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TRANSCANADA PIPELINES: AN EXPERT ADVISORY SYSTEM FOR PIPELINE OPERATIONS

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ABSTRACT

This paper describes a new approach to provide advanced advisory information intended to complement the systems used by Gas Controllers operating the TransCanada gas pipeline. The "Advisory System" is based upon Gas Controller knowledge and experience captured into an expert system and integrated with signal processing of SCADA in real-time.

The Advisory System continuously applies its knowledge seeking and identifying deviations from normal and efficient operation, determining whether these deviations are significant, and presenting warnings and possible causes through a web-enabled user interface. The technology monitors both steady-state variations from normal operation and the transient effects of unintentional or abnormal conditions. Discussed are system requirements, and the unique approach taken to monitor, tune, evaluate and communicate conclusions. The results achieved, Gas Controller feedback, and future directions are presented, including the successful rapid detection of a linebreak incident.

INTRODUCTION

One of TransCanada's core businesses is the transmission of natural gas from the Western Canadian Sedimentary Basin to major Canadian and export markets safely, efficiently, and profitably. The coordination and control of a 38,000 km gas pipeline with up to 7 parallel lines using 3,800 MW of power is a difficult and complex process requiring the combined efforts of the Gas Controllers and a dedicated team of technicians and engineers. This requires each Gas Controllers to monitor and respond to a wide and varied information load.

The Gas Controller's primary function is the safe and effective operation of the pipeline system while achieving scheduled gas receipts and deliveries. The most important tools used are SCADA systems, gas receipt and delivery schedules (Nominations), maintenance schedules, model simulations, and weather data. The Gas Controllers are required to scan the system for upsets or emergencies while operating valves and compressors as necessary for safe and efficient transmission of scheduled gas volumes. It is in fact difficult for a Gas Controller to continuously maintain vigilance to detect inefficient or abnormal conditions while attending to routine operations that require their concentration.

The goal was to provide Gas Control with consolidated and concise information to allow the Gas Controllers to make timely and accurate decisions crucial to the operation and safety of the pipeline, facilities and population at large. This resulted in the creation of a decision support application that we have characterized as an Advisory System.

Objectives of the Advisory System are:

1) To continually scan the SCADA system for steady state or transient deviations from normal or efficient operation.
2) Alert and inform the Gas Controller of a deviation in a timely manner.
3) Complement but not duplicate information from SCADA and other tools.
4) Be flexible and easily extended to monitoring of additional conditions.

When the requirements for these problems were analyzed, it was recognized that a detailed transient simulation was not necessarily the right tool for all of these applications. They do require knowledge of hydraulic characteristics, but could be based on telemetry observations alone. Expert System technology was then considered. The goal of this paper is to communicate our experience in applying this technology to real-time operations support.

APPROACH AND METHODS

The Advisory System uses an expert system to analyze dynamic pipeline hydraulic conditions. In describing the approach, we will first differentiate the expert system method of modeling from a hydraulic simulation. We then characterize those aspects of an expert system suitable for real-time pipeline applications. Finally, the potential applications of the technology are explored. These theoretical models form the basis for the design and implementation described below.

Comparison of Hydraulic Models and Expert System Methods

A Gas Controller relies on knowledge of pipeline behavior and calls upon those rules relevant to a given set of observations to make operational decisions. He does not create a detailed hydraulic model in his head to perform this task. For example, if a Gas Controller sees a compressor station where suction pressure is increasing, and discharge pressure is decreasing, he will quickly recognize this as an effective loss of compression on the basis of that pattern alone. Detailed hydraulic analysis of the pipeline state or compressor are not necessary to arrive at this conclusion.

By contrast, a hydraulic simulation model is based upon hydraulic *equations of state.* The equations depend upon a precise definition of components and conditions to describe the pipeline in greater detail than is available directly from inputs or telemetry. These *detailed results* are valuable and can be essential for a number of applications. The hydraulic simulation model, in steady state and transient variations, is widely used and its benefits and limitations understood. However, it need not be the only means to analyze hydraulic behavior.

The expert system strategy is similar to the 'observation and knowledge' approach of a Gas Controller rather than the 'equation of state' strategy of a hydraulic simulation. The expert system does not create a detailed definition of hydraulic state. Rather, it applies pattern recognition to arrive at conclusions about the possible cause of observed effects. In software this is not a common strategy and no metrics exist to substantiate if it would indeed be successful or what the benefits and limitations might be. Nonetheless expert systems do have some characteristics of merit for such analysis.

Applicability of Expert System Technology

In an expert system logic, is defined *declaratively* through rules (acted on by an inference engine) rather than *procedurally* through programs. One consequence is that the design need not necessarily predict all possible logical paths through the rules: conclusions can be inferred through broad, obtuse or unanticipated inputs. Also, only those rules pertaining to a given circumstance are exercised, resulting in potential for very good performance. However, this non-deterministic behavior also poses validation difficulties.

In terms of analyzing pipeline operations, these characteristics have several beneficial implications. For detecting unusual behavior the designer need not necessarily create the *procedures* that correctly handle all possible input scenarios: rather he only *declares* the patterns of interest. Secondly, the system only processes those rules relevant to the data patterns observed. Processing only relevant relationships as opposed to global solutions has significant performance advantages. This is comparable to the Gas Controller that ‘calls upon’ knowledge applicable to a given observation. However, the Gas Controller's attention must be spread between many tasks; an expert system can continuously monitor the entire system 24 hours a day, remaining vigilant for unusual or potentially catastrophic events. Thirdly, the patterns that describe unusual behavior may be distinct enough that knowledge of precise telemetry values may not be necessary to come to certain types of conclusions.

Thus potential exists for a system that is effective under a wide variety of input conditions, fast enough for real-time applications, tolerant of data anomalies, and provides continuous reasoned monitoring of the pipeline.

Applications for Expert System Technology

The categories of problems that were recognized as suitable to this type of analysis can be divided into two groups: steady state and transient. Each day Gas Controllers are given an operations plan and are responsible for operating the pipeline as close as possible to this optimal plan. Steady state patterns in pipeline telemetry can be identified in real-time to point out conditions interfering with optimized operations, or indicate that recommendations are not working as intended. For example:

Pressure Anomalies: Pressure relationships at or between stations that are unusual or inefficient.

Operational Bottlenecks: Relationships between the lines at a series of stations indicating potential for more optimal compression or throughput usage.

The TransCanada mainline attempts to achieve steady state operation, but a system this large is seldom without transient behavior. These transients may be due to external factors (nomination changes), intentional operations (unit start/stop), or abnormal/undesired events. It is detection and identification of the abnormal and undesired events that can provide value to Gas Controllers.

For example, if a non-telemetered valve unintentionally opens or closes, that can be identified indirectly by observing the resulting pressure and flow transients in the vicinity. Alarms exist to indicate pressure or other hydraulic limits have been exceeded, but analysis of trend patterns revealed that many events have signatures that can be identified well before alarms occur. Some events may never become severe enough to generate an alarm, but still affect the efficient operation of the pipeline.

Two transient signature examples are:

Linebreak:
- Upstream station: flow increasing AND pressure decreasing.
- Downstream station: flow decreasing AND pressure decreasing.

Uncommanded Mainline Valve Closure:
- Upstream station: flow decreasing AND pressure increasing.
- Downstream station: flow decreasing AND pressure decreasing.

The unique benefits of an expert system as applied to these applications have similarly unique risks. The design and implementation considerations of a robust and consistent rulebase operating in real-time are significantly different than for a procedural program, as is the validation of such a system. Integration and user interface issues are also important for a successful application.

DESIGN AND IMPLEMENTATION

Design Methodology and Rulebase Structure

The most obvious of the design and implementation issues was what rules to define, and how to define them. The solution required a tight collaboration between pipeline operations experts and the expert system designer. In designing and implementing the rules, an iterative or Spiral Model of development was employed. Rulebased systems are particularly effective in early prototyping, and refactoring of the rulebase was performed at a rate that is difficult to achieve in procedural systems. In the course of doing so, some important success factors were identified.

One such factor is the overall strategy of rule implementation. Rules were designed in such a way that the fundamental *logical relationships* between facts were coded into the rules, but that the *sensitivities* of these rules to input data and conclusions were parameterized. Thus the effective response of the entire system is highly pliable by manipulation of parameters alone.

Latter designs extended this concept by making a concerted effort to minimize reliance on the accuracy of telemetry, and instead depend more heavily on pattern relationships among the telemetry inputs. In this way the system remained surprisingly insensitive to data anomalies. Rather than constrain conclusions on the basis of precise values, broad ranges were used, and specific values applied only to identify a level of relevance to conclusions. This resulted in a system with the ability to communicate not only conclusions, but also the degree to which it is confident in those conclusions.

Expert Collaboration and Development Team Considerations

The nature of the above design strategy implied that the applications required a great deal of tuning to achieve the responses desired. The pipeline expert users most valuable role was not simply in the initial definition of rules so much as was their ability to identify what response characteristics required changing and by how much. Frequent iterations for such tuning lead to rapid improvements in the quality of results. The tuning parameters have stabilized significantly over time, also contributing to our confidence in their validity.

Another important success factor was the skill set for development of the rulebase. Not only are several software-engineering skills heavily put to the test in the design of a rulebase, but also a working knowledge of the domain was critical in valid and effective interpretation of expert recommendations into a rulebase. Also, it was a considerable learning experience for the expert users to discover just how much detail is required in a rulebase to implement what is perceived as a relatively straightforward problem.

Critical Architectural Components

Thus far we have discussed the role of an expert system in the development of this Advisory System. But it is the level of integration of the expert system with existing and supporting infrastructure that made it practical. This included using low latency interfaces to SCADA, asynchronous messaging, custom signal processing and web deployment. The Java programming language was the glue that bound these systems together. JESS, the Java Expert System Shell (Ernest Friedman-Hill and Sandia Laboratories), integrates seamlessly with Java and that contributed significantly to the effectiveness of the architecture. Development of the steady state applications provided the means to implement many of these key components. But the transient applications demanded a great deal more of the tools. Of these architectural components the signal processing was perhaps the most crucial.

For transient applications it was initially thought that simple rate-of-change information would suffice as input. But in fact extensive signal processing was required to convert a raw SCADA signal into a series of distinct, well defined and valid transient events in real-time. Numerous methods were investigated ranging from FFT techniques to edge detection algorithms borrowed from the image processing domain. In the final analysis a set of custom algorithms was designed that took advantage of filtering techniques, edge detection techniques and the constraints known to exist on pipeline telemetry data. These also had to be fast. The use of software Adapter and Proxy Design patterns implemented in Java provided good conceptual separation between signal processing software and the rule engine without sacrificing performance or physical integration.

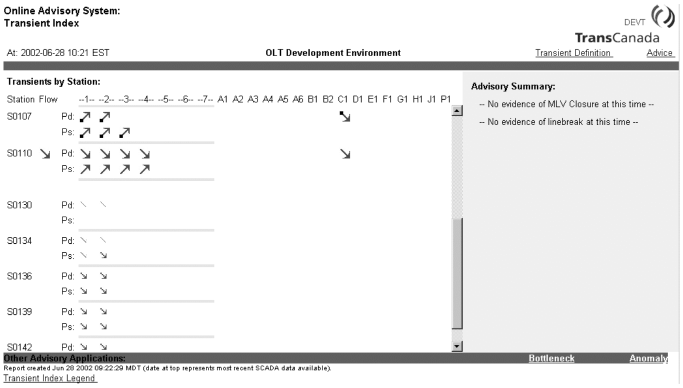
The combination of signal processing (to produce distinctly characterized transients) and an expert system (to perform pattern recognition) was perhaps one of the most instrumental conceptual factors in this Advisory System implementation. One final hurdle remained: how to communicate this information to Gas Controllers in an effective manner.

Communicating Conclusions: User Interface Design

The project team was constrained by some stringent requirements in the Gas Control environment. The Advisory System had to integrate into the control environment by complimenting but not duplicating SCADA, minimize interaction effort on the Gas Controllers part and draw the Gas Controllers attention to anomalies when necessary. Finally, Advisory System conclusions had to be effectively explained.

The latter task is quite important for an expert system. Simply communicating its conclusions is not sufficient – it must also be able to explain how it arrived at that conclusion. For an application to state "*There exists very strong evidence of a linebreak between station X and station Y*" is a bold assertion. If a Gas Controller is to have any faith in such a conclusion it is necessary to back up the claim with *the supporting and possible refuting reasoning* used to arrive at this conclusion.

These requirements were met through the use of a carefully designed web enabled interface. Where web pages were not sufficient, java applets were used to enrich the UI. Gas Control found the results of the transient analysis component of itself a valuable and useful display tool that compliments the SCADA system nicely. This *Transient Index* is essentially a summary display of the primary hydraulic transients that are, or have recently occurred on the pipeline (Figure 1). Based on principles of small multiples and layering, a display of transients was created that can be quickly scanned to achieve a sense of the overall behavior of the system. Gas Controllers have used this display alone to identify issues with the pipeline. The information on this display has been deemed sufficiently valuable to Gas Control that one monitor on each console is dedicated to displaying it continuously.


Online Advisory System:
Transient Index

At: 2002-06-28 10:21 EST

OLT Development Environment

Advisory Summary:

-- No evidence of MLV Closure at this time --

-- No evidence of linebreak at this time --

Report created Jun 28 2002 09:22:29 MDT (date at top represents most recent SCADA data available).

Figure 1. Transient Index Report showing typical transients for daily operations. Station S0110 C1 unit has shut down. This is causing packing at the upstream station, and the controller is responding by backing off unit C at 107. Stns 130-142 are drafting, a result of increased demand in the eastern provinces and states. None of these patterns generate abnormal conditions.

If an anomaly is detected, an Advisory System summary entry is automatically displayed, along with a bold pop-up dialog for severe warnings. If the Gas Controller wants to see the explanation supporting this conclusion, a single link will take him to a detailed page describing the evidence used to argue for and against the conclusion. Links from the explanation page (or the Transient Index) can be used to display trends of the raw and signal processed telemetry from which these conclusions ultimately originated; thus fully explaining the conclusions by way of textual and graphical support.

Contributing to the success of the user interface was the ongoing consultation, feedback, and training of Gas Controllers. They were given a voice throughout development, observed in their work, and trained on the benefits and limitations of this unique technology. As a result the tool is used effectively and meets their expectations well.

Testing and Validation

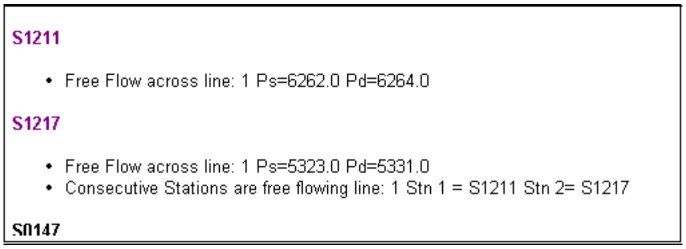
Testing and validation was a critical component of the software development process. In the case of linebreak detection, clearly one cannot create or wait for such an event to actually occur in order to validate the application! The solution was to develop a test bed that could mimic part or all of the real-time system. Test cases included not only fabricated scenarios (white box testing), but also data from historical linebreak events on the pipeline. By demonstrating that linebreaks that actually happened in the past could be detected quickly we were able to validate the model. The end users were sufficiently satisfied with this performance that the application was approved for production use.

In addition to the test bed, the development versions of the applications are always running against a real-time data feed. This gives us 7x24 testing of the development system on real data. By the time an application goes to production we are confident in it's abilities and limitations because it has been running under those same conditions, almost constantly, since the day it was created.

APPLICATION RESULTS AND FINDINGS

The iterative development strategy involved increasingly complex applications, each building upon knowledge captured in rules, design skills and infrastructure implemented in the previous iteration. Initial applications represent patterns detected under steady state conditions such as pressure anomalies and operational bottlenecks. Subsequent applications moved on to transient detection and pattern recognition in the form of rapid linebreak detection and mainline valve closure detection.

Pressure Anomalies



S1211

- Free Flow across line: 1 Ps=6262.0 Pd=6264.0

S1217

- Free Flow across line: 1 Ps=5323.0 Pd=5331.0
- Consecutive Stations are free flowing line: 1 Stn 1 = S1211 Stn 2= S1217

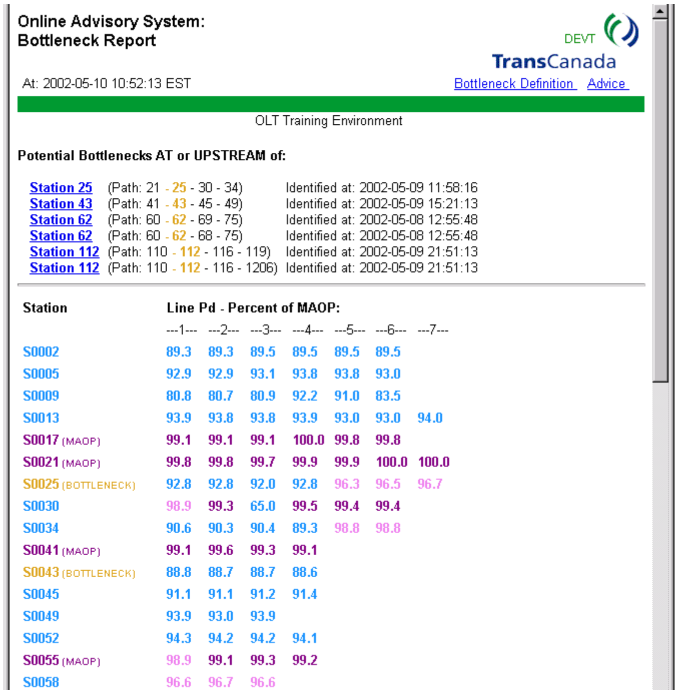
S0147

Figure 2. Sample of the Pressure Anomaly Report noting consecutive stations free flowing.

Our simplest application was pressure anomaly detection. This application identifies system operating patterns that are recognized as inefficient. The rules were simple and could have been implemented in any number of more conventional means. But it provided the context to construct a basic SCADA interface, integrate pipeline configuration rules and display system infrastructure while adding business value. For example, Figure 2 shows a section of the pressure anomaly report. Consecutive stations free-flowing the same line can occasionally occur when the Gas Controller is re-configuring up to 7 parallel lines. This application detects such configurations and advises Gas Controllers appropriately. As a consequence, the incidence of such operationally inefficient conditions has reduced substantially.

Bottleneck Detection

Operational Bottleneck detection represents the next level of sophistication. This application uses steady state relationships to determine potential throughput bottlenecks in the pipeline. The logic is based on the operating pressures of individual lines (up to 7) considering conditions up to 4 stations away to determine that a throughput bottleneck may exist.



Online Advisory System:
Bottleneck Report

At: 2002-05-10 10:52:13 EST

Bottleneck Definition Advice

OLT Training Environment

Potential Bottlenecks AT or UPSTREAM of:

Station 25 (Path: 21 - 25 - 30 - 34) Identified at: 2002-05-09 11:58:16
Station 43 (Path: 41 - 43 - 45 - 49) Identified at: 2002-05-09 15:21:13
Station 62 (Path: 60 - 62 - 69 - 75) Identified at: 2002-05-08 12:55:48
Station 62 (Path: 60 - 62 - 68 - 75) Identified at: 2002-05-08 12:55:48
Station 112 (Path: 110 - 112 - 116 - 119) Identified at: 2002-05-09 21:51:13
Station 112 (Path: 110 - 112 - 116 - 1206) Identified at: 2002-05-09 21:51:13

Station	Line Pd - Percent of MAOP:						
	---1---	---2---	---3---	---4---	---5---	---6---	---7---
S0002	89.3	89.3	89.5	89.5	89.5	89.5	
S0005	92.9	92.9	93.1	93.8	93.8	93.0	
S0009	80.8	80.7	80.9	92.2	91.0	83.5	
S0013	93.9	93.8	93.8	93.9	93.0	93.0	94.0
S0017 (MAOP)	99.1	99.1	99.1	100.0	99.8	99.8	
S0021 (MAOP)	99.8	99.8	99.7	99.9	99.9	100.0	100.0
S0025 (BOTTLENECK)	92.8	92.8	92.0	92.8	96.3	96.5	96.7
S0030	98.9	99.3	65.0	99.5	99.4	99.4	
S0034	90.6	90.3	90.4	89.3	98.8	98.8	
S0041 (MAOP)	99.1	99.6	99.3	99.1			
S0043 (BOTTLENECK)	88.8	88.7	88.7	88.6			
S0045	91.1	91.1	91.2	91.4			
S0049	93.9	93.0	93.9				
S0052	94.3	94.2	94.2	94.1			
S0055 (MAOP)	98.9	99.1	99.3	99.2			
S0058	96.6	96.7	96.6				

Figure 3. Bottleneck Output

In Figure 3, the display color codes line pressures as a % of Maximum (seen as shades of gray), organized by station (vertical) and pipe line # (horizontal). The coloring quickly identifies areas on the pipeline that are at their limit, and those that are not. This graphically supports the bottleneck conclusion, and can equally be used in any number of ways to compliment the SCADA presentation of the pipeline state

The results indicate that there is *potential* for a bottleneck. This style of advice was crucial to user acceptance. It in effect states to the Gas Controller that "according to the Advisory System's (relatively finite) rules, there *MIGHT* be a problem". This tone leaves the final call to the Gas Controller, and rightly so. The expertise captured in the Advisory System is deep with regard to bottlenecks, but is nowhere near the breath of knowledge that a Gas Controller has. Nonetheless, these pointers often focus the Gas Controller to an area of concern.

Rapid Linebreak Detection

Early detection of linebreaks was considered the most important application of the Advisory System. The nature of telemetry responses are such that linebreaks are invisible for two minutes or more and of insufficient magnitude to be observable for up to a further five minutes. Even after that time, alarms will not be created and analysis would be required to confirm that a rupture has occurred. The objective was to be able to identify a line break ideally in the first seven minutes.

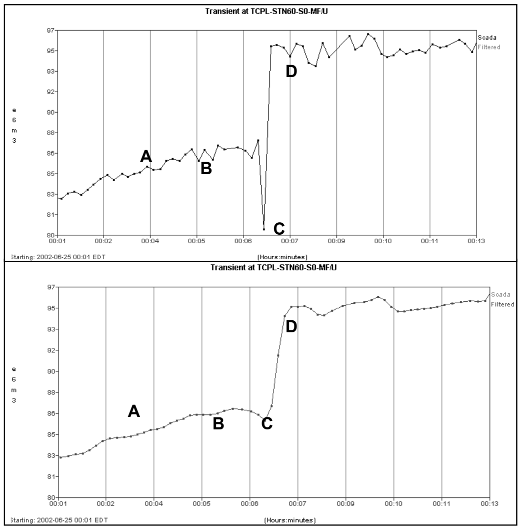
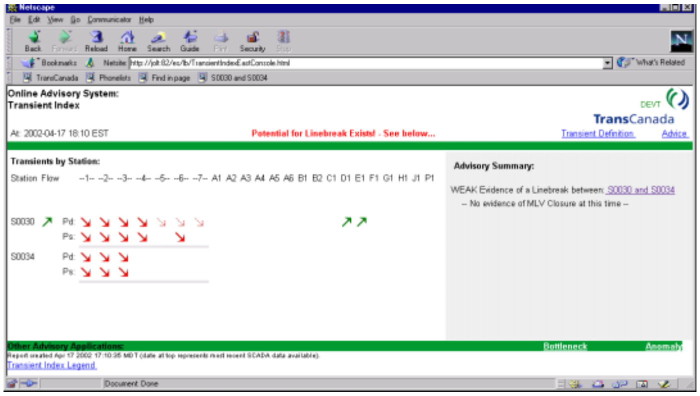


Figure 4. An illustration of the signal processing challenges. Plots are Flow x Time: Top is raw signal, bottom is filtered. One transient from C to D. Note (A) weak trend not to be considered a transient, (B) (C) reduce noise and errors but (D) maintain sharp edges *and* identify transient boundaries fast.

Transient Signal Processing Results. Figure 4 is an example of a flow signal in transient and demonstrates some of the signal processing challenges. The signal to noise ratio is very high, and while the human eye can easily see a transient starting the last third of this trend, software methods to accomplish this in real-time are immature.

This processing has to occur very quickly to be of use in Rapid Linebreak Detection. The signal processing algorithms are **O**(1) efficiency resulting in a 4ms/datapoint processing rate (Sun ES3500). Typical latency is collectively under one minute from field through SCADA, signal-processing software, the expert system through to report generation at the control console. Of this time, core expert system pattern matching takes on average 3 seconds for the complete pipeline system per analysis cycle; validating that performance can easily meet real-time demands.



http://jolt:82/es/lb/TransientIndexEastConsole.html

Online Advisory System:
Transient Index

At: 2002-04-17 18:10 EST

Potential for Linebreak Exists! - See below...

Transients by Station:

Station Flow --1-- --2-- --3-- --4-- --5-- --6-- --7-- A1 A2 A3 A4 A5 A6 B1 B2 C1 D1 E1 F1 G1 H1 J1 P1

S0030 ↗ Pd: ↘ ↘ ↘ ↘ ↘ ↘ ↘ ↗ ↗
Ps: ↘ ↘ ↘ ↘ ↘

S0034 Pd: ↘ ↘ ↘
Ps: ↘ ↘ ↘

Advisory Summary:

WEAK Evidence of a Linebreak between: S0030 and S0034
-- No evidence of MLV Closure at this time --

Report created Apr 17 2002 17:10:35 MDT (date at top represents most recent SCADA data available).

Figure 5. This is the Transient Index report as it would have initially appeared to the Gas Controllers 9 minutes after the line break at Brookdale occurred (played back on April 17).

Pattern Recognition for Rapid Linebreak Detection.

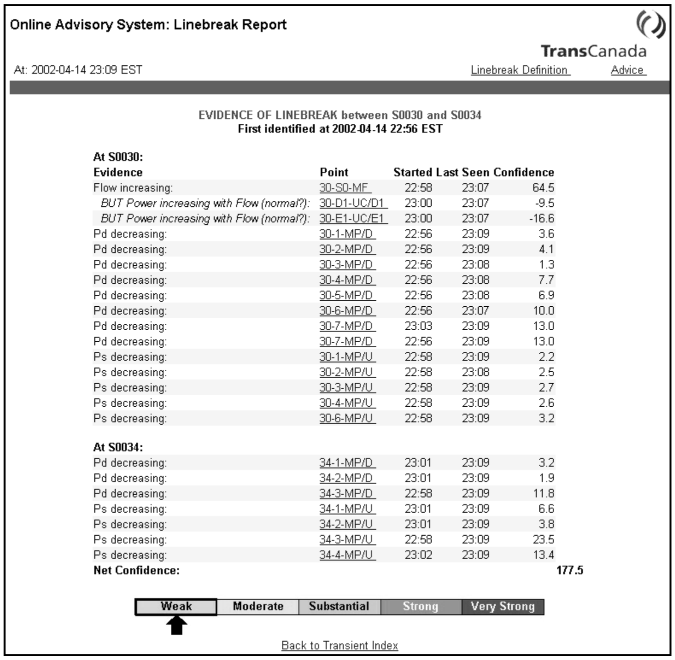
The 'classic' pattern for a linebreak is upstream pressure dropping, flow increasing, downstream pressure dropping, flow dropping. The linebreak application detects this pattern, but must also detect more subtle patterns. Historical cases indicate that seldom are all four transients observed for actual linebreak scenarios in a multi-line system (Figure 5). So detecting a linebreak with 3 of the four signature patterns was necessary. But many operational events can also mimic 3 of the 4 patterns, requiring analysis of the patterns in terms of operational events. The expert inference engine applies rules to both support and refute the linebreak hypothesis. Notification to Gas Controllers occurs only when the system acquires sufficient confidence in the linebreak explanation.

The Linebreak explanation page takes the form seen in Fig. 6.

Confidence in the assertion ranges from **Weak** to **Very Strong**, according to the weight and sum of the evidence. Also displayed is individual supporting and refuting evidence (with a link to each trend), timing of transients and relevance of evidence to the conclusion. This reporting style gives the Gas Controller all he needs to be notified, assess and confirm the conclusion.

False Alarms. This method of reporting generates false alarms. It has been tuned to purposely do so. If it never generated a false alarm, that would indicate that the tuning could tolerate greater sensitivity. Currently, a false alarm is generated roughly once a week - the user community deems this acceptable.

An unexpected benefit of the false alarming is that they often alert Gas Controllers to unusual situations that are not linebreaks. Because the rulebase automatically reasons away many common operational situations, a false alarm is typically generated under one of two scenarios: a) An unusual event has occurred (likely involving falling pressures), or b) Gas Controller actions have generated linebreak-like transients. In both cases the Gas Controllers actually approve of this behavior! They know it may alert them to some other anomaly, or acknowledge that their actions have created a linebreak-like pattern. This confirms to them that the Advisory System is indeed monitoring the pipeline as it should.



Online Advisory System: Linebreak Report

TransCanada

At: 2002-04-14 23:09 EST

EVIDENCE OF LINEBREAK between S0030 and S0034
First identified at 2002-04-14 22:56 EST

At S0030:

Evidence	Point	Started	Last Seen	Confidence
Flow increasing:	30-S0-MF	22:58	23:07	64.5
BUT Power increasing with Flow (normal?):	30-D1-UC/D1	23:00	23:07	-9.5
BUT Power increasing with Flow (normal?):	30-E1-UC/E1	23:00	23:07	-16.6
Pd decreasing:	30-1-MP/D	22:56	23:09	3.6
Pd decreasing:	30-2-MP/D	22:56	23:09	4.1
Pd decreasing:	30-3-MP/D	22:56	23:08	1.3
Pd decreasing:	30-4-MP/D	22:56	23:08	7.7
Pd decreasing:	30-5-MP/D	22:56	23:08	6.9
Pd decreasing:	30-6-MP/D	22:56	23:07	10.0
Pd decreasing:	30-7-MP/D	23:03	23:09	13.0
Pd decreasing:	30-7-MP/D	22:56	23:09	13.0
Ps decreasing:	30-1-MP/U	22:58	23:09	2.2
Ps decreasing:	30-2-MP/U	22:58	23:08	2.5
Ps decreasing:	30-3-MP/U	22:58	23:09	2.7
Ps decreasing:	30-4-MP/U	22:58	23:09	2.6
Ps decreasing:	30-6-MP/U	22:58	23:09	3.2
At S0034:				
Pd decreasing:	34-1-MP/D	23:01	23:09	3.2
Pd decreasing:	34-2-MP/D	23:01	23:09	1.9
Pd decreasing:	34-3-MP/D	22:58	23:09	11.8
Ps decreasing:	34-1-MP/U	23:01	23:09	6.6
Ps decreasing:	34-2-MP/U	23:01	23:09	3.8
Ps decreasing:	34-3-MP/U	22:58	23:09	23.5
Ps decreasing:	34-4-MP/U	23:02	23:09	13.4
Net Confidence:				**177.5**

Figure 6. Initial Linebreak Explanation Report from Brookdale Linebreak Incident.

Detection Timing. By running historical linebreak data through the test environment, we were able to confirm that not only can the system identify linebreaks, but it can do so quickly. Table 1 shows results of time to detect linebreaks from their best known start time.

Historical Linebreak event	Classic Pattern	Time to detect, minutes
Case 1	Yes	7
Case 2	No	9
Case 3	No	9
Case 4	No	15
Case 5	No	**Not detected**

Table 1. Time to detect historical linebreaks.

A significant characteristic of the times described in Table 1 is that, in all of these cases, the transients had not yet exceeded normal operational range when the initial indications began. The Gas Controller did not detect the linebreaks from SCADA within these times achieved by the Advisory System. Thus there is real opportunity for Gas Controllers to gain valuable minutes in the detection and subsequent actions required for a linebreak situation.

Case 5 in Table 1 merits explanation. While performance of this application is adequate for production use, there are still circumstances where a linebreak can occur and the SCADA data is either unavailable (loss of telemetry) or too complex (unit and/or valve operations) to be discriminated by the current version of the system.

Linebreak at Brookdale. The Rapid Linebreak Detection Application's first actual event was the detection of the Brookdale linebreak on April 14, 2002. At 23:00 EST, Line 3 (of 7) ruptured near the town of Brookdale, MB. The application notified the Gas Controller 9 minutes after rupture took place (see Figures 5 and 6). At that time, the pressure transients were only -109 kPa (-16psi) upstream and -300 kPa (-44psi) downstream (initial pressure 6070kPa (880psi)). These transients were still well within normal operations range, and not at a particularly high rate of change, (~33kPa/min) but the system was able to establish enough evidence in a linebreak pattern to notify the Gas Controller.

A review of the evidence page above (the initial report received by the Gas Controller) reveals that this was not at all a classic linebreak signature. The flow transient from the downstream station was delayed and of low amplitude as it originated from a unit not connected to the ruptured line. Further complicating the situation, the two units upstream were running at low power and so were able to increase power to reduce the rate of decay of discharge pressure despite the loss of gas. The increase in power was treated as a partial explanation for the flow increase reducing the confidence in the detection of the linebreak. The expert system was able to apply its rules and correctly interpret all of these complicating and competing factors, while still generating an alarm within nine minutes. Within 11 more minutes the confidence escalated to **Very Strong**: the maximum rating possible (by this time the Gas Controller had already initiated emergency response procedures).

Gas Control was very pleased with this result. External indications (a phone call) came at virtually the same time as the initial Advisory System warning. Without the Advisory System, the Gas Controller would have required several minutes of analysis to identify and confirm what was happening to the pipeline. The overall conclusion is that the Advisory System has demonstrated its value and greatly assisted the Gas Controllers in this event.

MLV Closure detection

The Mainline Valve (MLV) Closure Detection is the most recent addition to the suite of applications in the Advisory System. This application attempts to detect mainline valves that have closed without command and/or telemetry indication. On a pipeline with up to 7 parallel lines, much of it in remote locations, these closures can be difficult to identify. The additional challenge with this application is that the scale of the transients can be very subtle (as little as 10% flow change) and that this pattern can be mimicked by many operational conditions.

At this point the ability to detect an MLV closure is good, but *discrimination* from operational events has opportunity for improvement. Unlike Linebreak detection, actual MLV closure tests could and were conducted. The initial system response was fair, allowed tuning parameters to be improved. After the new parameters were applied, all test cases were detected. Because this pattern can be mimicked by several other (flow constricting) events, we still see some false alarms. Additional discrimination pattern rules will improve the quality of results.

Overall Gas Control Feedback on the Advisory System

The most compelling measure of value of the system is the response from Gas Controllers. Most Gas Controllers actively incorporate the Advisory System tools and displays into their work. All pay attention to the anomaly messages and follow them up. Confidence in the system varies from Gas Controller to Gas Controller, but most are quite excited by the applications. A common sentiment is that the Advisory System is "another pair of eyes" watching the pipeline.

FUTURE DIRECTIONS

In many ways the timing of this technology application was opportune. Computing devices are now networked and fast enough to consider these applications in real-time. Today's software architectures and languages allow for dissimilar platforms and products to be linked. Finally, expert inference engine algorithms and implementations have matured sufficiently to be practical business tools. This sets the stage for even better applications in the future.

We have only just scratched the surface of possibilities using this technology in terms of pipeline applications. Only a few hydraulic patterns and inputs have been implemented; many more are possible. Already these techniques have been extended into real-time compressor unit health monitoring, for example. While the techniques have proven themselves production worthy, there is still much opportunity to make significant improvements upon them, including increasingly rich inputs and patterns.

Hydraulic Simulation and Expert Systems as Collaborative Technologies

Although expert system methods have been differentiated from simulations methods, there is in fact a great opportunity to combine these very different modeling techniques to the benefit of each. Simulation results can be fed into expert systems further refining the types of patterns detectable, and adding evidence to strengthen conclusions; particularly where no telemetry exists.

Likewise expert systems can be used as a means to direct, constrain, or collaborate on those aspects of simulation that are not best served by hydraulic equations of state. Control system models, optimization (including non-hydraulic factors), and design refinements are examples. Finally, both could be used in a form of feedback loop: For example a simulation could provide detailed hydraulics for a given set of inputs, and an expert system could evaluate the resulting state, refining the simulation inputs based on knowledge of hydraulic or non-hydraulic patterns and constraints.

CONCLUSIONS

Our conclusion is that expert system technology is indeed viable and has practical value in terms of the analysis of pipeline hydraulics behavior. This value is complementary to existing tools for Gas Control. It leverages the business's investment in SCADA and extends the Gas Controller's ability to operate the pipeline safely and effectively. The rapid detection of the Brookdale linebreak and resulting value for Gas Controllers reacting to this incident confirms these conclusions.

Factors of successful design and implementation include tight collaboration between pipeline experts and software developers. Software development skill set, rigor in methodology and particularly testing are all significant. Processing raw SCADA data into a form usable for pattern recognition was a fundamental consideration. Usability of the tool and suitability in context are important for ensuring value and acceptance to the user community.

Through the Advisory System, Expert System technology has demonstrated it's value for operations at TransCanada Pipelines, and we are excited at the possibilities it holds for the future.

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