Case Study
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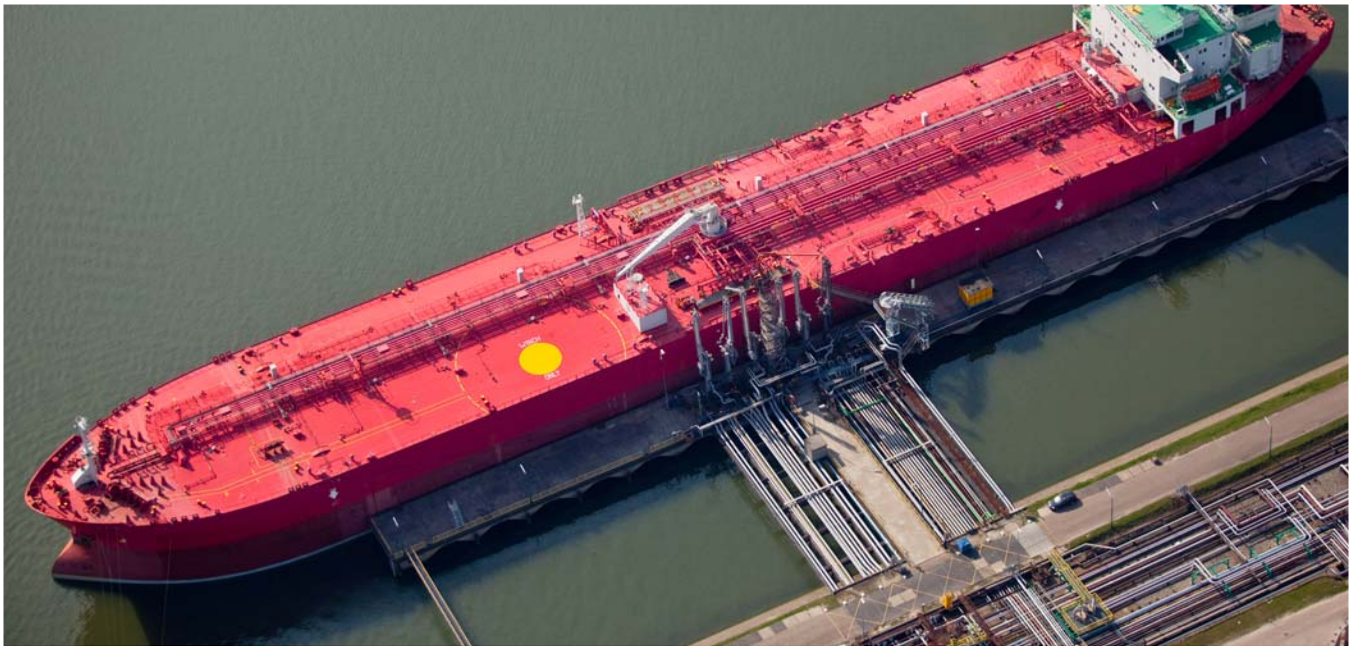
Practical Implementation of a Leak Detection System in a Transient Thermal Environment



Abstract

Louisiana Offshore Oil Port's (LOOP LLC) primary business interest is offloading foreign crude oil from tankers moored off the Louisiana coast through a 48-inch diameter, 45-mile long pipeline. Crude oils that enter the pipeline originate from all over the world and vary widely in temperature.

In LOOP's control center, the pipeline controllers use a software model based leak detection system to monitor the pipeline operation. The model is based on the real time simulation of the flow coupled with a thermal model to simulate the heat transfer to and/or from the pipeline and the environment. The ground thermal model is a solution of the heat conduction equation in the ground around the pipeline.

This paper discusses the thermal effects observed during implementation of a leak detection system on the LOOP pipeline, and how those effects were accounted for in order to maintain high levels of leak detection sensitivity.

Introduction

LOOP LLC offloads crude oil from supertankers, pumps it through a buried pipeline into underground storage in salt dome caverns, and delivers it to refineries throughout much of the southern and mid-western United States. LOOP's facilities consist of a Marine Terminal located in the Gulf of Mexico 18 miles off the coast of Southeastern Louisiana, a booster pump station located just inland near Port Fourchon, Louisiana, and the Clovelly Dome Storage Terminal located about 25 miles inland near Galliano, Louisiana.

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The Marine Terminal consists of two connected platforms in water 117 feet deep. This water depth allows VLCC (very large crude carrier) and ULCC (ultra large crude carrier) supertankers with up to 90 feet drafts to moor at one of three Marine Terminal single point moorings. Up to four 6600 horsepower pumps that can be used, if necessary, to inject the crude oil into one of 9 underground storage caverns. The caverns are filled with a combination of brine (saturated salt water) on the bottom and crude oil floating on top. The brine is displaced when injecting oil into the cavern. To overcome the static pressure of the brine and displace it, the pipeline must effectively pump oil "uphill" from a hydraulic standpoint.

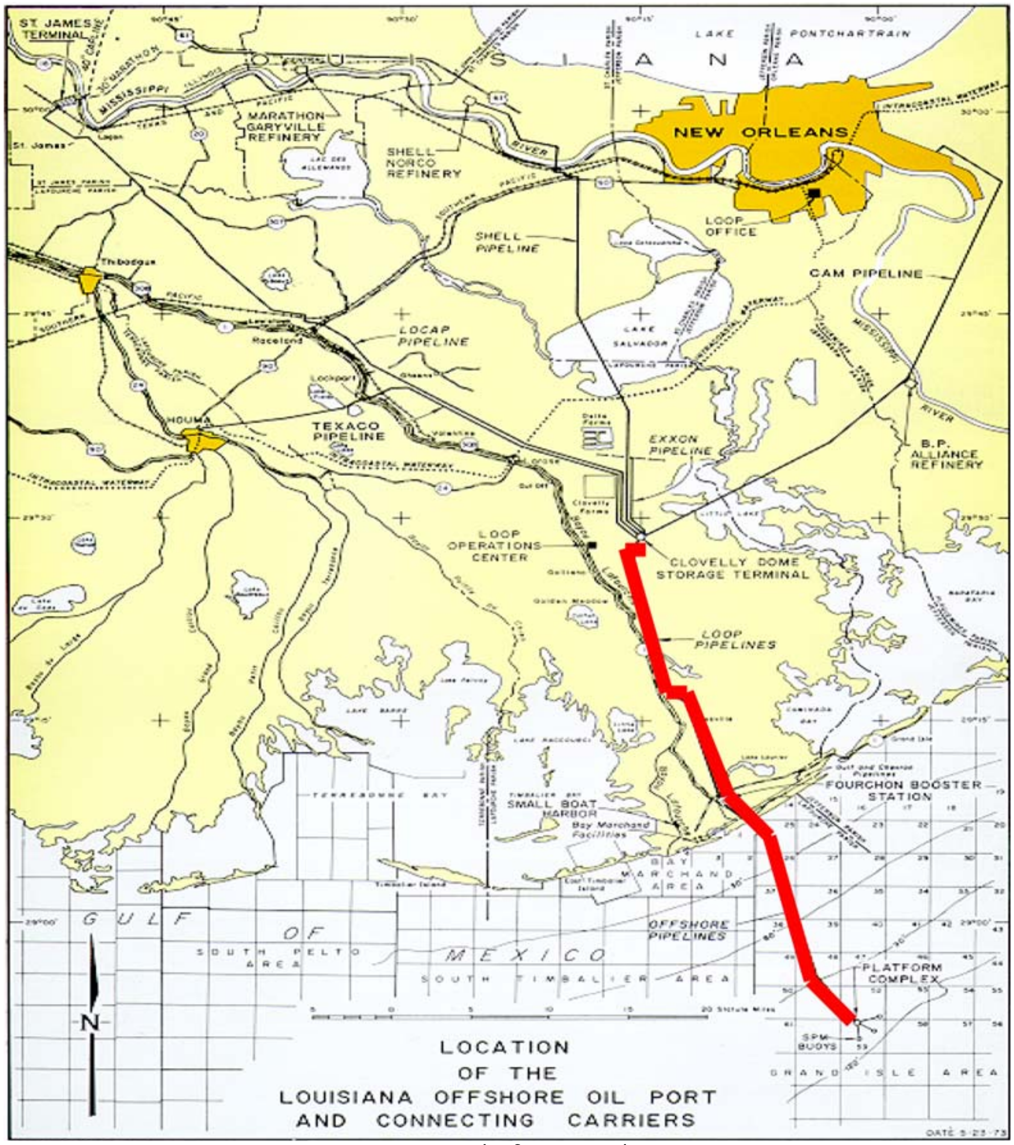

Figure 1. Path of LOOP Pipeline

The elevation profile of the LOOP main oil line (Figure 2) is relatively flat except for the origin of the pipeline at the Marine Terminal platform that is about 117 feet above sea level. From the Marine Terminal platform the pipeline drops vertically to the seabed at about -115 feet ASL. The pipeline then rises gradually with the sea bottom to the shoreline where it is buried until it breaks the surface inside the Fourchon Booster Station. From Fourchon, the pipeline is buried a safe distance under many bayou and canal crossings until it once again surfaces at about 6 feet ASL inside the Clovelly Dome Storage Terminal facility.

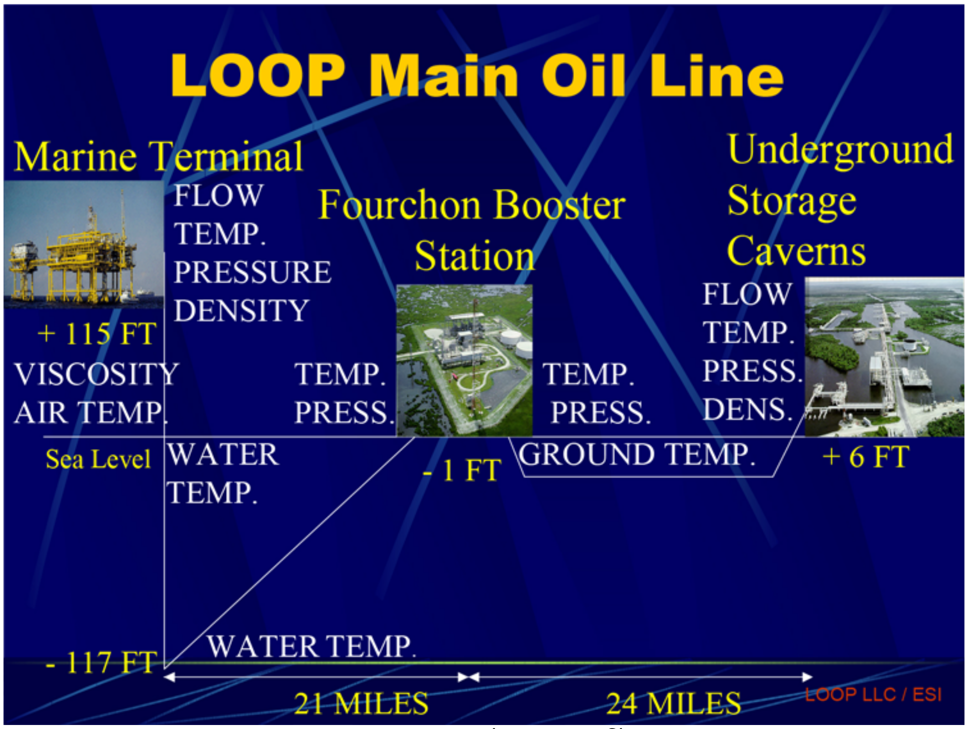

Figure 2. LOOP Elevation Profile

Instrumentation

LOOP maintains accurate instrumentation at the Marine Terminal, Fourchon, and Clovelly. Pressure transmitters are located at the pipeline origin at Marine Terminal, at both the inlet and outlet of the Fourchon Booster Station, and at the end of the pipeline at the Clovelly Dome Storage Terminal. The distance between pressure transmitters is therefore a little over 20 miles. Each of these is backed up by a nearby identical transmitter. Four temperature transmitters are positioned at the same four locations as the pressure transmitters. Clovelly has a nearby backup temperature transmitter. The Marine Terminal and Clovelly employ densitometers to provide specific gravity readings. A backup densitometer is located about a mile upstream of the primary one at Clovelly. The Marine Terminal measures viscosity of the product entering the pipeline.

A set of 7 turbine meters is located on the Marine Terminal and another set of 7 turbine meters is located at Clovelly to provide accurate flow measurement. There are 5 sixteen-inch diameter and 2 ten-inch diameter meters at Marine Terminal and 5 sixteen-inch diameter and 2 eight-inch diameter meters at Clovelly. The smaller meters provide accurate flow measurement at low flow rates that cannot be achieved with the larger meters.

Additional instrumentation is installed along the LOOP main oil line to provide environmental temperature data. The Marine Terminal instruments measure air temperature at the platform, water temperature at the surface, and water temperature near the bottom of the seabed. Fourchon Booster Station has a ground temperature measurement adjacent to the pipeline within the station.

Pipeline Operations

The LOOP Main Oil Line transports up to 50 different types of crude oil imported from all parts of the world. The oil is transported in supertankers of various sizes having different onboard pumping equipment. The tanker's pumping capability is the main factor in establishing the flow rate for the pipeline during that tanker's discharge. A given tanker's maximum flow rate ranges from 40,000 to 90,000 barrels per hour. This rate is highly transient due to tank switches onboard the tanker and switches at Clovelly from empty to full caverns or vice versa. These flow rates result in a normal main oil line pressure of 400 to 500 psi at the origin and discharge side of the booster station and 200 to 300 psi at the suction side of the booster station and at the termination.

The result of handling crude oil from such a wide variety of sources is that the product characteristics from one batch to the next always change. One tanker's discharge is usually followed by the next tanker's discharge after a brief shutdown of less than half an hour. One supertanker can also offload multiple crude types over its typical one or two day discharge. Physical properties of the crude oils transported by LOOP vary greatly. Specific gravity ranges from 0.77 to 0.92. Standard viscosity ranges from 1 to 300 centipoise. Product temperature ranges from 60 to 120°F and can change at a rate of over 20°F per hour.

Although the location of South Louisiana in a subtropical climate does not normally produce extreme environmental conditions, seasonal changes are significant. The temperature of the seawater covering the offshore segment of the pipeline ranges from 65° to 87°F. The temperature of the soil/marsh covering the onshore segment of the pipeline ranges from 67° to 85°F. A combination of wintertime environmental conditions and a tanker with a hot cargo can produce a product versus environment temperature difference of 50°F. Conversely, a tanker discharging a cold cargo in summertime can produce a product versus environment temperature difference of -25°F.

The volume of crude oil contained in the LOOP main oil line is approximately 500,000 barrels at standard conditions of 60°F and atmospheric pressure. At operating conditions, the volume ranges from about 494,000 barrels at high product temperatures to about 499,000 barrels at low product temperatures. A tanker with a hot cargo being offloaded into a much cooler pipeline or a tanker with a cold cargo being offloaded into a much warmer pipeline is a frequent operational event for the LOOP pipeline. Such an event can result in the rate of change of the pipeline volume due only to temperature changes of up to 900 barrels per hour.

LOOP is aware of the transient thermal environment in which the pipeline is being operated and realizes that any real-time transient model that is used for pipeline leak detection on the main oil line must include a significantly configurable and tunable thermal model. The desired result is a sensitive, reliable, robust, and accurate software leak detection system.

Leak Detection System

In May 2000, LOOP LLC contracted Emerson (formerly Energy Solutions International) to provide a software-based leak detection system with a real-time transient model for the LOOP main oil line.

The software package installed is named PLDS and is based on the real time simulation of the flow in the pipeline with a rigorous transient model driven by SCADA data. The main application of the package is leak detection, but it also provides batch tracking, pig tracking, and other applications.

The system detects leaks in pipelines by performing an accurate transientcompensated volume (mass) balance for defined sections of the pipeline each SCADA scan. The volume balance is the net flow into the section minus the change in line pack (mass). The net flow comes from all flow meters, in and out of the pipeline and is named flow balance. The change in line pack, is named packing rate and is generated by the model using pressure and temperature measurements. The flow balance and packing rate are completely independent. When there are no leaks, the volume balance should be around zero, below the threshold. When leaks occur, the volume balance represents the leak size and should be above the threshold.

The flow model is coupled with a thermal model that handles the energy equation for the pipeline fluid, the heat transfer in the pipeline surroundings and the handling of ambient temperature beyond the pipeline surroundings.

The pipe surroundings are modeled as a set of 7 concentric shells of identical or different properties, named thermal shells. The first shell is the pipe itself. More shells are configured for handling pipe coating and insulation. The inner boundary is the pipe wall, assumed to be at the fluid temperature and the outer boundary is at a radius less than the burial depth of the pipe. For the transient model the conduction problem is solved numerically with the inner temperature boundary being the pipe wall temperature and the outer boundary being the ground temperature. The conductive heat flow at the inner boundary becomes the heat loss or heat gain of the fluid. The heat flow in the flow model's energy equation comes from the heat conduction coefficient and first shell temperature from the ground thermal model on the previous time step.

The simulation of the heat transfer from the pipeline into the surroundings is based on the measured ground temperature, with transducers installed at a distance from the pipe. The sensors provide the outer boundary condition temperature to the ground thermal model.

The system must be configured with information about the ground, the soil type, the number of concentric thermal shells, the thickness of the thermal shells, the thermal conductivity of the shells, the heat capacity and the density of the shells, to be able calculate the ground thermal profiles in the transient situation surrounding the pipe.

The heat transfer information has to be determined before each thermal shell surrounding the pipe is configured. The number of thermal shell types depends upon the types of pipe being used and the terrain in which the pipe is buried. If the same type of pipe is buried underground and then passes through a river, then at least two different thermal shell types would be necessary to describe the properties of the thermal shells, contained in each type.

The biggest challenge in tuning the model is setting the values in the configuration. There are infinite numbers of sets of values, but only one set will be physically correct and correspond to reality. A number of sets will work correctly in some situations, but not in other situations.

This initial manual tuning is successful once it results in accurate modeled temperature of the product as it progresses down the pipeline. The combination of a wide range of product temperatures being transported, the pipeline being partly offshore and partly onshore, and seasonal environmental condition variation made the configuration and tuning of the temperature modeling software an interesting and challenging task for the LOOP project.

Seven months of data (from January 1 to July 31, 2002) were replayed and monitored. In this time frame, over 200 thermal fronts were analyzed. More than 30 batch interfaces had over 15°F difference in temperature.

The remainder of this discussion will focus on just one such thermal interface: a cold batch (Troll) shipped from Norway followed by a hot batch (Mayan) shipped from Mexico.

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Figure 3 shows linefill snapshot of 2 pipelines. The top bar chart is the MOL line where the MAY batch (gray) is pushing the TRL batch (green) out of the line.

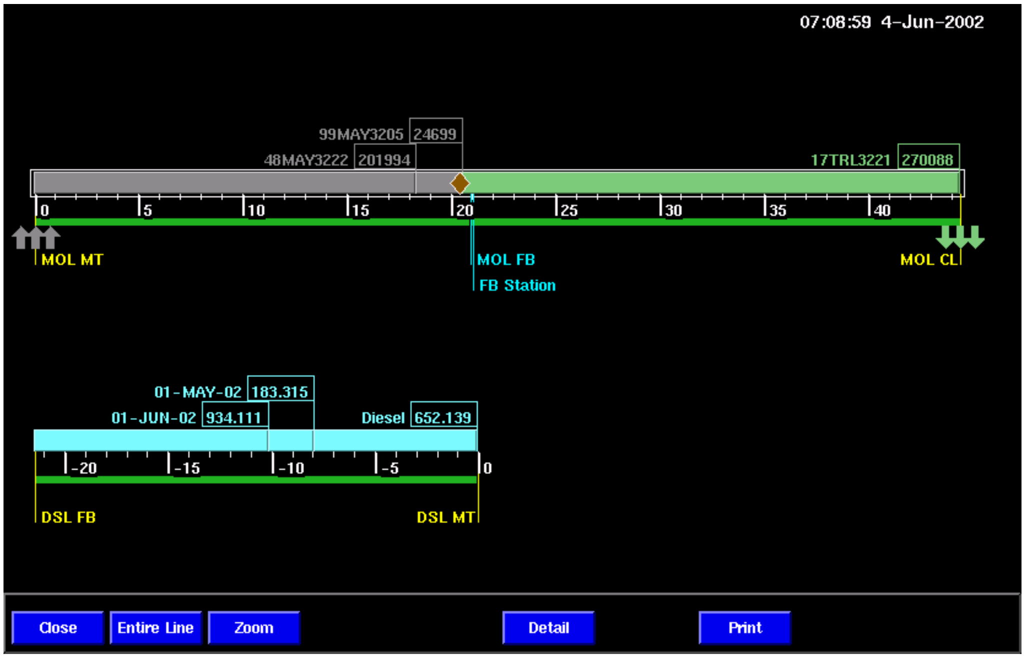

Figure 3. Linefill Chart with 2 Pipelines

Figure 4 shows a snapshot of the modeled temperature profile (cyan pen) in the MOL line when the hot front reaches Fourchon Station at milepost 20.9.

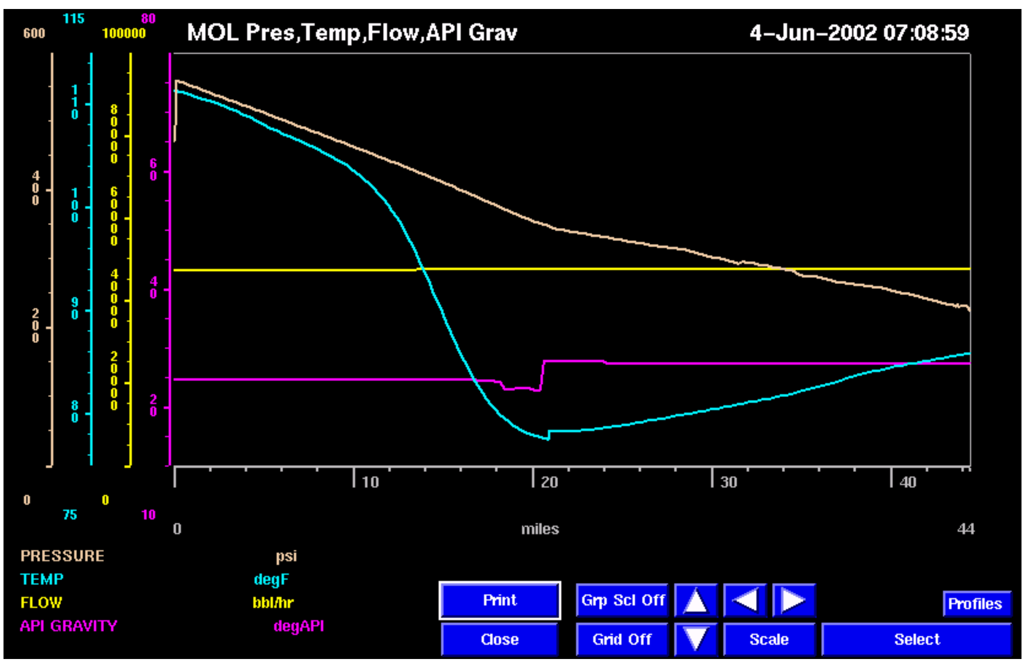

Figure 4. MOL Temperature Profile

Both Figures 3 and 4 were taken at the same time, on June 4, at 07:08 a.m.

The next graph, Figure 5, represents the trends of 4 temperature measurements along the line. The most recent time is represented to the right of the graph, with older values being to the left. The trend shows the temperature interface between a cold batch and a hot batch. The trend shows 2 days of data. Following the brown pen from left to right, it can be noted that before the early morning on June 4, a cold batch enters the line at 68°F and over time reaches 78°F. Early in the morning on June 4, a hot 110 degree Fahrenheit batch is injected in the line for about 17 hours. At the inlet point in the pipeline at the Marine Terminal, the temperature difference between the hot and the cold batch is 32°F (110-78).

When the product reaches the mid point, at Fourchon station (yellow and cyan pen), the hot product is 100°F and the cold product is 80°F. The temperature difference between the hot batch and cold batch is 20°F at Fourchon station. Downstream at Clovelly (the pipeline outlet) the difference between the hot batch and the cold batch is only 5°F (purple pen).

At Clovelly, after the products traveled 45 miles of pipeline, the hot batch is cooler and the cold batch is warmer. The environment influenced the batch temperature: the hot batch is cooler due to heat loss to the cooler ground, and the cold batch is similarly warmer. The warming of the cold batch is significantly enhanced because the preceding hot batch heated up the ground.

There are some discontinuities in the product temperatures and they occur when the pipeline is shut down.

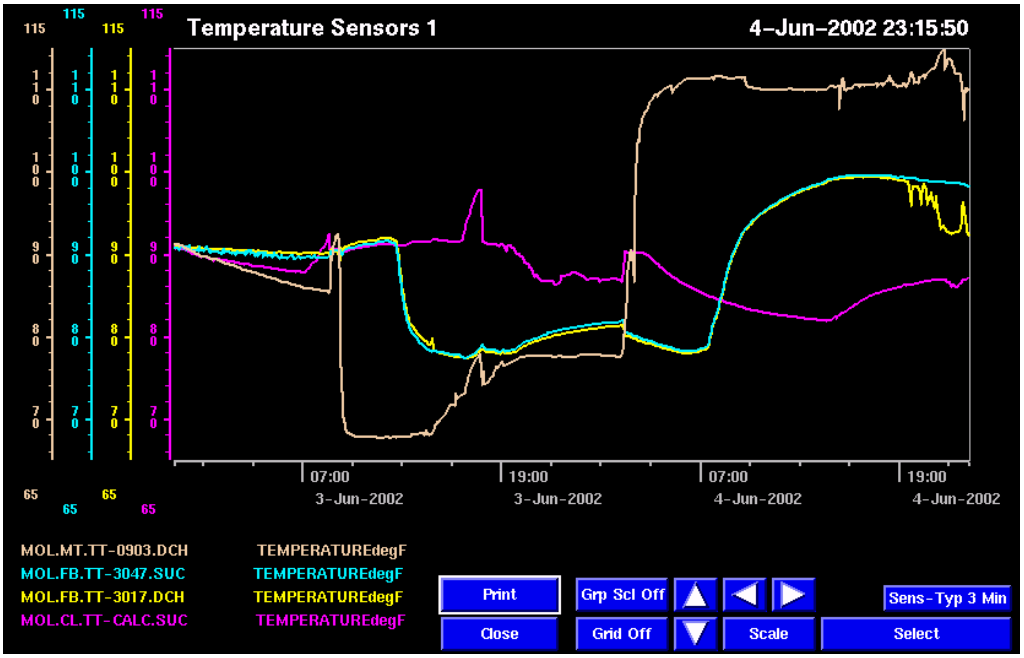

Figure 5. Trends of Temperature Measurements at 4 Points in the Line

Calculated temperatures can be compared with measured temperatures at locations downstream in the pipeline. These trends give detailed information about the accuracy of the model.

The graph trend in Figure 6 shows the calculated temperature (cyan pen) tracking the measured temperature well (brown pen). During the interface transition through Fourchon station (milepost 20.9), the calculated temperature lags several minutes behind the measured temperature. The discrepancy between the measured and calculated temperature reaches 3-4°F during the steepest part of the thermal transition from the cold to the hot product.

The graph trend in Figure 7 shows that during the thermal transition through the Fourchon station, the model calculates an imbalance of 80 barrels per hour (brown pen) - not large enough to exceed the threshold (purple pen) to create a false alarm. An alarm is issued when the brown pen moves above the purple pen. The volume balance (brown pen) is the difference between the flow balance (cyan pen) and the packing rate (yellow pen).

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Both trends (in Figures 6 and 7) are captured at the same time and have the same time range on the X-axis to allow correlation of thermal events and imbalances.

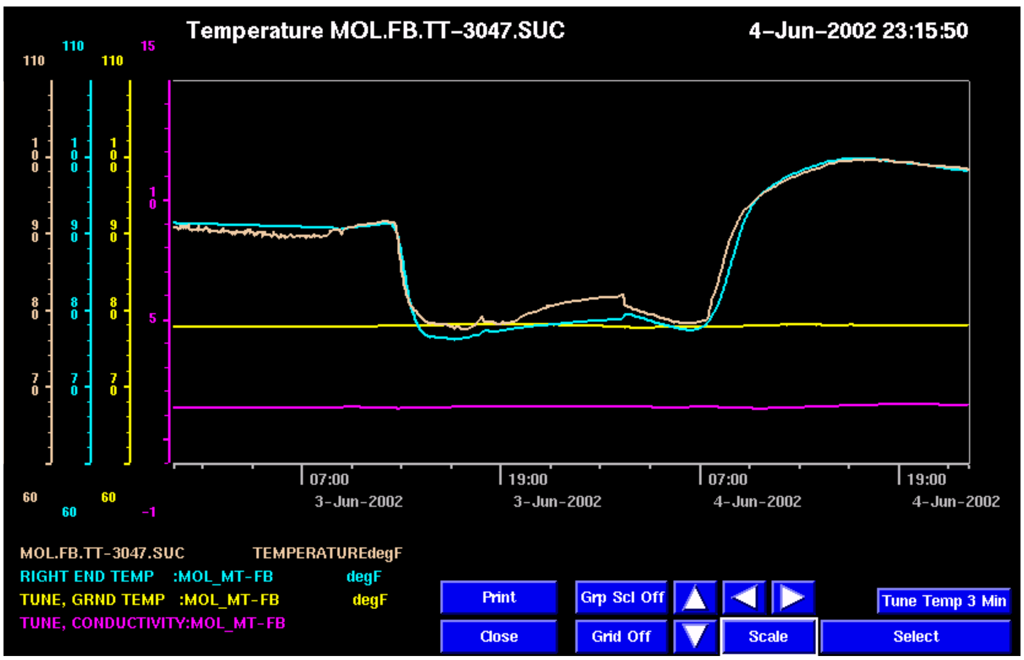

Figure 6. Trend of Measured Temperature and Calculated Temperature at Fourchon Station

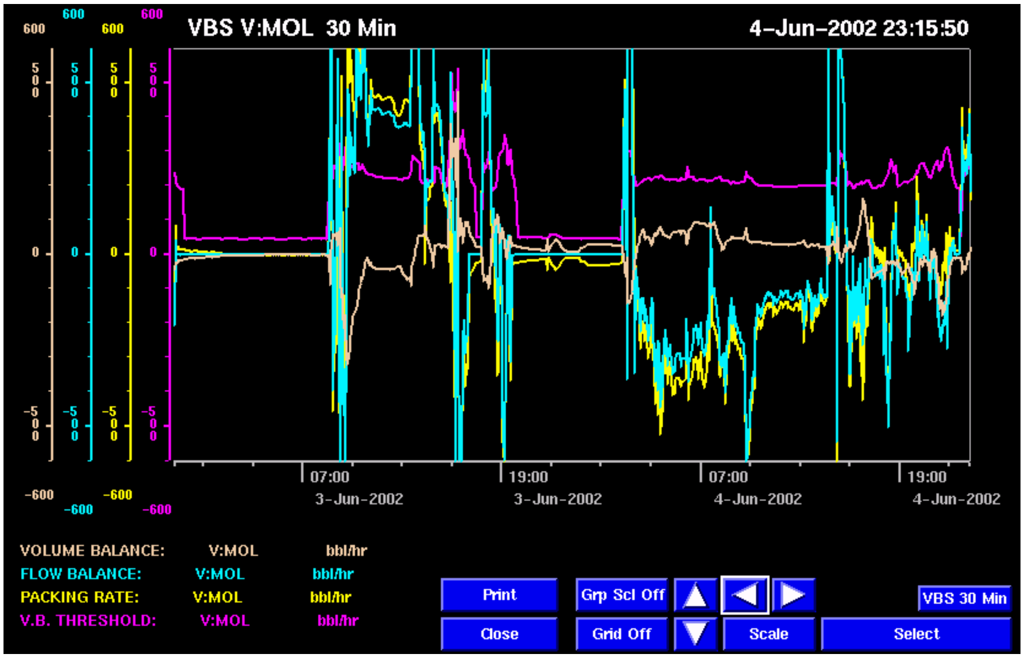

Figure 7. Leak Detection Trend, Tracking is Good with No False Alarms

The next two graphs (Figures 8 and 9) show the thermal tracking at Fourchon station when the ground thermal model is not configured and tuned properly. In the first abnormal scenario (Figure 8), the thermal conductivity is set 20 times higher for the first thermal shell. The calculated temperature lags behind the measured temperature and several hours elapse before the calculated and measured data match again.

In the second abnormal scenario (Figure 9), the model is configured with a heat capacity 20 times smaller than normal. In this case, the discrepancies between the calculated and measured temperatures are large and the model calculates imbalances of 400 barrels per hour - large enough to generate a false alarm (Figure 10).

The trends on Figures 8, 9, and 10 are on same time line.

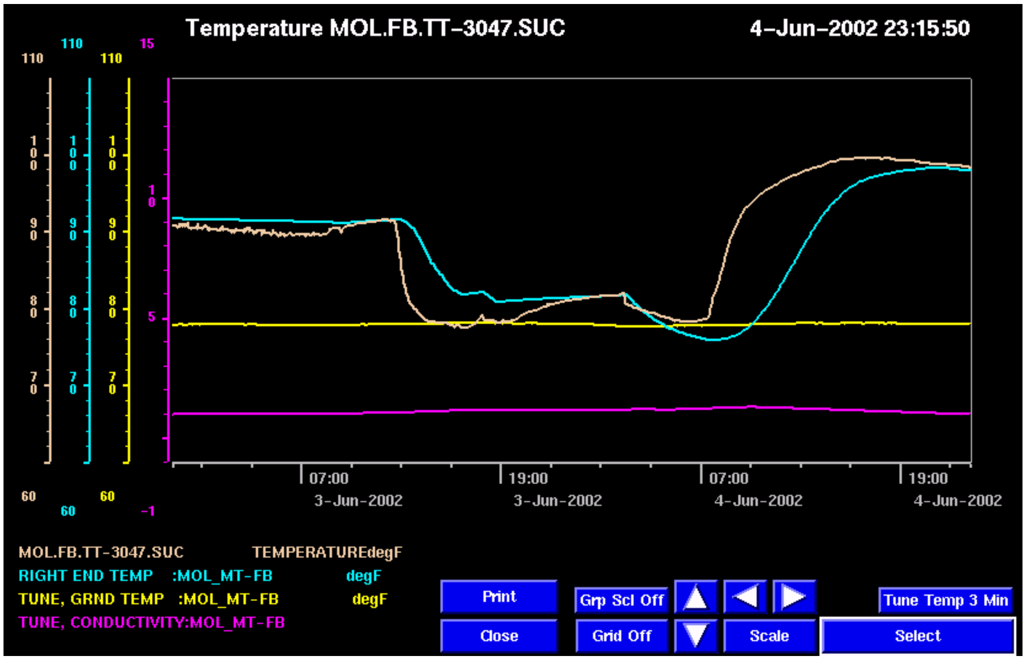

Figure 8. Thermal Vonductivity is Configured 20 Times Higher for the First Thermal Shell.

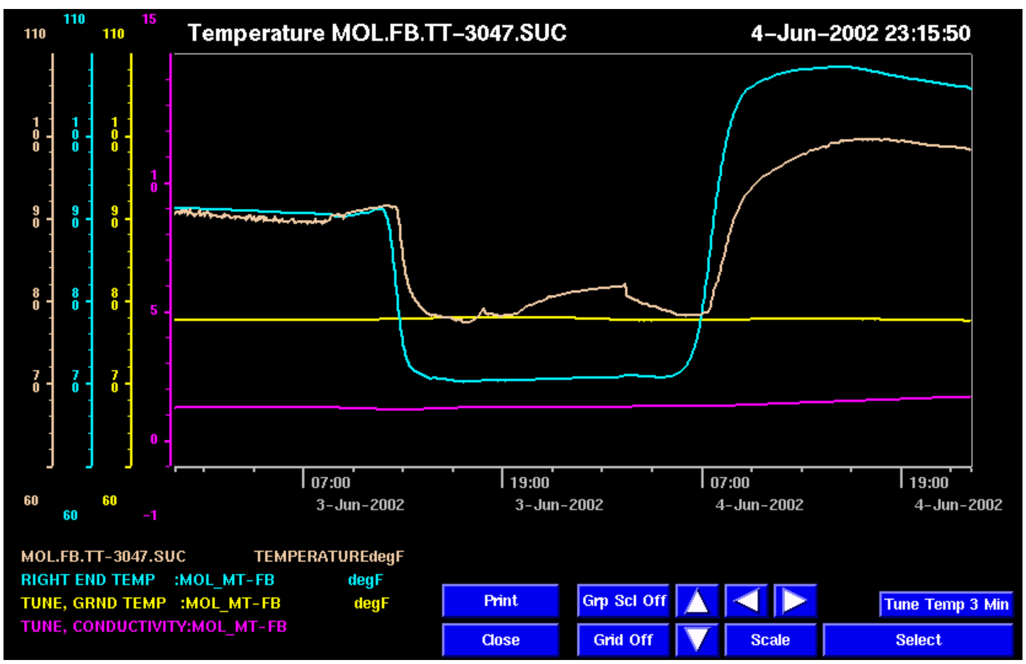

Figure 9. Heat Capacity is Configured 20 Times Smaller Than Normal

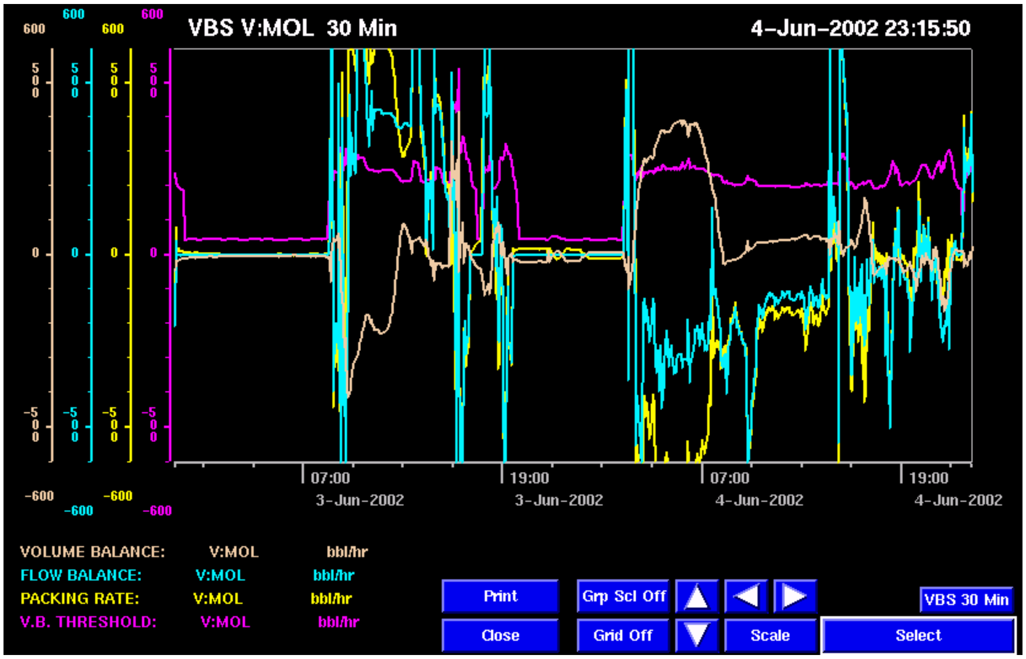

Figure 10. Leak Alarm Generated by the Model. The configuration is set with a very low heat capacity (20 times smaller than normal).

In other operational scenarios, the pipeline may be shutdown with hot or cold batches in the line. The season with cold ground or warm ground affects the direction of the heat transfer to and/or from the pipeline and the surroundings. The product temperature will move toward the environment temperature, but it will do so very slowly. Pressures in the line are greatly affected by a shutdown, changing several psi per hour. In some prolonged shutdown cases, a slack line condition was developed at the point with the highest elevation in the pipeline (MT). A very long shutdown is required for a pipeline filled with cold or hot products to reach the equilibrium with the environment.

During a New Year's shutdown (4 days from Dec 30, 2001 through Jan 2, 2002), the product cooled off 10°F (from 100°F to 90°F), but did not reach the ground temperature (around 70°F). It is assumed that in wintertime it would take about 2 weeks for a hot product to reach a cold ground temperature. However, this piece of information was important in determining the magnitude of the heat capacity of the thermal shells (as a total). The analyst had to distribute the total heat dissipation through all 7 thermal shells configured for the pipeline.

Temperature measurements used for model boundary conditions or for tuning are inaccurate during shutdowns. During a shutdown condition, temperature measurements indicate the ambient temperature (of a small exposed piece of pipe) instead of reflecting the product temperature in the buried pipe. The temperature measurement for the left end of a pipe segment is used as a boundary condition for the model. The right end temperature measurement is used for automatic tuning and may drive the tuning in a wrong direction if it is inaccurate. This issue forces the model to keep very tight tuning parameters (thermal conductivity and ground temperature) during shutdown conditions. The model slows the thermal tuning, so measurements affected by ambient temperature do not reach and influence the model calculations.

The graph trend in Figure 11 illustrates several pipeline shutdown periods where the temperature measurement (brown pen) moves toward the ambient temperature, while the calculated model temperature (cyan pen) changes very little during shutdown conditions.

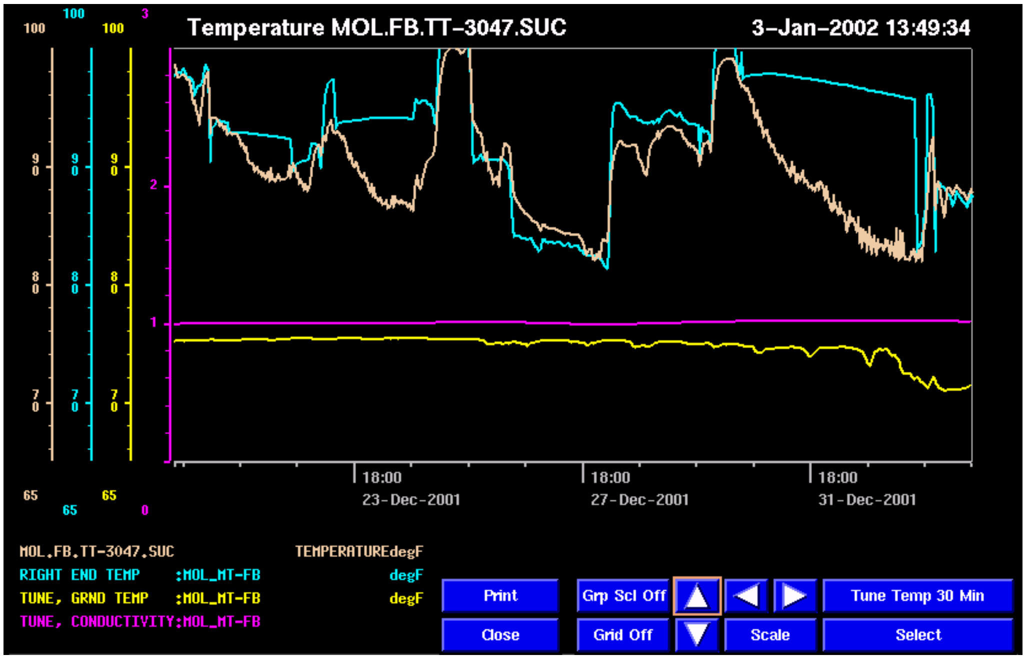

Figure 11. Trend with Measured and Calculated Temperatures during Numerous Shutdowns

Since moisture content for the buried part of the pipeline changes seasonally and the local weather causes large changes in thermal conductivity, the thermal conductivity calculations would have to be repeated often to accurately reflect these changes.

Also, the type (mixture of sand, gravel, and cement) and porosity of the concrete that wraps the pipeline offshore is unknown. These unknown values make it difficult to accurately determine the thermal conductivity and heat capacity of the concrete. Additionally, the thickness of concrete wrap is uneven along the pipeline.

Difficulties encountered in handling thermals in the model were:

- Thermal problems cannot be separated from other operational and instrumentation issues. Errors in thermals show as small-to-medium size imbalances in longer Leak Detection Periods.
- Requires large quantity of datasets to be re-played to let the thermals set in. With a batched line, playback of at least several weeks of data is required.
- Requires replay of both summer and winter data with thermal interfaces traveling without stops or with prolonged shutdowns
- Requires replay of hot batches followed by cold batches, and cold batches followed by hot batches.
- For many flow regimes there is ambiguity in the choice of ground temperature and thermal conductivity. There are many combinations of Ground Temperature and Thermal Conductivity that will produce the correct downstream temperature for a specific flow regime, but only one combination is physically correct and so only one combination will produce the correct downstream temperature for all flow regimes.
- With very slow automatic tuning of the thermal conductivity and faster tuning of the ground temperature, variable flow conditions will eventually produce correctly tuned values of both parameters. Eventually means, in this case, months – which practically means never, because over such a long period there will be changes in the pipeline operations, instrumentation and ground itself which will invalidate the tuned values.
- It is still unknown how long it takes for various products to reach equilibrium with ground temperature.

At the beginning of the project, after the initial tuning was completed, the model issued a false alarm for each thermal interface with more than 10°F difference between cold and hot batches. Now the leak detection system is free of false alarms caused by the thermal fronts.

Project steps to eliminate false alarms caused by thermal interfaces:

- The project was started up with thermal configuration data from an onshore, buried, 18-inch crude oil pipeline (different than LOOP).
- Temperature measurements along the pipeline were monitored during flowing and shutdown operation to verify they are not the primary cause of imbalances for leak detection. The imbalances were due to imperfect knowledge of the factors affecting the heat transfer between the pipe and the ground. The result was that the model temperatures at the end of the pipeline (Clovelly) were correct within 2-3°F while the model temperatures in the center of the pipeline (Fourchon) were off much more (10-12°F).
- Verified the thermal conductivity tuning parameters and ground temperature tuning parameters.
- The heat capacity had to be increased dramatically for LOOP line from those of the 18-inch line. With the increase in heat capacity, the calculated thermal front lags behind the measurement. After the increase of the heat capacity, the leak detection had only one false alarm for a 6-month period of operation.
- Thermal conductivity of the first thermal shell had to be decreased 6-8 times to get the calculated thermal front arrival time and slopes to match the measurement at Fourchon station.

The system was approved and commissioned on April 15, 2002. The cooperation and commitment of both parties - the customer and the vendor - has contributed significantly to the success of this project. This cooperation is expected to continue with the goal of further strengthening the thermal model and getting configuration parameters even closer to reality.

Conclusions

A complex pipeline like LOOP needs a leak detection system equipped with a rigorous thermodynamic model that avoids the generation of false alarms caused by the thermal interfaces.

The false alarms caused by thermal problems interfere with a leak detection system's ability to find and locate small leaks.

The process of zeroing in on the right thermal parameters is lengthy, repetitive and requires a full commitment of all the parties involved in the project. Otherwise, it is not possible to achieve accurate modeling results.

Bibliography

Jerry Modisette – Notes on Ground Heat Flow and the Assignment of Heat Capacities in the Energy Equation

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