ABSTRACT

Refining NZ is New Zealand’s only oil refinery and the leading supplier of refined petroleum products to the New Zealand market, including gasoline, diesel, jet fuel and other products. It supplies most of the fuel needs for Auckland through a 169 kilometre (105 mile) long, 273 millimetre (10.75 inch) diameter pipeline terminating at the Wiri Terminal in South Auckland.

To meet the growing demand for jet fuel, Refining NZ started a pipeline capacity increase project in 2017. The first 2 of 3 phases of this project have been completed with the 3rd phase due to kick-off in 2019.

Refining NZ rely on an Online Real-Time Transient Modelling (RTTM) system to provide decision support applications for the pipeline controllers such as batch tracking, scraper tracking and leak detection. The RTTM was updated in 2017 to include the changes made in the pipeline operation. On September 14th, 2017, Refining NZ experienced a significant incident on the pipeline which threatened their business.

This paper details how Refining NZ use their RTTM as a decision support tool, some key learnings from the incident, including analysis of the incident using the RTTM, and what Refining NZ has done to improve its operations as a result of the incident and the subsequent analysis.
RAP transports four fluids: Regular Petrol (Gasolene), Premium Petrol, Diesel and Jetfuel. Table 2 describes these products:

<table>
<thead>
<tr>
<th>Product Code</th>
<th>Fluid</th>
<th>Reference Density (kg/m³) (@ 1 bar, 15.5°C)</th>
<th>Dynamic Viscosity (cP) (@ 20°C)</th>
<th>Dynamic Viscosity (cP) (@ 30°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Regular Petrol</td>
<td>733</td>
<td>0.341</td>
<td>0.298</td>
</tr>
<tr>
<td>2</td>
<td>Premium Petrol</td>
<td>711</td>
<td>0.331</td>
<td>0.289</td>
</tr>
<tr>
<td>3</td>
<td>Jetfuel</td>
<td>793</td>
<td>0.664</td>
<td>0.474</td>
</tr>
<tr>
<td>4</td>
<td>Diesel</td>
<td>835</td>
<td>1.7479</td>
<td>1.2471</td>
</tr>
</tbody>
</table>

Table 2 - RAP: Fluid Properties

A project to increase the capacity of RAP is underway. The project has three distinct phases:

- **Phase 1**
  - Upgrade Marsden Point flow meters (Nov 2017)
  - Upgrade 2nd pump at IPS2 (Nov 2017)
  - 3 key valve actuators replaced at valve sites (May 2017)
  - Pressure increase: 75 barg to 87 barg (1088-1262 psig) (Jun – Aug 2017)

- **Phase 2**
  - Utilisation of Drag Reduction Agent

- **Phase 3**
  - Pressure

Phases 1 and 2 are already complete. Phase 3 remains at the conceptual stage.

The pipeline is well served by instrumentation. There are pressure transmitters at the downstream side of each block valve, and a densimeter and pressure transmitter 3 kilometers (1.86 miles) out from the delivery station. The intermediate pumping stations are served by ultrasonic flowmeters, pressure transmitters at the suction and discharge sides, and a discharge temperature transmitter.

**Real Time Transient Model**

Emerson (then Energy Solutions International) installed a PipelineManager™ Real Time Transient Model (RTTM) on the RAP in 2010, replacing an earlier implementation that was commissioned in 2005.

The RTTM uses measured pressure as a boundary condition: specifically, the configuration is a segmented pressure/pressure model, with each segment being a linear chain of devices between pressure instruments.
Effectively, this gives a series of individual models (segments) between each block valve/pump station location.

The pump stations are modelled as black boxes, with no detailed pump configuration being included beyond an indication as to whether the station is operational or in bypass. The RTTM represents the head increase across each station as a break in the pressure segments either side of the station.

The RTTM’s thermal model uses measured temperature as an upstream boundary condition. Heat transfer to the surrounding soil is modeled through a series of concentric thermal shells. Again, the pipeline is broken into linear segments of contiguous pieces of equipment. In this case, there are three individual segments: Marsden Point to IPS1, IPS1 to IPS2, and IPS2 to Wiri Terminal, as per Figure 4.

The fluids are modelled using API Table 6B [1].

The flows at the upstream and downstream extents of each pressure bounded segment are compared against that of their neighbours (in the case of the first and last segment, these are the fiscal metering at Marsden Point and Wiri Terminal). Discrepancies are minimised by an iterative process that tunes the specific pressure drop per unit length of each segment.

Similarly, the calculated temperature at the downstream of each thermal segment is compared against the next available downstream temperature measurement, and the ground thermal properties are tuned in an iterative manner to minimise the difference. Provided the thermal parameters of the pipe and its surroundings are reasonable, this gives a good temperature profile along the pipeline.

Tuning processes are automatically suspended if a leak warning or alarm exists.

The RTTM uses a model-compensated volume balance approach to detect and locate leaks within the pipeline system. Measured flows (flow balances) are compared against the transient model-generated packing rate to establish a volume balance for sections (volume balance sections) of the pipeline (See Figure 5).

Volume Balance is given by the formula:

\[ \text{Volume Balance} = \text{Flow Balance} - \text{Packing Rate} \]

Equation 1 - RTTM: Volume Balance

Leaks are detected by analysing the volume balances. For a pipeline with no leaks and accurate data, the volume balance should be zero. In practice, the volume balance always contains noise due to inaccurate data and other causes. Leaks cause positive volume balances. A leak is alarmed if the positive volume balance is sufficiently above the noise level for an acceptably low probability of a false alarm. Alarm thresholds are dynamic, based on statistical analysis of uncertainty in recent hydraulic behavior.

Leaks are located by comparison of the computed flow balances at the ends of the volume balance sections (nodes). The node flow balance is the net flow into the node. Some of the flows into and out of a node may be measured; the model calculates other flows. Again, the node flow balance should be zero in the absence of leaks and errors. A leak causes positive calculated node flow balances at the end nodes of the hydraulic model segment, with the larger node flow balance occurring at the node nearest the leak.

Once a leak has been detected, located and verified (if required), the information about the leak is made available to the User Interface, and to SCADA if desired.

All volume balance section calculations are averaged over
multiple leak detection averaging periods. The RTTM integrates scan results over time for each historical processing period. The leak detection results are then computed using a moving window average of the historical records associated with the individual leak detection period. Each leak sub-section and leak detection period has its own associated alarm and warning thresholds.

**Pipeline Rupture**

At 11:56am local time on 14th September 2017, the pipeline suffered a leak. The leak made international news due to disruption to flights caused by the reliance of Auckland International Airport on fuel from the Refinery.

Earlier that morning the pipeline had tripped accidentally during a test of the fire detection systems at IPS2. During the restart process, while only one IPS1 pump had been restarted, the pipeline tripped once more. This trip, a result of the leak was due to a low discharge pressure at Marsden Point.

Shortly after, the local low pressure protection at the Waipu Cove block valve station activated and closed the block valve at Waipu Cove, preventing any possibility of a pipeline restart.

The location of the leak was KP8.85 (MP5.5), which lies between Marsden Point Refinery and the Waipu Cove valve site, close to the Ruakaka River:

![Figure 6 - Leak: Leak Location](image)

Incident management planning was started before the leak was confirmed and once the leak location was identified, the incident management response was immediately initiated, with the initial focus on protecting people and environment.

The full extent of the damage to the pipeline only became clear after two days. This was due to a high water table in the area. Extensive dewatering systems had to be put in place to get the water table below the pipeline depth. Significant external damage to the pipeline was found around the leak site.

The cause of the leak is believed to have been mechanical damage caused historically by an excavator. The pipeline was last inspected in July 2014 by intelligent pig which showed no indication of any damage at the leak location, so the assumption is that the damage was caused between this date and the date of the leak.

The local area is one of farmland but was once a peat swamp and is known for buried swamp kauri timber, which is a valuable material. Excavators are used to prospect for the buried swamp kauri logs.

It is estimated that 100-120 m³ (629-755 bbl) of Jet fuel was lost as a result of this event.
Figure 7 - Leak: Leak Site Showing Mechanical Damage.

Figure 7 shows the leak site and the damage to the pipeline.

Northland Regional Council found that the discharge was beyond the control of Refining NZ, and concluded that Refining NZ could not reasonably have foreseen or provided against the damage, and commended the Refining NZ for their “outstanding response”

**Behaviour of the RTTM During Rupture**

The first event (caused by the IPS2 Fire system) occurred at 09:53 local time. The transients introduced resulted in a leak warning being issued from the 30 second Volume Balance Period:

Figure 8 - IPS2 Trip: Alarm Log

Figure 9 illustrates the behaviour of the Volume Balance module.

The second event is the pipeline leak, occurring just over two hours after the initial trip.

Figure 10 presents a timeline of the event. At 11:58:10, the Volume Balance had been in excess of 90% of the threshold for 6 RTTM cycles (30 seconds). Some 30 seconds later at 11:58:40, the Volume Balance had been in excess of the threshold for 9 cycles (45 seconds). At this point (140 seconds after the second trip), a leak alarm and an initial leak location was raised.

As time progressed, the leak alarm filtered through from the 30 second to the 1 minute Volume Balance periods. Note that the leak alarms clear relatively quickly. This is because the pipeline was closed in almost immediately – the trip that closed the ESD valves occurred within a minute and the intermediate block valves were closed 10 minutes after the rupture. The other factor in the rapid clearing of the leak alarms is that the leak was in a blocked-in segment that had no pressure instruments, making the leak no longer visible to the hydraulic model. In another pipeline with a pressure instrument on the blocked-in segment, the continuing loss of pressure from the leak would have continued the negative packing rate and continued the leak alarm.

Figure 11 shows the Volume Balance trends. At the time of the leak, the volume balance thresholds were still relaxed after the earlier trip due to a mechanism in place to increase the thresholds under startup or shutdown operations. A signal received by the RTTM from DCS indicates whether there has been a recent change in the status of any of the pumps at IPS1 and IPS2. If there has been, then the thresholds are relaxed for around 2 hours. One IPS1 pump was started at approximately 11:30 (97 minutes post initial trip), causing the relaxation period to restart.

The first indication in the RTTM that there is a problem is the
rapidly decreasing Flow Balance, caused by the trip at Marsden Point – Wiri continues to receive product for a further 100 seconds. See Figure 12, below. Note that the initial surge from Marsden is not visible in the Flow Balance trend because of the time averaging behaviour of the Volume Balance period.

![Figure 12 - Leak: Marsden and Wiri Flows](image)

Shortly after the initial Flow Balance excursion, rapid unpacking is seen in the Packing Rate. This drives the Volume Balance positive toward the threshold. Recall that the Volume Balance Threshold is a dynamic quantity calculated from numerous individually-weighted components, values for which are calculated during runtime by the RTTM. During the period of the rupture, the major contributor to the threshold is a component which is proportional to the rate of change of the greater of the Packing Rate or Flow Balance signals. The Threshold rapidly increases until it hits its configured maximum of 325 m$^3$hr$^{-1}$, at which point it saturates.

The rapid depressurisation of the pipeline continues for around 2 minutes. Beyond this point, the oscillations in linepack decay until the value is static.

![Figure 13 - Leak: Marsden Point Data](image)

Note that whilst the RTTM detected the leak very quickly, both the calculation of volume of fluid lost in the leak and the location would be improved by the installation of a pressure instrument in the one segment of the pipeline that does not include a pressure instrument when blocked in, coincidentally the segment containing the leak.

**POST-LEAK ANALYSIS**

**Meter Proving**

Examination of the model pre-leak shows some excursions in balance across the flowmeters. The meter balance can be seen to shift when the fluid being injected/removed at either end of the pipeline changes. This can be seen in Figure 14. Note that the “flow balance” is independent of the model, being the sum of instrumented flows at the boundaries of the model.

![Figure 14 - Meter Proving: Flow Balance vs Fluid](image)

The cause of this is the correction factors applied to the readings from the flow meters. The process Refining NZ use to derive these factors require a single-fluid linefill. After a recent meter replacement, the correction factors for each fluid had not yet been optimised.

![Figure 15 - Meter Proving: Volume Balance](image)

The effect of this is visible in the Volume Balance trends. Figure 15 covers the same period as Figure 14. Where the meter factors lead to a negative flow balance, the Volume Balance is also negative, and the net effect is a de-sensitisation of leak detection. The opposite is true when the meter factors lead to a positive flow balance. This had caused nuisance alarms from the RTTM in the past.

Figure 16 shows a trend of the Volume Balance parameters from the RTTM. There are two periods of significant transience. In the first transient, the Flow Balance and Packing Rate excursions are in phase and are broadly equal, so there is little effect on Volume Balance (recall Equation 1). The second transient however, displays some time skew, with the Packing Rate leading the Flow Balance, causing a negative Volume Balance excursion. This behaviour is indicative of an
instrumentation issue. Inspecting trends of flows at Marsden Point and Wiri Terminal (Figure 17) highlights the difference between the two transients: the first transient originates at Marsden Point, with the effects being seen at Wiri a few minutes later; the second affects only Wiri Terminal.

**POST-EVENT SYSTEM ENHANCEMENTS**

**Rupture Alarms**

As a result of this leak, Refining NZ has enhanced their Leak Detection strategy to ensure very large leaks and ruptures are detected as quickly as possible. To this end the RTTM has been supplemented with a non model-based application that serves to detect large leaks quickly and with certainty by statistical and pattern recognition analysis. Operationally, leak notifications from this application are dealt with in a different way to leak notifications from RTTM.

**Pipeline Operations**

The RAP Capacity Upgrade project saw the installation of a second pump at IPS2 (the installation was carried out after the leak). The control of this pump by operations was leading to changes in Volume Balance and subsequent false positives from the leak detection module. A supervisory application was developed by Refining NZ to automate the control of the pump when there are fluids of different densities present in the pipeline. This led to smoother volume balance behaviour during these operations, and reduction in the number of false positives.

Once commissioned, the Volume Balance thresholds were reduced, leading to increased sensitivity without the risk of false positives. Thresholds were reduced by 20% while still minimising false positive leak alarms. The earlier mechanism for relaxing the thresholds after a change in pump status was also revised, allowing Refining NZ to adjust the time for which the raised thresholds were in place.

**Additional Instrumentation**

During the leak, when the automated valves closed, the pipeline section between Marsden Point (Refinery) and Waipu Cove (Valve Site 1), had no pressure measurement, with the nearest measurements being isolated by the closed valves. This meant Refining NZ had no indication of the pressure in the section of the pipeline that suffered the leak. From the RTTM’s point of view, the effect is that the calculation of fluid loss and the location of the leak were less accurate.

Refining NZ are adding a pressure instrument on the upstream side of the Waipu Cove valve, which will provide a pressure indication when the pipeline is in a shut down state. The benefits of this for the RTTM include a more accurate calculation of fluid loss during a leak, and no-leak confidence during shut-down.
CONCLUSIONS

Whilst the leak was detected very quickly by the RTTM, and previous live leak tests have proven the compensated volume balance method to be exceedingly effective at detecting and locating leaks, there was room for improvement:

- Increasing the resolution of the pressure measurement at Wiri, and reducing the time skew between pressure and flow signals improves the accuracy of the model, allowing it to better handle transients.
- Optimising the meter correction factors for the different fluid types leads to improved metering, bringing with it better Flow Balance.
- The installation of the supervisory application allowed smoother control over pumping operations, making the line less transient in nature, and allowing the threshold relaxation during pump startup and shutdown to be lessened in magnitude and duration.
- Addition of a pressure instrument upstream of the Waipu Cove valve site will improve leak detection performance under shut-in conditions.
- Implementation of a secondary method of leak detection improves the ability of Refining NZ to detect large leaks extremely quickly and with high confidence.

The culmination of these activities bring about a more accurate hydraulic model, which allows both greater leak detection performance and confidence in the validity of leak alarms. In addition, further training was given to pipeline operators to further develop their understanding of pipeline dynamics and assessment/verification of abnormal pipeline situations.

REFERENCES

1. Manual of Petroleum Measurement Standards Chapter 11, Section 1

ACKNOWLEDGEMENTS

The authors would like to thank Refining NZ for their permission to publish this paper, and for their willingness and candour in sharing the experience with the pipeline transportation community as a whole.

Thanks are also due to Dr Greg Morrow and Dr Jon Barley for their time and patience in reviewing this paper.

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Neil has fifteen years experience of pipeline modelling, served with Emerson (formerly Energy Solutions International). Neil is involved throughout the project lifecycle, with a particular interest in customer support.

Neil also spent four years working as a consultant engineer with Serco Integrated Transport, where he was involved with the design, proof-of-concept and rollout of a country-wide IP Network for the Scottish Motorway Network.

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He has been with Refining NZ for 14 years and has been involved in the control of the Refinery Auckland Pipeline for most of his time at Refining NZ. In 2009, he was the customer technical focal point for the upgrade of the pipeline leak detection and batch tracking application.

Peter has 34 years of experience in the oil industry. For most of his career he has been involved in oil movements in some way. He started his career at the Engen Refinery in South Africa where he was involved in a major re-instrumentation project installing a DCS system as well as the installation of an Oil Movements and Blending application suite. Peter also spent 10 years as an application consultant at the Honeywell Oil Movements Application Center in Toronto, Canada, before relocating to New Zealand.
FIGURES

Figure 19 - RAP: Pipeline Route
Figure 20 - RAP: Schematic
Figure 21 - RTTM: Segmented Model

Figure 22 - RTTM: Segmented Thermal Model

Figure 23 - RTTM: Volume Balance
Figure 24 - Leak: Leak Location
Figure 25 - Leak: Leak Site Showing Mechanical Damage.

Figure 26 - IPS2 Trip: Alarm Log
Figure 27 - IPS2 Trip: Volume Balance

Figure 28 - Leak: Alarm Log
Figure 29 - Leak: Volume Balance

Figure 30 - Leak: Marsden and Wiri Flows
Figure 31 - Leak: Marsden Point Data

Figure 32 - Meter Proving: Flow Balance vs Fluid
Figure 33 - Meter Proving: Volume Balance

Figure 34 - Time Skew: Volume Balance
Figure 35 - Time Skew: Inlet vs Outlet Flow

Figure 36 - Time Skew: Wiri Flow vs Pressure