![PSIG Pipeline Simulation Interest Group]

PSIG 1003

Real Time Modeling System Supporting Pipeline Management and Field Operations.

Authors: Diana Gonzalez – Pipeline Application Expert, ECOPETROL S.A. Colombia, Jakob Buchert, Energy Solutions International Inc. Canada, and René L. Varon – VP Global Sales, Energy Solutions International Inc. USA.
Co-Authors: Juan Carlos Unriza Vargaz, ECOPETROL S.A. Colombia, Luis Carlos Eljach, Energy Solutions International Inc. USA

ABSTRACT

This paper describes in detail the key experiences of a well-established Oil & Gas company in Latin America related to the implementation and evolution of a Pipeline Advanced Application project; how these applications have helped the organization to improve the knowledge of its own networks, and how they have provided a solid foundation to manage the critical problem of product theft.

Ecopetrol S.A. (Ecopetrol) is responsible to build and operate the whole Colombian transport infrastructure and distribution of oil & gas and refined products by means of its 8,500 kilometer network of pipelines which run from the production centers to the refineries and ports in the Atlantic and Pacific oceans. Ecopetrol has the responsibility to guarantee supplies of oil and biofuels production throughout Colombia, whether its own production or through domestic or foreign third party providers (Figure 1).

Ecopetrol started implementing real-time online application technology in 1998, mainly motivated by the desire to eliminate hydrocarbon leaks, thefts and losses occurred in the provision of the transport service.

The paper is supported by field data gathered by Ecopetrol that describes the evolution and performance of the application as well as the overall performance achieved.

COMPANY DESCRIPTION

The pipeline network of Ecopetrol consists of 50 transportation systems, including more than 52 supply, delivery, storage and pump stations. The transportation network is grouped into two main systems: multiproduct pipelines and crude pipelines. Due to the complex topography of Colombia, including the Andes mountain chain located at the central and west side of the country, almost all of these pipelines have elevation profiles with dramatic variations from 0 meters to 3,000 meters (0 to 10,000 feet) and temperature changes of up to 30° C (54° F) within a few miles (Figure 2).

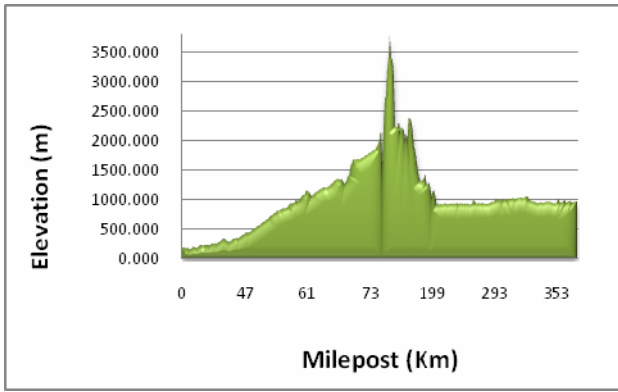**Figure 1. Colombian Pipeline Network**

Figure 2. Typical Pipeline Elevation Profile

Moving different types of products, and the availability and amount of volume demanded in the country, required that the transportation systems are able to operate with batches. Currently, about 44% of the network operates under this condition; 15 different products are transported, including gasoline, diesel, airplane gas, kerosene, and others. Table 1 lists the historical information about the volume transported by Ecopetrol from 2003 to 2008.

Indicator	Unit	2003	2004	2005	2006	2007	2008	2009
Volumes of crude transported	Thousands barrels per calendar day	426,6	445,2	443,8	471,1	516,6	542,3	669,9
Volumes of refined products	Thousands barrels per calendar day	152,2	155,1	159,4	180,7	193,8	209,5	235,4

Table 1. Ecopetrol's Transportation Capacity

Moreover, since 2002 Ecopetrol has been facing a complex problem due to an incremental amount of losses associated with product theft from its transportation systems. This problem has prompted the creation of a strategic program based mainly on the following points: assurance of field infrastructure, prevention procedures, police and national army response, control of the supply chain, creation of new laws, social management programs and technological improvements.
As a result of this initiative, Ecopetrol has achieved a substantial decrease in the theft of oil since 2002, as shown in Figure 3.

Among the technologies used to support the strategy of controlling refined product theft, Ecopetrol implemented software for leak detection and location, currently known as PipelineManager®, based on real time transient modeling technology, with applciations for leak detection and location, batch tracking and scraper tracking.
Although, this software has been installed since 1998 as a tool for the detection of breakdowns and faults in the pipeline, since 2005 Ecopetrol and Energy Solutions have focused their efforts in detecting illicit valves or product theft in order to support the strategy of eliminating theft.
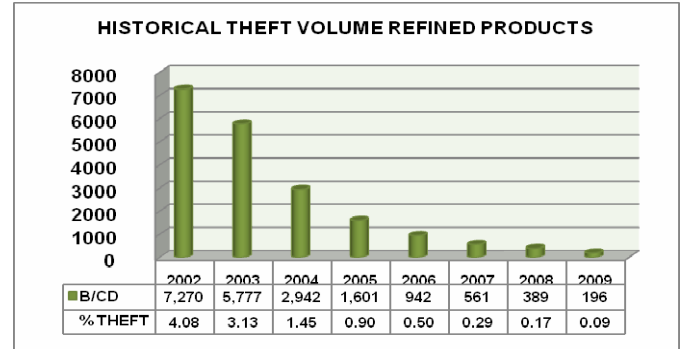

Figure 3. Evolution Of Theft Detection Achievements

Technology Background

Ecopetrol controls and operates all its multiproduct pipelines through a SCADA system located at the Main Control Center in Bogota. On top of the SCADA system Ecopetrol implemented a set of advanced applications. These applications are based on a real time transient model, which consists of a hydraulic and thermodynamic representation of the product's physical behavior while traveling through the pipelines. The model takes into consideration heat exchange with the surrounding environment, the physical properties of the pipeline and the physical properties of the transported products. The model thoroughly details the pipeline's present state under any operating scenario. Using the real time model as a platform for Ecopetrol's multiproduct pipelines the following applications have been configured: Leak Detection & Location, Shut-In Leak Detection, Batch Tracking, Scraper Tracking, and an Operator Trainer tool.

Currently Ecopetrol has all of its 14 multiproduct pipelines configured and running with applications for Leak Detection, Batch Tracking and Scraper Tracking.

The user interface brings several features of great importance for Ecopetrol to achieve its goal of reducing losses associated to product theft; among these features are:

–   Analytical Tools - These are used to help analyze system responses etc. One of these tools is the historical line fill and event capabilities. The user can view past line fill and events (like leaks) by dragging a time slider and selecting the desired date/time. It is also possible to enable animations of past behavior

–   Playback Mode – This module allows the system to record incoming data over a rolling time period. Two different files are stored: valid hydraulic state and boundary conditions. This information is used to replay the behavior of the system, running input data through a copy of the model that can reside either on-site, in an engineering or development environment or vendor offices for support

To describe the general features of the leak detection system it is important to initially define a series of terms that are usually used in the field, such as:

–   Leak Size- The flow value that is leaving the pipeline through the perforated orifice. In some instances it directly refers to the diameter of the orifice that has been perforated in the pipeline. This paper uses the term as a reference to the flow value.

–   System Sensitivity – Refers to the minimum leak size detectable by the application.

–   False Alarms – Refers to a situation where the system reports the presence of a leak when it doesn't exist.

–   Reliability – Refers to the maximum number of false alarms reported by the system during a specific period of time.

–   Robustness – Refers to the degree of system availability with respect to third-party failures and the application itself.

–   Threshold - The minimum level of variation in the system's response that can be considered as a leak event. The threshold is generally determined by the instrumentation available and its quality, the quality of communications, SCADA resolution, and the types of signal filtering employed by the application.

Socio-Economic Environment

The important value that hydrocarbons possess in modern societies makes pipelines vulnerable to the action of unscrupulous people or groups that are willing to take high risks in order to obtain economic benefits.

As time goes by, the information related with the technologies that operating companies use to detect these events has been made public; these groups have also progressively become more sophisticated in the way they operate in order to go unnoticed, and this is the main challenge to implementing a reliable theft-detection system. Leaks are normally uncontrolled events, while theft-related losses or illegal access points are controlled events by people with certain operational knowledge.

Those who engage in this activity have opted to open their illegal "Hot-tap" valves more slowly, subtracting product at lower flow rates that frequently are under the threshold detection of the least sophisticated leak detection systems. Under these conditions, operating companies require even more sophisticated and intelligent leak detection systems.

This drove Ecopetrol's requirement for a system capable of reaching greater sensitivities with less false alarm incidences. Especially important is the capability of providing the operator with additional information in order to make an analysis to determine the real cause of a specific disturbance in the pipeline.

Project Evolution

Motivated mainly by the product-theft situation, Ecopetrol launched an initiative in 1998 to implement a set of advanced applications after completing the installation of its SCADA system.

The initial scope of the project included the supply of the technology and the configuration of three lines in the system. The application provided at that time was a UNIX based application, running on two main servers with a hot-standby architecture.

The implementation of this first phase helped both Ecopetrol and the vendor to identify several points to potentially improve the overall performance of the solution. The extreme elevation changes of the Colombian topography, as well as the frequent diameter changes in these pipelines, were two important factors to be considered and managed by the technology.

On the other hand, the requirement to install and maintain the recommended instrumentation in the field and the reliability of communications and data gathering devices were also important tasks for Ecopetrol.

However, since the very beginning of the commissioning of the systems, the results have been tangible. Operations groups were able to start detecting major illegal hot-taps and sending crews to remove such devices.

Expansion of the technology continued during the following six years, with additional projects to include new pipelines and to upgrade the application.

In 2001 the system was migrated to a Microsoft Windows$^{®}$ Server platform and then in 2003 a big initiative was launched to implement a technology transfer program. The main objective of this program was to improve the sensitivity of the system and to train an "elite group" within Ecopetrol to take full advantage of all the capabilities of the system.

In 2006, as fast as Ecopetrol had improved its systems and strategies in leak detection, the theft behavior changed. The sizes of the "leaks / thefts" were getting smaller and the periods of product theft were shorter and not continuous. This required big changes in order to overcome the situation,
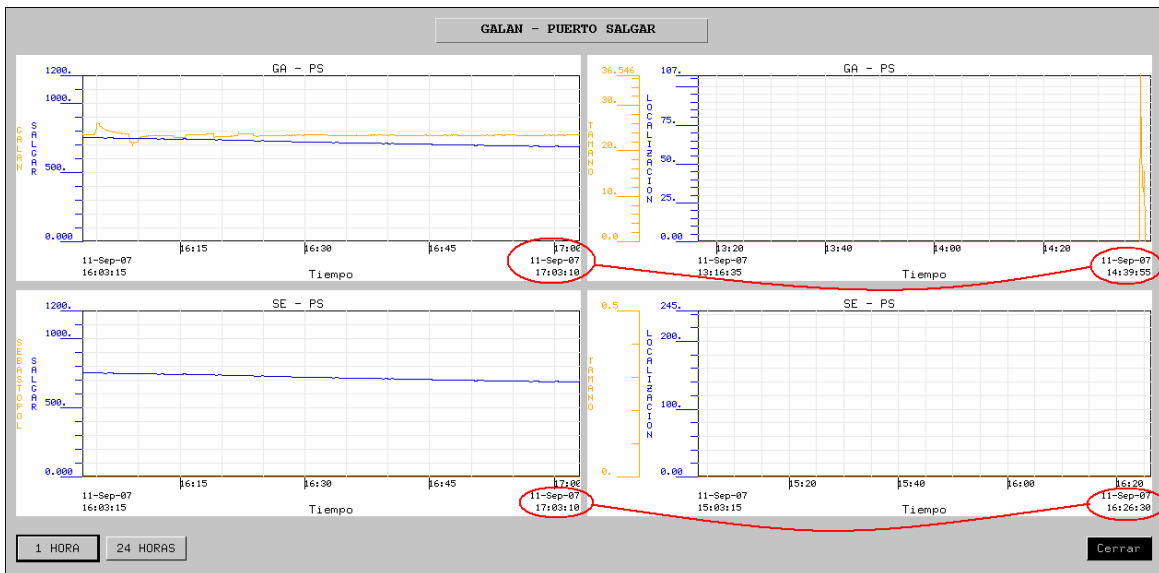
Figure 4. Delay in Leak location and size trend.

beginning with the basic infrastructure of the leak detection system: the field instrumentation. Those instruments had completed their duty cycle and their accuracy and repeatability were not good enough to provide adequate information to the leak detection system to deal with this new pattern of leaks.

At the end of 2006 Ecopetrol started to upgrade all its pressure and temperature instrumentation in the field. The upgrade process became one of the main strategies to improve the performance of the system to face the new conditions.

That was the first step, but before moving any further, Ecopetrol needed to put a program in place to maintain the new infrastructure. To do so, Ecopetrol included those instruments in the same program that provides maintenance to the instrumentation that supports custody transfer processes.

In 2007, Ecopetrol moved forward with the next step of its program, restoring the redundancy of the system to assure its high availability. It was necessary to reconfigure the SCADA communication processes and watchdog processes. However, one issue remained: one of the hydraulic processes was breaking down periodically, which was an indication that the database was growing beyond its permitted limits, so Ecopetrol extended the maintenance program to also include the application software. These strategies helped to increase the system availability and therefore allowed the operators to increase usage of the system.

Once the operators started to manage the system, they came up with a list of the next improvements to make:

- Navigation: Review, validate and improve all the system screens.
- Trend and span time: Revision, validation and improvements to the leak location and leak size trends. A delay problem with these trends was identified that affected the evaluation of results (Figure 4).

- Update configurations: Some new delivery stations had been installed and other old ones had been eliminated. The system reported in some cases a permanent leak during a delivery or was using incorrect instrument values, generating errors in the hydraulic model.

In order to take care of these recommendations; Ecopetrol did a comprehensive revision of every menu, command button and screen in the system. Almost all the changes were focused on the user interface (GUI).

The objective of this effort was to standardize the navigation procedures and the span of the time in each trend. Ecopetrol also eliminated deliveries in order to discard non-existent instrumentation.

At the same time, Ecopetrol was validating the entire database configuration in order to ensure that the model reflected operational conditions and current field instrumentation.

All the configurations were updated to include new stations, new instrumentation, and to remove equipment that was no longer in operation on each pipeline.

Overall, by the end of 2007, Ecopetrol had improved the availability of the system. Many suggestions were implemented and software issues were solved. However, Ecopetrol had not done anything about the performance of the system.

In 2008 Ecopetrol was looking for strategies to improve the performance of the system, and following vendor recommendations, Ecopetrol started to review all the elevation and diameter profiles.

A detailed report was created identifying possible deviations between the elevation and diameter profile data initially provided by Ecopetrol and the real condition of the pipelines.

This prompted Ecopetrol to create a new set of elevation and diameter profiles. These were obtained by the Physical Integrity Group in Ecopetrol using techniques such as intelligent scrapers and GPS mapping (Global Positioning System). These confirmed vendor observations of elevation and diameter discrepancies.

The raw elevation data provided by the Physical Integrity Group was very detailed; there were many samples per kilometer and not all of them could be configured in the system. The solution was to implement a sampling method that eliminated the space redundancy, only including new data when the difference with the previous data point was considered to be significant.

Figure 5 shows a comparison between the old configured elevation profile, the new elevation profile (raw data) and the elevation profile after implementing the sampling method. The old profile was very different from the real profile of the line with many deviations, mainly in the highest mountain section, which generated large errors in the hydraulic model calculations.
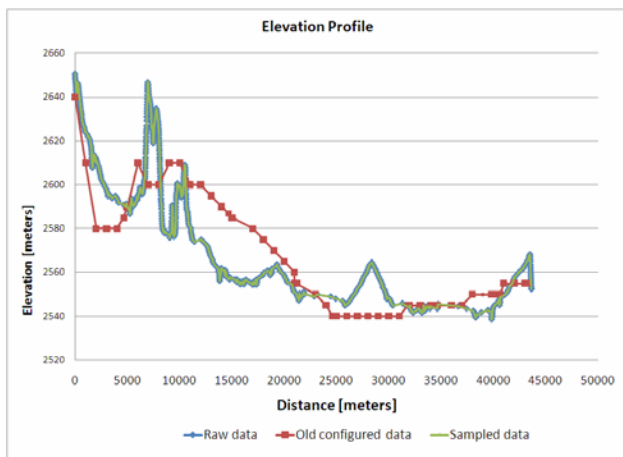

Figure 5. Elevation Profiles.

With the corrected profiles the overall performance of the model was improved. The diameter profile was updated, which also helped to provide more accurate line fill information, thus improving the estimations of the batch tracking module.

With new profiles and more accurate line fill information, the differences between the measured flow and flow calculated by the model were decreased so that the accuracy, especially the leak location, of the system was improved. Thresholds were also reduced without compromising the reliability of the application with regard to false alarms (Figure 6).

Appendix – Elevation Profile Validation describes in detail the hydraulic analysis performed and conclusions reached with regards to the elevation profile problems after evaluating the behavior of the model.

After going through this process, the operators were getting more and more interested in learning new things about the system. Ecopetrol prepared two manuals for primary support to operators; this action was the second strategy for ensuring system availability.

At the end of 2008 Ecopetrol started to update the system with new software releases. The new GUI was one of the most important improvements of the new version (Figure 7).

During 2009, all the pipeline configurations were migrated to the new version of the software. The configuration philosophy had changed since the previous version; now it is handling special operational conditions without using additional strategies or instrumentation, which simplified the model configurations.
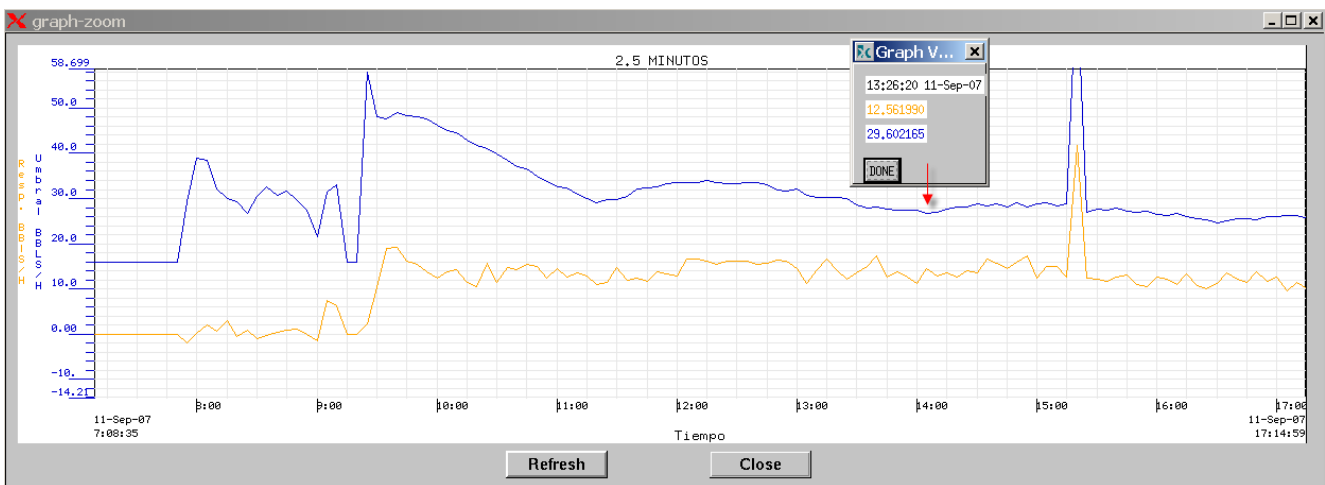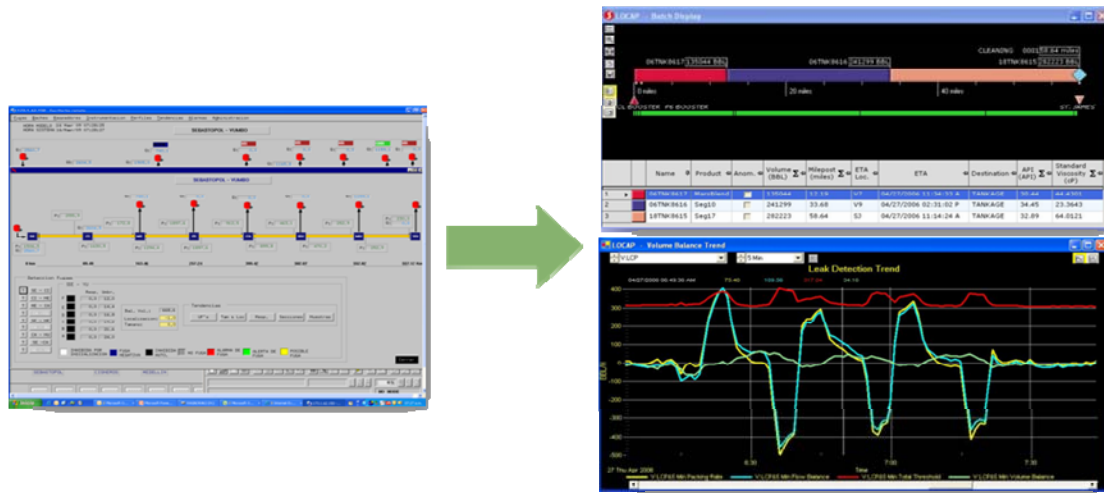

Figure 6. Modified Threshold.

Figure 7. Old versus new GUI

Performance Evaluation Process

As part of the evolution process, and in order to improve the overall usage of these tools, Ecopetrol started to evaluate the system performance in 2007 with regard to leak detection and location by the creation of two main indicators:

$$\text{Percentage of Detected Leaks} = \frac{\text{Number of Leaks Detected by the System}}{\text{Reported Leaks}}\ \%$$

$$\text{Percentage of Located Leaks} = \frac{\text{Detected and Located Leaks Detected by the System}}{\text{Reported Leaks}}\ \%$$

"Percentage of Detected Leaks" only evaluates the system performance in leak detection, i.e., if the system generated an

Leak Size	Allowed Deviation in Location
3.0%	+/-10.0%
4.0%	+/-7.5%
5.0%	+/-6.0%
6.0%	+/-5.0%
7.0%	+/-4.0%
8.0%	+/-3.5%
9.0%	+/-3.0%
10.0%	+/-2.8%
11.0%	+/-2.6%
12.0% or larger	+/-2.5%

Table 2. Allowed Deviation % for leak location – Percentage based on the size of the segment of balance defined in the configuration

These measurements have been useful to represent the evolution of the System. Figure 7 shows the values of the indicator in 2007, the first period (January-June 2007) was reported by the operators without administrative oversight. The value was less than 20 percent, which would mean that just twenty leaks of one hundred leaks were detected by the

system. However, this significantly underestimated the real performance; what it was reflecting was that the operators did not use the system and did not take action to follow up on the real performance. The initial goal was therefore set to 50%, because Ecopetrol had just started the improvement process.

In August 2007, Ecopetrol made a process change so that the indicators were measured and followed by the system administrator and then validated by the operators. The indicator value increased and exceeded the initial goal (Figure 8).
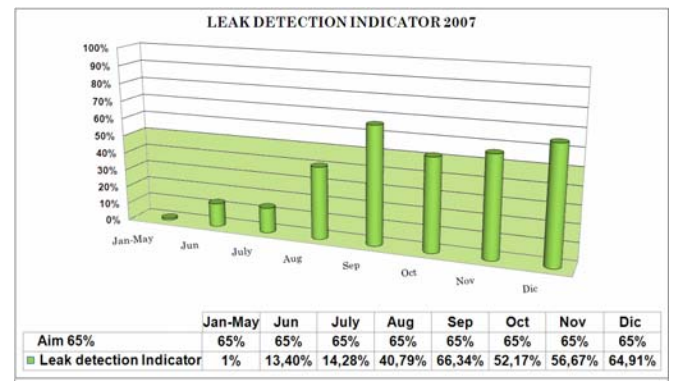

	Jan-May	Jun	July	Aug	Sep	Oct	Nov	Dic
Aim 65%	65%	65%	65%	65%	65%	65%	65%	65%
Leak detection Indicator	1%	13,40%	14,28%	40,79%	66,34%	52,17%	56,67%	64,91%

Figure 8. Leak Detection Indicator 2007

At the beginning of 2008, the new goal was 65%. The improvement process was showing its results and the previous goal had to increase according to Ecopetrol necessities and the new performance (Figure 9).
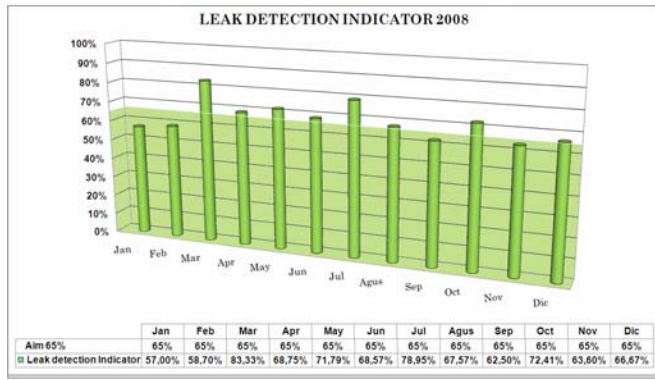
	Jan	Feb	Mar	Apr	May	Jun	Jul	Agus	Sep	Oct	Nov	Dic
Aim 65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%	65%
Leak detection indicator	57,00%	58,70%	83,33%	68,75%	71,79%	68,57%	78,95%	67,57%	62,50%	72,41%	63,60%	66,67%

Figure 9. Leak Detection Indicator 2008

At the end of 2008, the system upgrade process was started. The implementation of the new version had to increase the sensitivity (minimum size leak detected), and enable the application to detect leaks in slack flow conditions, as well as shut-in. The indicators for leak detection and leak location were set to reach at least 70% (Figure 10).
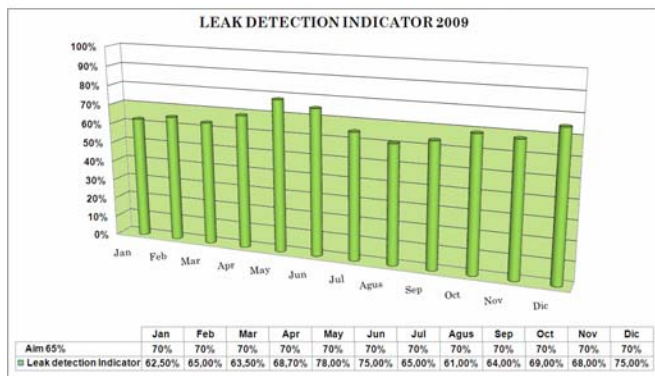

	Jan	Feb	Mar	Apr	May	Jun	Jul	Agus	Sep	Oct	Nov	Dic
Aim 65%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%	70%
Leak detection indicator	62,50%	65,00%	63,50%	68,70%	78,00%	75,00%	65,00%	61,00%	64,00%	69,00%	68,00%	75,00%

Figure 10. Leak Detection Indicator 2009

It was the first time in the entire evaluation process that leaks under slack-flow and shut-in conditions were considered in the calculation of the performance evaluation criteria. It meant that the universe of detected leaks was increased because previously these kinds of leaks could not be detected.

Overall the expected performance of the system was achieved; Ecopetrol continues its efforts to improve even further the sensitivity of the application. Efforts related to field instrumentation, operator training, and system tuning are being identified as the main initiatives for 2010.

CONCLUSIONS

Through the implementation and evolution of such a big project, several lessons and key points were learned that ensured at the end of the process the success of the project and the usability of the system. This section summarizes some of these key items.

Information Management

Many parameters are involved in the achievement of satisfactory leak detection performance in a pipeline. The relevance of these parameters, which include elevation, instrument accuracy, thermal properties, etc. vary depending on the specific characteristics of the pipeline. For example, in steep topographies it is critical to have accurate elevation data; in exposed pipelines, thermal modeling and tuning is far more relevant than it is for buried pipe.

For the Ecopetrol system it was critical to classify pipelines based on their specific characteristics and focus on the areas with higher impact on final leak detection performance. This approach shortened the time required to achieve better results, increasing confidence in the system and bolstering Ecopetrol's interest in getting more pipeline data; all part of a healthy implementation cycle.

System Performance Evaluation

Good results were evidently the major goal in the Ecopetrol implementation. The first challenge after initial implementation was determining how to measure how much better the new system was compared to the previous system. Before real leak tests were performed, a solid estimation of system performance was needed; even more so when considering false leak alarms as part of the "performance" equation.

The most important source of information was the CCMO (Operation Control Center at Ecopetrol) report on leak events, especially those confirmed by field personnel. As mentioned before, this information was cross referenced with the new and previous leak detection system events to estimate each system's leak detection and location performance. At the same time, false alarms were being recorded and tabulated in order to be considered in the performance estimation. The higher performance of the new system became clear, even from the beginning, so a more elaborate analysis for the new system continued after the initial estimation.
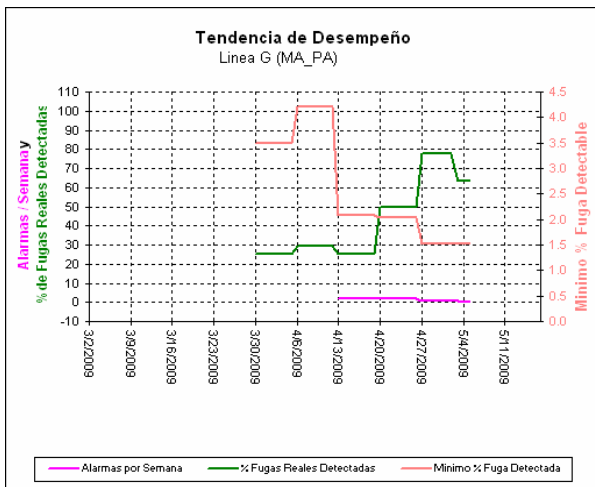
Figure 11. Performance Tracking

Figure 11 shows an example of performance tracking for a particular pipeline. This was an easy way to estimate the impact of implementation changes on each particular pipeline.

Most of the pipelines were ultimately tested with controlled pipeline leaks, confirming the previously calculated performance of the leak detection system for that particular pipeline.

Data Project Management

The success of Ecopetrol has been based on close collaborative work with the technology vendor and a strong commitment to expand the use of the application within its own organization. Big efforts have been made by Ecopetrol to create a strong environment for using the application, from field instrumentation to internal organizational changes and working externally to coordinate with third party organizations.

Microsoft SharePoint® was used as the repository for all this valuable information. Successful implementation upgrades were recorded in SharePoint to be applied to all applicable systems. Since a large group of engineers were involved in the implementation, sharing this information was critical for the success of the project.

Knowledge Transfer

Different levels of knowledge transfer were required to make the Ecopetrol implementation successful. The initial, and perhaps the most important, was pipeline data transfer from Ecopetrol to the implementation team. A huge amount of data was available, so it was important for the implementation team to guide the client to obtain the data which had the higher impact on the desired results. The client learned from this process and identified which data was to be presented to the

implementation team with higher priority.

The implementation team itself shared data using SharePoint as noted above. High impact implementation upgrades were shared among the group and individual changes became overall system changes. New ideas were discussed in periodic team meetings and some of them implemented with excellent results.

The final knowledge transfer was from the implementation team to Ecopetrol. The leak detection personnel were empowered via a set of training sessions, ranging from basic to advanced levels of training, making them comfortable in working with the system and even proposing implementation upgrades for some of the pipelines.

Total Solution

Quality assurance in the operation and management of transport pipelines cannot rely alone on the availability of advanced applications. It is fundamental to follow an operating plan, with its respective procedures. This plan includes the maintenance and operation of advanced applications, but at the same time interaction with other work teams must support the final objective.

The key for success is to have a coherent plan to cover all the aspects of this kind of implementation, including: true description of the pipeline physics (elevation, pipe diameters, station location, etc.), availability of accurate field instrumentation, dependable and well-configured field data-gathering devices (RTUs, PLCs), consistent communication systems, robust SCADA platform, state-of-the-art and user-friendly technology for advanced applications. Overall, the most important factor is to have a support team to make sure that operators understand and take advantage of all the tools that this technology provides. Operators are at the top of this entire complex IT structure, so it is fundamental to gain their support and confidence to use make good use of these applications.

ACKNOWLEDGEMENTS

Appendix A - ELEVATION PROFILE VALIDATION

As described above, one of the most important contributions of using applications based on real time modeling was that this application helped Ecopetrol to identify critical problems with pipeline elevation profiles. Ecopetrol had been using this data to evaluate operations and to plan expansions, so it was extremely important to identify and correct these deviations. This section of the paper describes how the problem was detected and what recommendations were made.

Background of the Process

Live leak tests on various lines were performed by taking out known amounts of product at selected locations. Results of the leak tests were investigated in order to validate the Leak Detection Module (LD) performance and model configurations. Described here is the analysis of two particular cases where the location was not predicted with sufficient accuracy by the LD during the live test.

The main conclusion of the analysis was that significant leak location errors could be caused by uncertainties in the elevations when batches of significantly different densities were moving along sections with significant elevation gradient (slope).

Case 1

For case 1 the evaluated pipeline section is 56 km (35 miles) long with an 8" diameter and elevations ranging from 193 to 853 m (633 to 2799 feet).

During the leak test the evaluated section was filled with 2 different batches at 8:04 AM before the test started: Diesel (API gravity 32.3) in the left part (6904 bbl), and gasoline (API gravity 58.2) in the remainder of the section (besides a small buffer of different product separating the 2 main batches, which is irrelevant for the purpose of the evaluation).

The flow rate into and out of the section is metered at each end, and calculated by the LD within the section. This is illustrated in Figure 13 showing the 2 first sections of the pipeline model (also showing typical, total inventory volumes). The figure shows especially the location of pressure meters (P), temperature meters (T), metered flow rates (Q_{in}, Q_{out}) and calculated flow rates (Q_{ups}, Q_{dws}).

Case 1 Replay

The LD was setup in an offline environment allowing for replays using SCADA data from the period of the leak test. The calculated leak location (distance in km from the section inlet) for the replay of the original case 1 is shown along with other key results in Figure 12. The real leak was located at 40 km (25 miles).
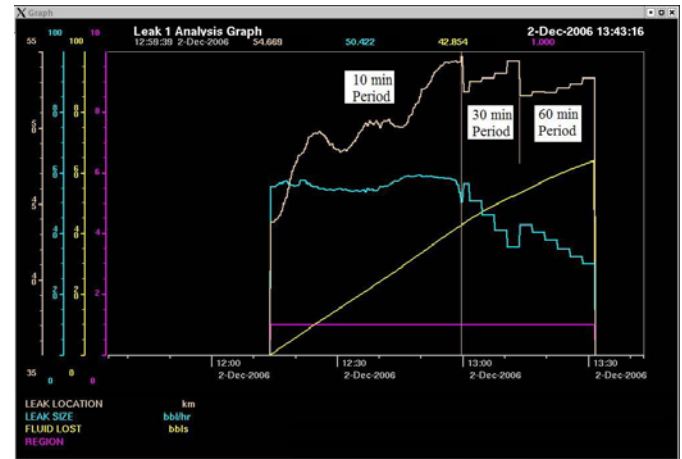

Figure 12. Leak analysis graph obtained for replay of the leak test for case 1 using the originally configured elevation profile.
(The graph is based on LD detection periods 10, 30 and 60 min as shown. Naturally the 30 and 60 min periods continue for a while after the leak is actually finished).

Relation between Flow Error and Leak Location Error

The leak location method of the LD is complex in the sense that it accounts for the effect of varying batches (densities and friction factors) and diameters over the section.

However, as an approximate estimate of the location, consider the following simplified relation:

$$x = L \frac{UF_{dws}}{UF_{ups} + UF_{dws}} \qquad \textbf{Equation 1}$$

Where:

x is leak location
L is section length
$UF_{dws} = Q_{dws} - Q_{out}$
$UF_{ups} = Q_{in} - Q_{ups}$

Q_{dws}, Q_{out}, Q_{in} and Q_{ups} are defined in Figure 13.

This equation relates the leak location directly to the difference between calculated and measured flow downstream in the section. It means that a location error will correspond to a flow error, defined as calculated minus measured value, downstream in the section.

The result of equation 1 for the actual case is approximately that a 5 bbl/hr flow error (downstream) is equivalent to a 5 km (3 miles) location error, a 10 bbl/hr error is equivalent to a 10 km (6 miles) location error, a 15 bbl/hr error is equivalent to a 15 km (9 miles) location error, etc.
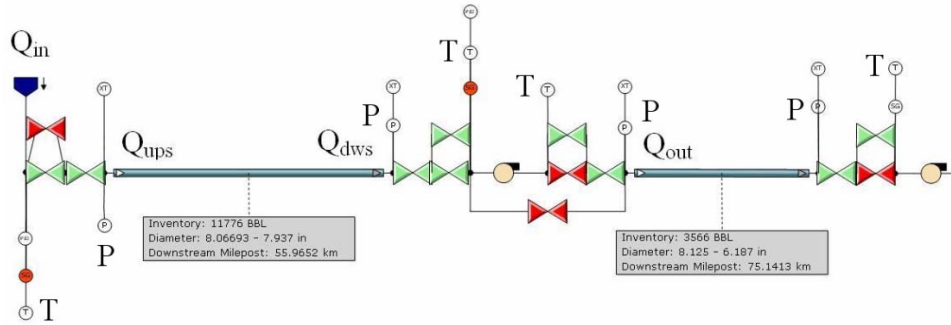
Figure 13. Definitions for the evaluated and adjoining pipeline section

By replaying the LD on the leak test data it turned out that a flow error developed in the model during the leak.

Figure 14 shows the difference between measured and calculated flows upstream and downstream in the section, extracted from the replay. Note that the flow error in fact is varying over the duration of the leak corresponding to the location error in Figure 12. Before the leak, the absolute difference was mostly less than 5 bbl/hr; but at the end of the leak test it was around 15 bbl/h – which explains the 15 km (9 miles) location error.
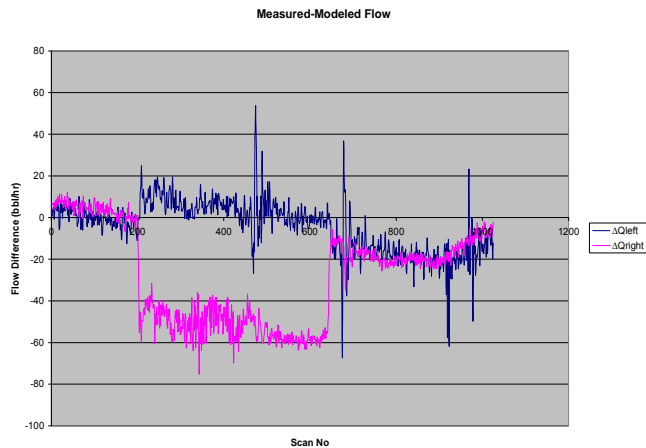
Note: $\Delta Q_{left} = Q_{in} - Q_{ups}$
        $\Delta Q_{right} = Q_{out} - Q_{dws}$

Figure 14. Difference between measured and modeled flow in left and right end of section.

Impact of Special Batch Movements and Pipeline Slope

According to the line fill and elevation information, for case 1 a diesel/gasoline batch interface is moving uphill at the last part of the section with varying slopes, typically 4% - 6%. During the leak test that lasted from 12:00 to 13:00, this batch interface moved approximately 5 km (3 miles) in distance from around position 50 km (31 miles) to the end of the section.

The mainline flow, as driven by given pressures in each of the section ends, will depend on the slope (elevation gradient) along which the batch interface is moving. Referring to the definitions in Figure 15, consider a batch interface located somewhere between L_1 and $L_1 + L_{hill}$.
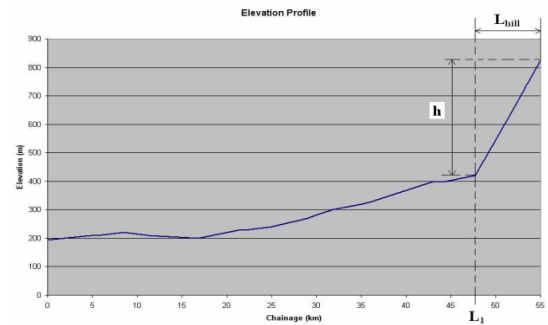

Figure 15. Definition of some terms

An analytical expression for the flow was derived by utilizing the fact that the LD is calculating the flow rates using pressures in each end of the section as boundary conditions. The resulting expression is provided in equation 2, which is valid for a given, fixed pressure difference over the section:

$$Q = \sqrt{\frac{\alpha g (\rho_2 - \rho_1)\xi + \Delta p_{f0}}{(c_1 - c_2)\xi + \Delta p_{f0}/Q_0^2}} \qquad \textbf{Equation 2}$$

Where:

Q:	Flow rate
α:	Slope of hill, $\alpha = h/L_{hill}$ (Figure 15)
g:	Acceleration of gravity
ρ_2:	Density of downstream batch
ρ_1:	Density of upstream batch
ξ:	Position of batch interface relative to L_1, $0 \le \xi \le L_{hill}$ (Figure 15)
Δp_{f0}:	Initial friction pressure loss in the whole section
c_1:	Friction pressure loss coefficient upstream of batch interface, $c_1 = 8 f \rho_1 / (\pi^2 D^5)$; where f is friction factor and D is inner diameter
c_2:	Friction pressure loss coefficient downstream of

batch interface,
$$c_2 = 8\, f\, \rho_2 / (\pi^2\, D^5)$$
Q_0:   Initial flow rate in the section

This relation between flow and batch interface position for different slopes is shown for case 1 in Figure 16. If for instance the real hill is steeper than in the model, the model will overestimate the flow as a heavier batch is pushed uphill. The difference between the purple line (representing the configured slope, 4.36%) and the yellow line (representing an imagined slope, 5.9%) at the end of the graph is approximately 15 bbl/hr. This value is in agreement with the flow error at the end of the leak test, which therefore can be expected to be explained by small errors in the slope of the pipeline.

The slope depends on the elevations, which can be associated with large uncertainties.
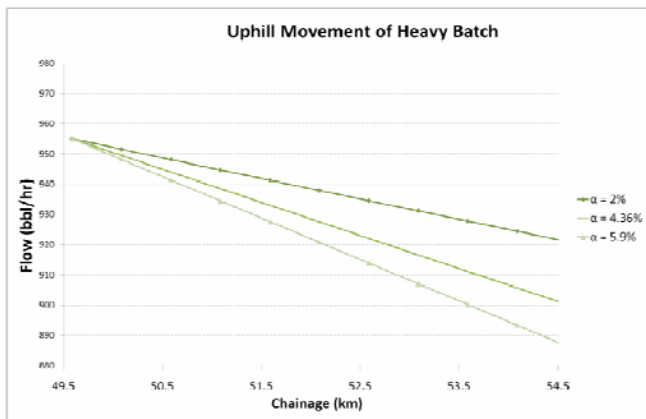
Figure 16. Theoretical calculation of flow as a function of batch interface position for different pipeline slopes, at constant pressure difference over the evaluated section for case 1.

Test of Alternative Elevation Profile

Due to the obvious sensitivity of the location to elevation errors, an alternative elevation profile was tested by another replay on the real time data from the leak test for case 1. Only the slopes of the section where the batch interface is moving during the leak matter for the leak location. Therefore only elevations in the last 6 km (3.7 miles) of the evaluated section were changed during the replay.

The elevations are generally associated with large uncertainties. In the past, evaluations of static pressure measurements over the section had suggested a correction at 103 m (338 feet) for end-to-end elevations.

The graphs in Figure 17 show the originally configured elevations and the alternative elevations tested. The differences between the current and alternative elevations are 75 m (246 feet) or less, hence within the uncertainty range. Also shown are the pipeline slopes and approximate distance traveled by the batch interface during the leak.
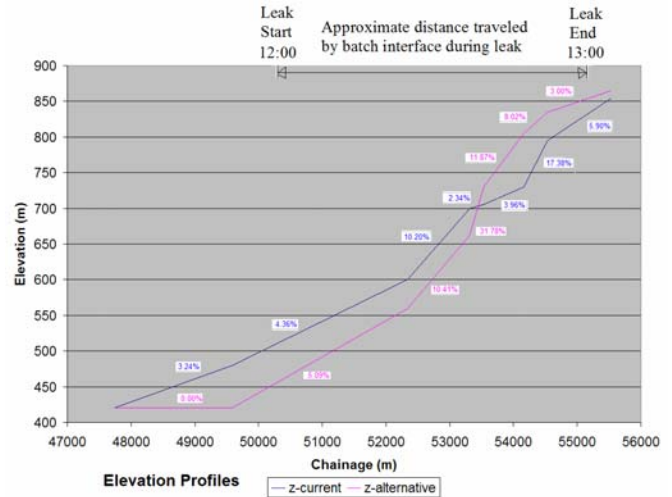

Figure 17. Configured and alternative elevation profiles

Recall that Figure 12 shows the LD leak analysis graph for the current elevations. Figure 18 shows the same graph for the alternative elevations. The location range changes from the original 44-55 km (27-34 miles) to 37-45 km (23-28 miles). According to Figure 19 the average location calculated for the alternative profile is 41.7 km (25.9 miles), which is close to the real location.

Clearly, the alternative elevation profile reduces the development of flow and location errors.
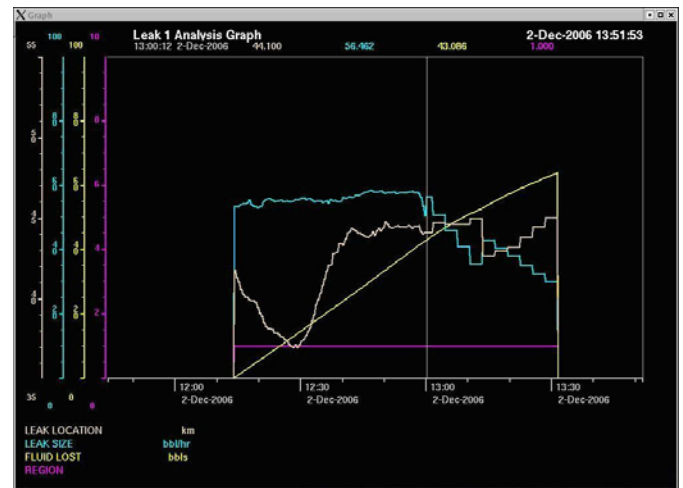

Figure 18. Leak analysis graph obtained for tested, alternative elevation profile.
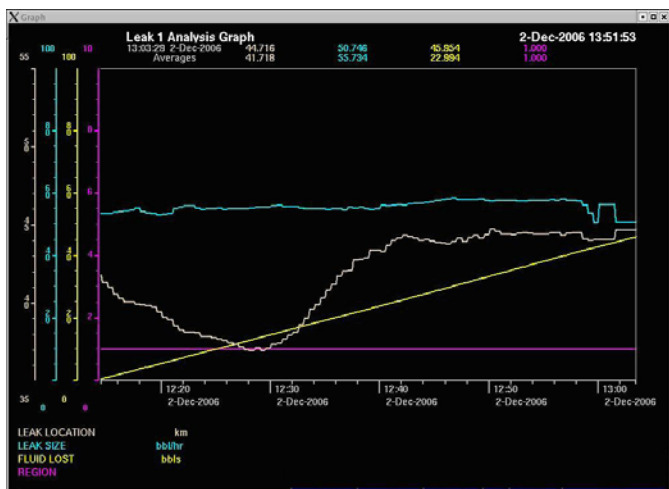
Figure 19. Leak analysis graph obtained for tested, alternative elevation profile, zoomed in.

Before and after the leak, the automatic tuning of flow of the LD is active, which will eliminate the impact of most elevation errors, whereas during the leak the auto-tuning feature turns off automatically. For this and other reasons the described replay does not provide a guaranteed correct elevation profile. The purpose of the replay is solely to demonstrate the impact of elevation errors. However, a better profile may be obtained by including more intermediate points than is shown in Figure 17 and also by observing calculated flows while the auto-tuning feature is turned off before and after the leak.

Case 2

For case 2 the evaluated pipeline section is 153 km (95 miles) long with a 10" diameter and elevations ranging from 910 to 1210 m (2986 to 3970 feet). The section, as measured from the inlet of the entire pipeline, starts at 400 km (249 miles) and ends at 553 km (344 miles).

Two tests were carried out in the evaluated section for case 2. At the start of the leak tests, near the leak location, the section contained batches with head positions and densities as shown in Table 4.

Product	Head Position (km)	API Gravity	Density at 80 ˚F (kg/m³)
Jet	435.6	42.3	808
Diesel	444.1	32.3	858
Gasoline	469.6	58.2	739
Gasoline	485.5	55.9	748
Gasoline	517.3	58.2	739

Table 4. Initial batch head positions and densities in the evaluated section for case 2.

The real location of both leaks tested for case 2 were 429 km

(267 miles). The first test succeeded with the leak correctly located. The second test was done less than an hour after the first test and resulted in leak locations ranging between positions 400 and 454 km (249 and 282 miles) (Figure 20).
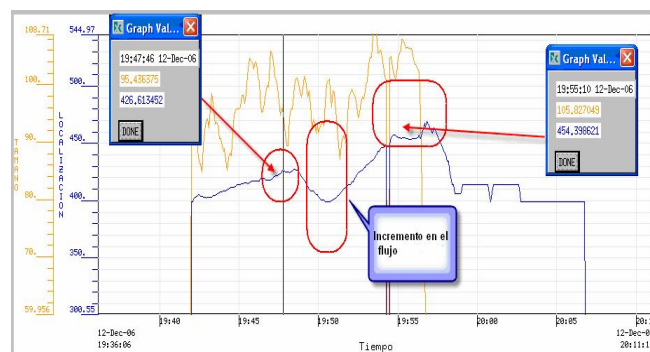

Figure 20. Leak analysis graph obtained during the live leak test - case 2

Only this second test is described further in the following.

Case 2 Evaluation

Unlike case 1, case 2 was not setup in a replay model. Instead the case was just evaluated directly from the results of the live leak test.

In the following the assumption is discussed that the location error can be explained in the same way as for case 1 by elevation uncertainties.

Measured flows in each end of the evaluated section are shown in Figure 21. The flow changes can be related to the type of batch interface movements already described along with elevation gradients.
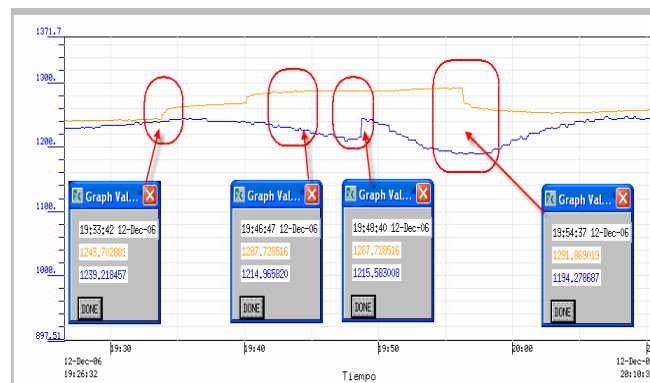

Figure 21. Measured flows upstream (orange color) and downstream (blue color) in the evaluated section for case 2.

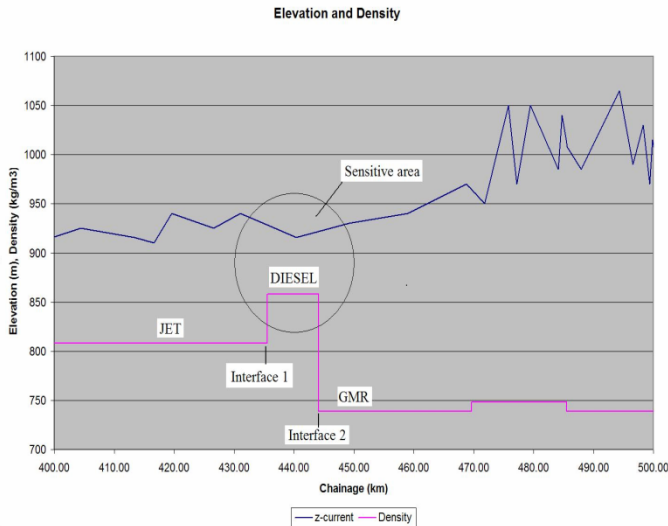The profile of elevations and densities according to Table 4 is shown in Figure 22.

Figure 22. Profile of estimated density and originally configured elevation for case 2

Figure 22 shows especially the expected sensitive area with regards to elevation error impact on the leak location during the test, due to the location of batch interfaces 1 and 2.

Again, using equation 2, the flow error due to errors in elevation gradient (pipeline slope) can be evaluated, see Figures 23 and 24. The slopes originally configured in the model were very modest (-0.26% and 0.16% as shown in blue color in the figures). The sign of the slopes reflect that, according to Figure 22, batch interface 1 is moving downhill, and batch interface 2 is moving uphill.
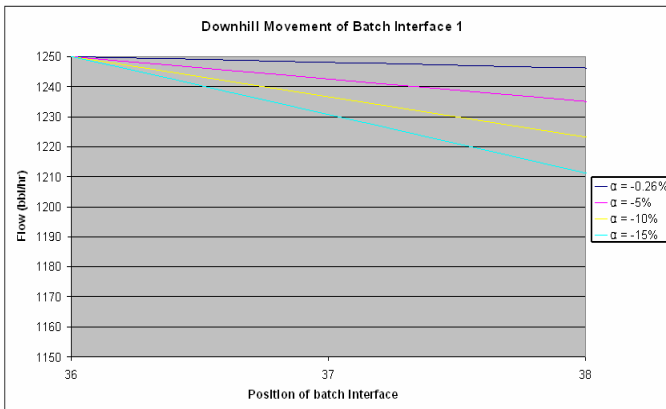

Figure 23. Flow as a function of distance between batch interface 1 and start of section for different negative pipeline slopes, at constant pressure difference over the section.
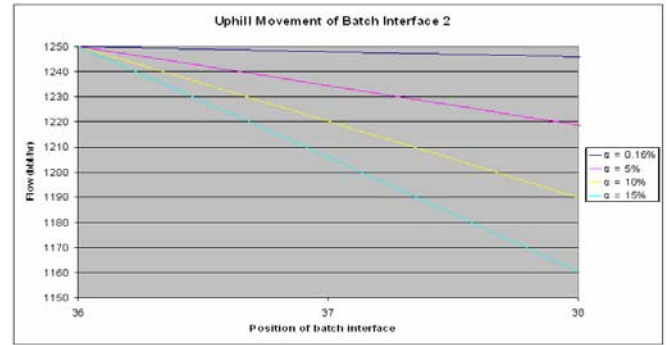

Figure 24. Flow as a function of distance between batch interface 2 and start of section for different positive pipeline slopes, at constant pressure difference over the section.

As a first evaluation, it is noted that the sign of the slopes and the difference in densities between the two interfacing batches are such that the real flow will tend to decrease due to the movement of both batch interfaces. The total flow decrease is in fact the sum of the two calculations (Figures 23 and 24). With too small slopes (absolute) in the model, the modeled flow would therefore tend to decrease too little compared with the measured value. This is a good, first confirmation of the assumption discussed. It follows that the error source could be a missing, or too small, downwards elevation peak in the sensitive area marked in Figure 22.

For a further evaluation, consider the recorded range of leak location: From 426 to 454 km (265 to 282 miles) within an 8 minute period. This range corresponds approximately to a flow error at 454 – 426 = 28 bbl/hr developing in 8 minutes, i.e. approximately *a 100 bbl/hr increase in 30 minutes.* Figures 23 and 24 cover the approximate distance traveled by the batch interfaces in 30 minutes. Therefore the values at the end of the graph for the current model configuration (blue color) minus the corresponding values for the other graphs are the possible flow errors over a 30 minute period.

For a given elevation slope error, batch interface 2 contributes about twice as much as interface 1 to a flow error due to the larger density difference over the interface. Therefore, if only the movement of interface 2 is considered for a rough estimate, it is seen that:

- An un-modeled downhill movement will cause a negative flow error (too small leak location).
- An un-modeled uphill movement will cause a positive flow error (too large leak location).
- *A slope at approximately 15% for the elevation peak in the sensitive area marked in Figure 22 is necessary to explain the location error this way.*

Hence a very likely event is that batch interface 2 was moving along the downwards slope of a missing peak in the beginning of the leak test, and then upwards during the rest of the leak test. *This is confirmed by the leak location in Figure 20 first*

decreasing, then increasing.

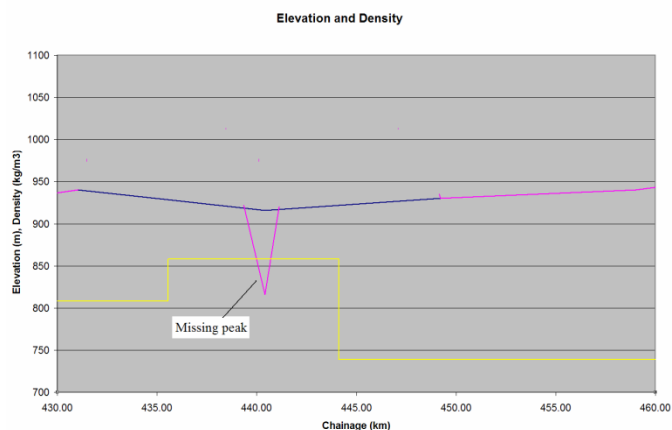Figure 25 shows a likely, approximate position and size of this missing elevation peak.

Elevation and Density

Figure 25. Elevation profile zoomed in with possible missing peak.

RECOMMENDED CHANGES

As a result of the recommendations described so far, based on the investigated leak tests, initiatives were taken to measure the elevations for many of the operated pipelines in the field. The elevation profiles were then revised accordingly in the LD. Figures 26 and 27 show the resulting elevations as they are configured today for the sections discussed in this paper. Figure 26 also includes the tested elevation profile for the replay of case 1 shown in Figure 17.

Many of the expected tendencies are confirmed by the field measurements. It is noted especially that the changes in elevation slopes are of the same order of magnitude as the predicted values for both cases. For instance, an upwards elevation slope at 17% for the revised profile, within the sensitive area marked in Figure 22, was found to be in agreement with the expectations; this is shown in Figure 28.

On the other hand it is clear that there are certain differences between the suggested and revised profiles. For instance the expected downwards slope for case 2 in Figure 25 is not confirmed, although the upwards slope is. The situation in the beginning of the leak test may instead be explained by a rapid flow change, as measured at the end of the section (see Figure 21). But altogether the predicted impact of elevation errors on leak location has been confirmed by the elevation measurements.
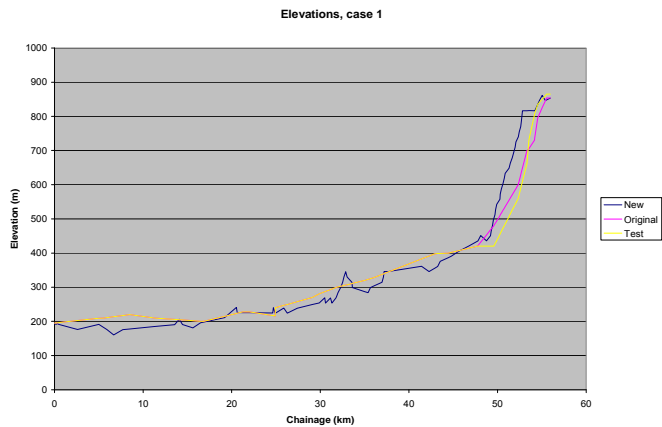
Elevations, case 1

Figure 26. Original and new elevation profile for the section evaluated under case 1
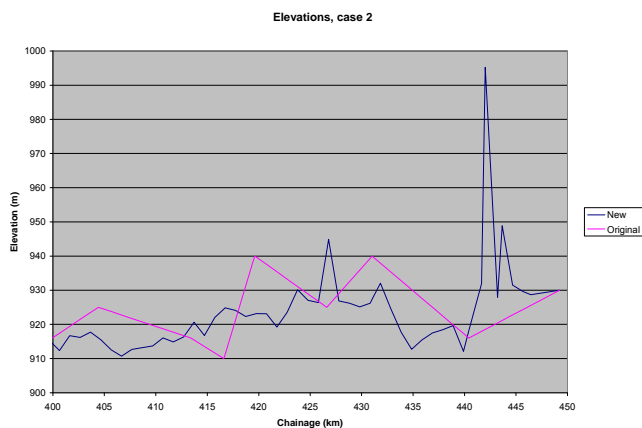
Elevations, case 2

Figure 27. Original and new elevation profile for the section evaluated under case 2
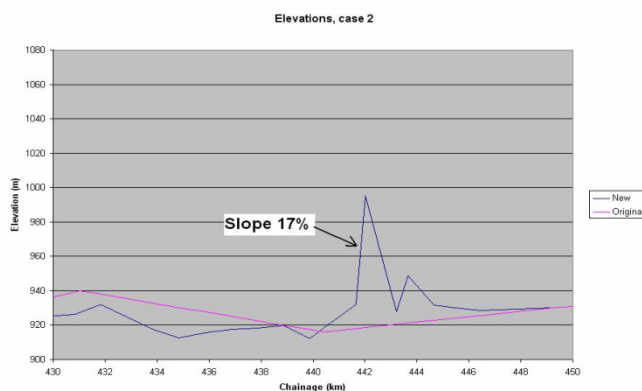
Elevations, case 2

Figure 28. Original and new elevation profile from figure 26, zoomed in for the sensitive area of the section evaluated under case 2