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# Developing and Implementing a 'Full Scope' Operator Trainer Simulator for the TransCanada Keystone Pipeline

Kevin Nelson, Telvent; Shawn Smith, Telvent; Mark Malinowski, TransCanada Pipelines

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## ABSTRACT

In parallel with the design and construction of the Keystone pipeline, TransCanada and Telvent developed a fully integrated simulation environment including a dynamic hydraulic model, production SCADA system, simulated programmable logic controllers (PLCs), online leak detection, and batch tracking. This system served to test and develop control logic, the SCADA database, SCADA applications, online leak detection, and operational procedures prior to putting the pipeline in to production. Not only did this system allow Keystone to meet its regulatory training requirements, but it was able to predict interactions between field and control center pressure control systems, identify vulnerable areas of the pipeline during scenarios, verify over pressure protection systems, and allowed for initial tuning of the leak detection system prior to line fill.

## INTRODUCTION

Typically the development of SCADA systems, online applications, control systems, and dynamic pipeline simulations are done as separate or sequential exercises. For existing pipelines this is often a product of technological development over the life of the pipeline. For smaller pipelines or new branches on larger existing lines, it is often impractical to invest in line-specific simulation or training systems. The Keystone Pipeline provided the unique opportunity of developing a full scope training, analysis and testing system for a large-scale green field project including all of these dynamic online systems. Through the course of the project a number of unexpected advantages were gained through what has been termed “full scope simulation.”

The Keystone Pipeline is a 1,854 mile (2,984-kilometre) crude pipeline beginning in Hardisty, Alberta and delivering to markets at Wood River and Patoka, Illinois and in the future to Cushing, Oklahoma (See Figure 1). It utilizes approximately 537 miles (864 kilometers) of existing gas pipeline and is designed to initially carry 435,000 barrels per day, which will later be increased to a nominal capacity of 590,000 barrels per day.

The original purpose of this full scope simulator was to train operators on the specific dynamics of the Keystone pipeline; however, the core advantage of the system lies in the ability to dynamically test “live systems” in an offline environment that is nearly indistinguishable from the real world. Great strides were made in pre-tuning and testing of online leak detection, batch tracking, pressure control, batch cutting, swing logic and terminal control. In addition, engineering and support staff gained hands on training and experience with “live” systems while assisting in the development of the training system. The end result is a higher preparedness for operators, shorter commissioning times for online systems, and an efficient start up process for the pipeline. In the end this translates to an operation that is safer, more efficient, and more cost effective.

## PIPELINE APPLICATION TESTING

For existing pipelines, new online analysis and SCADA systems can be implemented in parallel with existing infrastructure, which allow these systems to be fully tested against real data without interrupting normal operations. With green field projects this is not possible; therefore, commissioning and start up rely heavily on point-to-point check outs and real-time adaptation of online systems. By integrating the SCADA system with a hydraulic simulation including simulated remote terminal untis (RTUs), which utilized the same data protocols as the real field devices, the production SCADA system was effectively convinced that it was looking at the real pipeline. It was then possible to perform a thorough design analysis of online applications, configuration of field telemetry, instrumentation alarms, scaling ranges, and change of state alarming. Testing of pipeline protection software within the SCADA system and communication (with simulated data) between the SCADA system and online models was also made possible.

As an example, the SCADA system has instrument fail range checking alarms configured for analog points. When the simulator and the SCADA system were first connected, many of these alarms were activated for conditions that should have been considered normal. As this was early on in the project, this pointed out areas in which SCADA development was still underway. In some other cases this showed that the simulation was outputting the value to SCADA in the wrong units or, more often, using the wrong data type (i.e. signed 16 bit integer, 32 bit, unsigned, etc.) This is important not only in terms of training, but because it allowed us to verify the configuration of the data that the online simulation would be receiving during operations. The end result was an absence of telemetry problems when the online simulations went live.

Change of state alarming in a green field project is typically approached from the perspective of setting all high states to abnormal. The process is to then justify why an alarm presented to SCADA has no action required by the operator. Alarms of this nature then fit into one of two categories:

1. Informational only (typically used by Asset Reliability groups or offline analysis)
2. Not required to be telemetered from remote sites

A further refinement occurs by working with operations staff to categorize and prioritize the alarms. This process is generally referred to as Alarm Rationalization, and, in the case of Keystone, was a regulatory requirement. With a full scope trainer this process began immediately after the trainer and the SCADA system were connected instead of waiting for the system to go live. The result was a much clearer presentation of alarms to the operators and a more realistic training environment without nuisance alarms distracting the operator during training or when the system went live.

During integration testing, one of the first audits to occur was for the SCADA controller human machine interface (HMI). As simulation data was being sent from the simulator to the SCADA system, SCADA graphics were activated and displayed “realistic field” information. This information was audited and the SCADA graphics underwent a series of enhancements and optimizations based on operator feedback. For example, corridor pressure and temperature summaries were developed to allow operators to identify pressure and temperature anomalies quickly. In addition, a high level simulation summary was built which incorporated all the critical leak detection and batch tracking information for the entire pipeline. These types of improvements allowed the pipeline to be operated with a high degree of reliability from day one.

The SCADA system is responsible for executing many pipeline safety related functions including line trips. In these cases it was possible to test the execution of these commands, the feedback from the local PLCs, and the hydraulic response of the pipeline. In addition to testing the system component responses, this allowed controllers to get hands on experience for what different emergency conditions would look like on a “real” system, including the timing of hydraulic response and associated alarming for a variety of circumstances. For instance, a controller could directly observe the time it took for a pressure wave from a pump trip to reach the adjacent station, what the response would be at that station, and so on.

From a simulation perspective, this type of integration testing was used to account for delay between the execution of changes in the field and their realization in the online model. For instance, when a valve closes in the field it sends two signals to the SCADA system: the statuses of a closed and open limit switch. Initially the assumption was made that when a valve came off its open limit, it was closing, and vice versa; however, since there was no affirmative indication of direction of travel, situations came about during operator training where the simulation could be several minutes behind in a valve status.

In particular, valve status could be inaccurate if a valve was being operated at the station level. This problem might occur if a valve began to open but was then shut by a technician or by the local PLC due to some automated shutdown logic (overpressure, line trip, valve sequencing). The simulation would not realize that the valve was closed until the closed limit switch was reactivated, which could be as much as twice the valve stroke time plus the communication delay. In this case the model would think the line was flowing with a fully open valve for many minutes before a signal was provided to correct this. Having measured very little flow in the field, the simulation will interpret this as a leak and alert the operator.

The solution was to use an alternate approach, which was well vetted on other pipelines, that involves moving the valve in the model to a holding position when in a transition state and then quickly to its final position when a position limit signal is received. The choice of holding position depends on the valve size, Cv characteristics, actuator type, and timing. With a proper choice of valve timing and holding position in the simulation, this method is highly effective. Note that this type of challenge is very common in online analysis and the solution itself is not particularly remarkable. It is of interest, however, that the solution was developed and tested before the pipeline was in operation and, more importantly, did not need to be adjusted once online.

Initial leak detection tuning, which is normally done during live operation, was completed by executing various scenarios on the simulator. This enabled the online leak detection team to verify the proper acquisition of data from the SCADA system and train support personnel in analysis of this data. For example, in the valve status scenario discussed above, there is still an inherent error in the results the online model achieves. One part of tuning is to analyze how much error is introduced by valve position changes and adjust the alarming thresholds for leaks to account for this event. These types of events can be observed on 'balancing' displays which show the differential flow for a section of pipe, the calculated change in line pack for that section (based on pressure and temperature) and the difference between these values (see figure 2). After tuning the system, this type of example was used to train staff to recognize this behavior as normal so as to distinguish it from true leak events.

Another potential source of error addressed in tuning was communication delay. The SCADA and offline simulator have the ability to configure a polling rate between SCADA and the simulator. This reflects the polling rate between SCADA and field RTUs, which under some circumstances can be on the order of minutes. This type of polling delay, typically due to communication outages, may cause transients in online models, which in turn cause "false alarms". By looking at the expected operation and comparing that to the response of the leak detection model, the team was able to tune out potential false alarms. To accomplish this, the affected transmitters were first removed from use by the online analysis whenever SCADA detected a loss in communications. This solution presented with difficulties when the communication interruptions were short lived but still frequent. These short frequent outages caused a toggling of data that reduced the fidelity of the leak detection system. The final solution was to time out the last detected transmitter value upon a communication loss. Since a short outage would not fall within this time out, the toggling effect was averted and fidelity was maintained.

Another safety function of the SCADA system is to set high limits for station discharge pressure based on regional pipeline flow and other data. The simulation was used to verify the proper implementation of these applications for the online system. In addition, early use of the training simulator identified the need for the operator to be able to easily identify when the pressure set points provided are within the automated pressure set point limits. This feature was easily integrated into the SCADA system and graphics and greatly improved the operators' ability to evaluate pipeline pressure conditions quickly.

## ONLINE SIMULATION DEVELOPMENT

The choice of simulation control volume size was a vital decision early on in the project. In order to perform dynamic surge analysis using the method of characteristics, the simulation required control volumes large enough that a pressure transient could not pass through that volume in a single iteration of the simulation code. The counter to this is that the larger the control volume, the lower the hydraulic fidelity. These restrictions, along with the choice of simulation execution rate, determine the desired length of each control volume.

The two remaining degrees of freedom are processing power and simulation size. As the size of the simulation increases, the more processing power it requires to calculate a hydraulic solution. Therefore, for a given execution rate and hardware configuration, there is a limit to the number of hydraulic control volumes that can be resolved in the overall hydraulic calculation. The way to get around this is to break the simulation up into several smaller hydraulic simulations. The different simulations are then connected by pressure or flow boundaries to create a single model which can run at a sufficiently high execution rate on a single processor.

During the development of this system, many additional simulation features were developed. For example, in order to help operators train and monitor for abnormal situations during operations, non-telemetered points of interest were monitored within the simulation. The simulation would continuously calculate pressure in these areas, typically river crossings or elevation peaks, and trigger alarms in the SCADA system when there was danger of going over pressure or in to slack at that location. During training this allowed the operators to quickly identify places in the line where the pressure was out of normal operating ranges and recover before automated protection systems took action. In addition, this feature serves as an added safety protocol for pipeline operations.

## LINE FILL STRATEGY

There are many challenges to starting a new pipeline, particularly one that spans the continent, but none as challenging as the Albertan winter where temperatures can drop to -40 °F. As schedules were laid out, it became clear that some of the early operations would occur in the heart of the winter. This provides obvious real world challenges; the most important of these to the modeling process is the viscosity of the crude. By configuring the model to allow for seasonally varying temperatures, a training environment was created for operators to practice startup and shutdown operations under highly specific conditions. These conditions were then defined based on historical temperature data.

Having made this effort for the training environment, the concept was extended to the online leak detection and batch tracking system to improve initial fidelity of the online simulations. Typically an online simulation will require significant time, often many months, to gather enough data about local temperature conditions to account for heat transfer phenomena properly. The process works by dynamically adjusting the heat transfer coefficient of the soil to minimize error between real data and the current model estimates of temperature change between telemetered thermocouples. This process is necessarily slow because of the very low heat transfer rates in soil. Moreover, if the model were initialized for summer operation with the heat flux into the fluid, but were put online in the winter time where the flux was into the soil, the tuning would mathematically have to adjust the coefficient. The result of this adjustment would be a change in the sign of the coefficient and the value would lose physical meaning, making interpretation of the results problematic. Figure 3 and figure 4 demonstrate the difference in ambient temperature relative to a single starting condition. By providing a reasonable ambient temperature profile (as in figure 4) the model is able to account for errors in calculated temperature more quickly and ultimately provide more realistic estimates of overall heat transfer coefficients. If, however, the online system were started with an inaccurate ambient profile (as in figure 3) the simulated crude would begin to heat unrealistically and the model would begin to lose fidelity.

## CHALLENGES: SOFTWARE

In large systems, projects often get impeded by problems with software and, even more often, software integration. This project was no exception. Given the size of this pipeline, one of the greatest challenges was providing efficient communication channels between systems. In particular, it was a challenge to historize the vast amounts of leak detection data produced and provide real time hydraulic profiles and leak estimate data to the operator interface.

Specifically, the display containing the pressure profile from the online simulations had to be adapted to maintain an adequate update frequency. Every set of data contained approximately 20,000 values representing a single point in time. In addition, the Keystone SCADA system is designed to have multiple user access points to the simulation, meaning that controllers, schedulers, engineers, the control center supervisor, leak detection technicians, the SCADA manager, etc. could all be accessing the same data simultaneously from different locations. In this case, there can be 120,000 values being requested on every display refresh cycle.

To allow for multiple users to access this information, a data cache was developed outside the simulation. When a request was made of the simulation, the data would be retrieved and placed in the cache. All additional requests for that data would be answered with the data already in the cache. The cache would then periodically update the data it contained from the model. This ensured that every data request made to the model was unique. Furthermore, because the cache could lock each section of its data independently while it executed data updates, it maximized the time the cached data was accessible to user requests, allowing multiple threads to access it. In addition, the data protocol was changed from one with string capabilities to one which is strictly numeric, thereby increasing the speed at which the data could move across the network.

To improve the efficiency and usefulness of leak detection historization, a separate data stream was configured to move leak detection data to the SCADA database where both the user and historical server could access it. This has three distinct advantages. First, the SCADA system could directly interface with the online simulation in the same way that a remote terminal unit does. The operator or leak detection support personnel could alter leak detection parameters through the SCADA displays and observe feedback from the simulation to those changes. This also meant that high and low limits and alarming could be placed on these values through the SCADA system. Second, the SCADA system is already connected to the historian; therefore, any leak detection data that gets historized gets recorded in the same way as other SCADA data. This ensures that data is synchronous and easy to correlate with other recorded information. Finally, it removes the need to manage a separate historical process and makes the system easier to maintain in the future.

## CHALLENGES: DATA MANAGEMENT

To ensure accuracy of engineering data utilized by the model, a “cold eyes” review of engineering data was instituted. This means that unfamiliar parties would review the data entered in the simulation. In addition, formal change management processes were implemented. Key to this effort was the use of a “master configuration.” This configuration is a single data file that contains all the base elements used to model the pipeline. It was managed not by the simulation team, but by Keystone’s engineering group to ensure that the most accurate and up to date data was being used. This configuration was used in all modeling efforts and ensured that results from the training simulator were applicable in the online models and steady state analysis tools. This uniformity allows scenarios of interest identified by one group to easily be studied by other parts of the project team. For instance, the engineering group could develop line fill scenarios to optimize power and throughput which could then be adopted in the operator training environment to practice operating the line under those conditions.

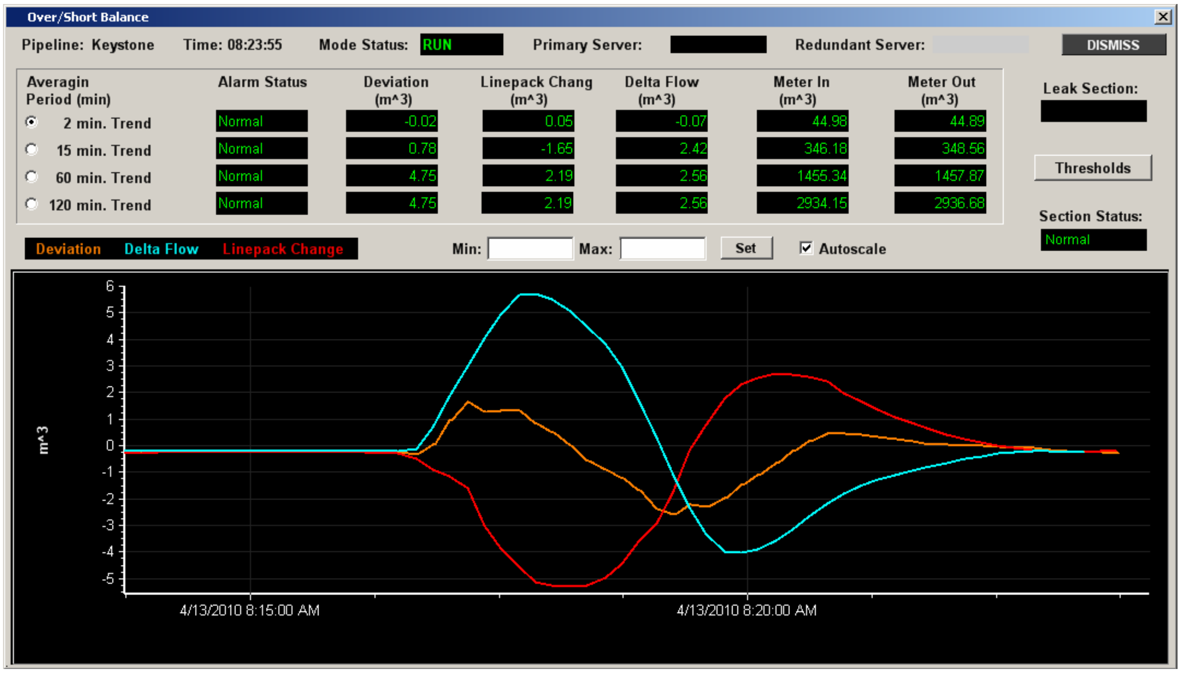
The full potential of these benefits would have best been realized if the modeling effort had begun earlier. On this project the SCADA system was well underway, albeit in a state of flux, by the time the modeling effort began. A greater level of efficiency may have been achieved had a process developed early on for synchronizing project data and automating the update process for simple changes through things like batch file distribution. To improve these processes, future projects of this nature should seek as much direct and frequent interaction between the simulation and design teams as is feasible.

## CONCLUSIONS

The use of full scope simulation for the Keystone pipeline was key to maximizing efficiency during online system development and startup of online SCADA and liquid applications.  It served to further enhance the readiness of controllers and support staff and assess control scenarios before pipeline operations began.  In the future, full scope simulation may be further expanded to include testing and development of the actual station PLCs and RTUs.  This would allow for complete testing of all computer systems before field implementation, reducing commissioning time and the probability of failures in the field.  These strategies are most useful if adopted very early on in the design of the pipeline.

# FIGURES

Figure 1: Keystone Map


Over/Short Balance

Pipeline: Keystone Time: 08:23:55 Mode Status: RUN Primary Server: Redundant Server: DISMISS

| Averagin Period (min) | Alarm Status | Deviation (m^3) | Linepack Chang (m^3) | Delta Flow (m^3) | Meter In (m^3) | Meter Out (m^3) |
|---|---|---|---|---|---|---|
| ● 2 min. Trend | Normal | -0.02 | 0.05 | -0.07 | 44.98 | 44.89 |
| ○ 15 min. Trend | Normal | 0.78 | -1.65 | 2.42 | 346.18 | 348.56 |
| ○ 60 min. Trend | Normal | 4.75 | 2.19 | 2.56 | 1455.34 | 1457.87 |
| ○ 120 min. Trend | Normal | 4.75 | 2.19 | 2.56 | 2934.15 | 2936.68 |

Leak Section:

Thresholds

Section Status: Normal

Deviation Delta Flow Linepack Change Min: Max: Set ☑ Autoscale

Figure 2: Simulator depiction of pipe section balancing trend during for a pump start up.

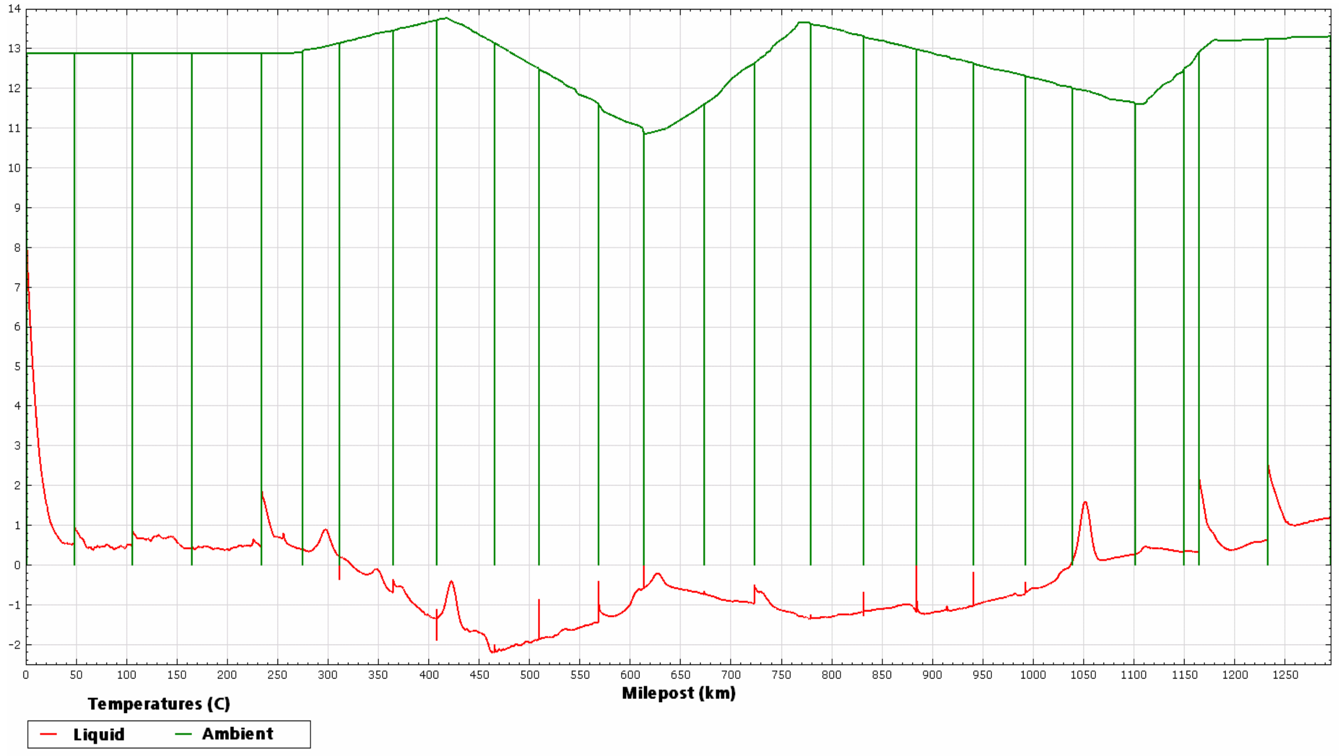


Figure 3: Temperature profile for a section of the Keystone Pipeline. The ambient profile is the estimated air temperature for this section of the pipeline on July 15th. The temperature profile is that if the crude oil for operation in February. This represents the potential for incorrect heat transfer within the simulation.

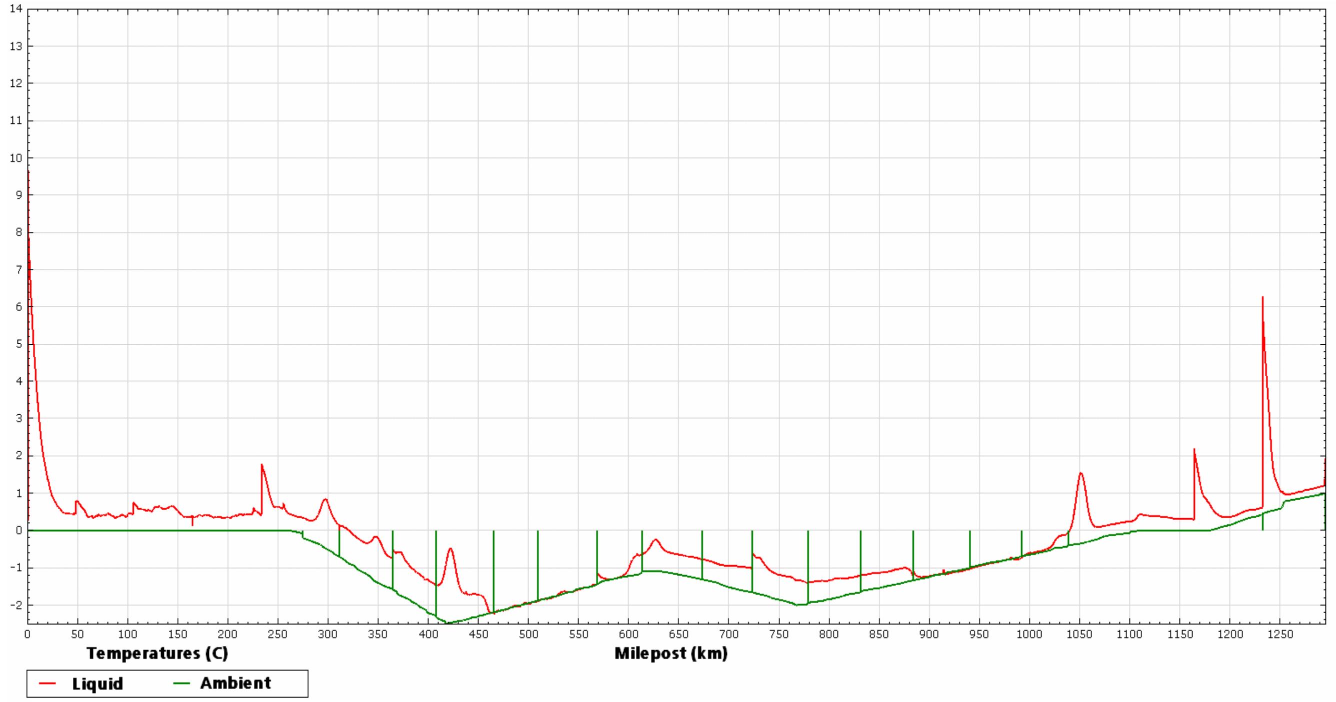


Figure 4: Temperature profile for a section of the Keystone Pipeline. The ambient and crude temperature are start up estimates for operation of the Keystone Pipeline on February 15th.