than 99% of the tabulated volume balance entries. In the case of the positive column, the number is compared to the signed volume balance, and hence ignores large negative deviations. In the case of the absolute column, the number is compared to the absolute value of the volume balance and hence is sensitive to both positive and negative deviations. The thresholds for leak detection were set as constant values at 125% of the 99% absolute value confidence level. The fraction of flow that the 99% confidence level represents is also tabulated; in the case of pipeline #1, the average flow, 4, is used to calculate the fraction of flow.
Leak size is represented as a percentage of typical flow (4 MMSCF/H in the case of pipeline #1). Leak location is represented as a percent of total pipeline length. “n/a” indicates that the detected location was unstable or otherwise uninformative. As leaks decrease in size, a degradation in location is characteristic of RTTM leak detection.

<table>
<thead>
<tr>
<th>Pipeline</th>
<th>Leak Size (%)</th>
<th>Location (%)</th>
<th>Time to Detect</th>
<th>Detected Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>#1</td>
<td>12-25%</td>
<td>50%</td>
<td>00:03:24</td>
<td>60%</td>
</tr>
<tr>
<td></td>
<td>2.5-7.5%</td>
<td>50%</td>
<td>00:50:00</td>
<td>62%</td>
</tr>
<tr>
<td>#2</td>
<td>10%</td>
<td>75%</td>
<td>00:14:00</td>
<td>77.5%</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>75%</td>
<td>03:50:00</td>
<td>82.5%</td>
</tr>
<tr>
<td></td>
<td>5-7%</td>
<td>3.1%</td>
<td>00:10:00</td>
<td>2.7%</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>3.1%</td>
<td>02:40:00</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>10%</td>
<td>34.4%</td>
<td>00:22:00</td>
<td>34.1%</td>
</tr>
<tr>
<td></td>
<td>1%</td>
<td>34.4%</td>
<td>03:50:00</td>
<td>36.3% and 13.7%</td>
</tr>
<tr>
<td>#3</td>
<td>8.5%</td>
<td>14.1%</td>
<td>00:17:00</td>
<td>10.9% and 21.9%</td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
<td>14.1%</td>
<td>02:30:00</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>7.5%</td>
<td>54.7%</td>
<td>01:13:00</td>
<td>48.4% and 62.5%</td>
</tr>
<tr>
<td></td>
<td>0.5%</td>
<td>54.7%</td>
<td>03:10:00</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>4.8%</td>
<td>95.3%</td>
<td>00:10:00</td>
<td>79.7% and 99.1%</td>
</tr>
<tr>
<td></td>
<td>0.4%</td>
<td>95.3%</td>
<td>02:00:00</td>
<td>n/a</td>
</tr>
</tbody>
</table>
FIGURES

Pipeline #1
Normal Operations

Figure 1 – Normal Operations – Flow
Figure 2 – Normal Operations -- Pressure
Figure 3 – Normal Operations – Volume Balance
Case 1a

Figure 4 -- Leak – Effect on Pressure Measurement
Figure 5 – Leak – Volume Balance, 1 Minute Average
Figure 6 – Leak -- Volume Balance – 1 Minute (Zoom)
Figure 7 – Leak – Volume Balance – 24 Hour Average
Case 1b

Figure 8 – Leak - Pressure
Figure 9 – Leak – Volume Balance – 30 Minute Average
Figure 10 – Leak – Volume Balance – 2 Hour Average
Pipeline #2

- 15 miles, 23" ID
- 10 Miles, 23" ID
- 50 miles, 23" ID
- 27.5 miles, 23" ID
- 60 miles, 23" ID
- 10 Miles, 23" ID
- 15 miles, 23" ID
- 10 Miles, 23" ID
- 50 miles, 23" ID
- 27.5 miles, 23" ID
- 60 miles, 23" ID
- 10 Miles, 23" ID
- 15 miles, 23" ID
Normal Operations

Figure 11 – Normal Operations – Segment 1 – Pressure
Figure 12 – Normal Operations – Segment 1 – Supplies
Figure 13 – Normal Operations – Segment 2 – Pressures
Figure 14 – Normal Operations – Segment 2 – Deliveries
Figure 15 – Normal Operations – Segment 3 – Pressures
Figure 16 – Normal Operations – Segment 3 – Deliveries
Case 2b

Figure 17 – Leak – Segment 3 -- Pressures
Figure 18 – Leak – Segment 3 – Volume Balance – 10 Minute Average
Figure 19 – Leak – Segment 3 -- Location
Case 2c

Figure 20 – Leak – Segment 3 - Pressures
Figure 21 – Leak – Segment 3 – Volume Balance – 4 Hour Average
Case 2d

**Figure 22 – Leak – Segment 1 -- Pressures**
Figure 23 – Leak – Segment 1 -- Flows
Figure 24 – Leak – Segment 1 – Volume Balance – 10 Minute Average
This figure shows the size change of the leak that occurs near the end of the 24-hour leak imposition.
Figure 26 – Leak – Segment 1 -- Location
Case 2e

Figure 27 – Leak – Segment 1 -- Pressures
Figure 28 – Leak – Segment 1 -- Supplies
Figure 29 – Leak – Segment 1 – Volume Balance – 4 Hour Average
Figure 30 – Leak – Segment 1 -- Location
Case 2f

Figure 31 – Leak – Segment 2 -- Deliveries
Figure 32 – Normal Operations – Segment 2 -- Pressures
Compare this figure to the previous one. With such a comparison during identical operations, the signature of the leak is clearly visible in the lack of rise that the “DELTA4.SP” pressure undergoes. But the signal does not show a kink or other abrupt change, so that without that comparison, the signal is not obvious.
Figure 34 – Leak – Segment 2 – Volume Balance – 10 Minute Average
Figure 35 – Leak – Segment 2 -- Location
Case 2g

Figure 36 – Leak – Segment 2 -- Location
Pipeline #3

320 miles, 46" ID
Normal Operations

Figure 37 – Normal Operations -- Pressures
Figure 38 – Normal Operations -- Flows
Figure 39 – Normal Operations – Volume Balance – 1 Minute Average
Figure 40 – Normal Operations – Volume Balance – 10 Minute Average
Case 3A

Figure 41 – Leak (2in) -- Flows

SUPPLY.FLW.Value
DELIVERY.FLW.Value
Figure 42 – Leak (2in) – Volume Balance – 10 Minute Average
Figure 43 – Leak (2in) -- Location
Figure 44 – Leak (0.5in) – Volume Balance – 2 Hour average
Figure 45 – Leak (2in) -- Flows
Figure 46 – Leak (2in) – Volume Balance – 10 Minute Average

Figure 47 – Leak (2in) – Volume Balance – 30 Minute Average
Figure 48 – Leak (2in) -- Location
Case 3c

Figure 49 – Leak (2in) -- Flows
Figure 50 – Leak (2in) – Volume Balance – 10 Minute Average
Figure 51 – Leak (2in) -- Location
Figure 51 – Leak (05.in) -- Flows
Figure 52 – Leak (0.5in) – Volume Balance – 2 Hour Average