Transportation Safety Board of Canada

Bureau de la sécurité des transports du Canada

PIPELINE INVESTIGATION REPORT
P05H0044

CRUDE OIL PIPELINE RUPTURE

TERASEN PIPELINES (TRANS MOUNTAIN) INC.
508-MILLIMETRE-DIAMETER TRANSFER LINE
NEAR ABBOTSFORD, BRITISH COLUMBIA
15 JULY 2005

Canada

Pipeline Investigation Report

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Summary

On 15 July 2005, at approximately 1030 mountain daylight time, an employee of Terasen Pipelines (Trans Mountain) Inc. discovered crude oil on the pipeline right-of-way, on the north side of Ward Road, Abbotsford, British Columbia. Before the discovery, the company had been delivering crude oil out of the Sumas Tank Farm when it received odour complaints from local residents. Approximately 210 cubic metres of crude oil was released into the surrounding area and made its way into Kilgard Creek. There were no injuries.

Ce rapport est également disponible en français.

Other Factual Information

On 08 July 2005, the Terasen Pipelines (Trans Mountain) Inc. (Terasen) system, which is owned and operated by Kinder Morgan Canada Inc., was delivering western Canadian crude oil from the company's Sumas Tank Farm, near Abbotsford, British Columbia, into the company's storage facilities in Puget Sound, Washington, United States. This movement of crude oil originated from the Sumas Tank Farm (see system schematic in Appendix A).

The movement of crude oil was remotely controlled and monitored by Terasen's control centre operators (CCOs) using a Supervisory Control and Data Acquisition (SCADA) system located at the company control centre (CCC). Crude oil is delivered to and from the Sumas Tank Farm via the Sumas Pump Station located on Terasen's mainline pipeline system (see Figure 1), via two buried pipelines: a 508 mm-diameter line (nominal pipe size of 20 inches) built in 1957 and a 610 mm-diameter line (nominal pipe size of 24 inches) built in 1962. The 508 mm pipeline was constructed with a 6.35 mm (0.250 inch) wall thickness and a pipe grade 359 (American Petroleum Institute grade 5LX-X52).

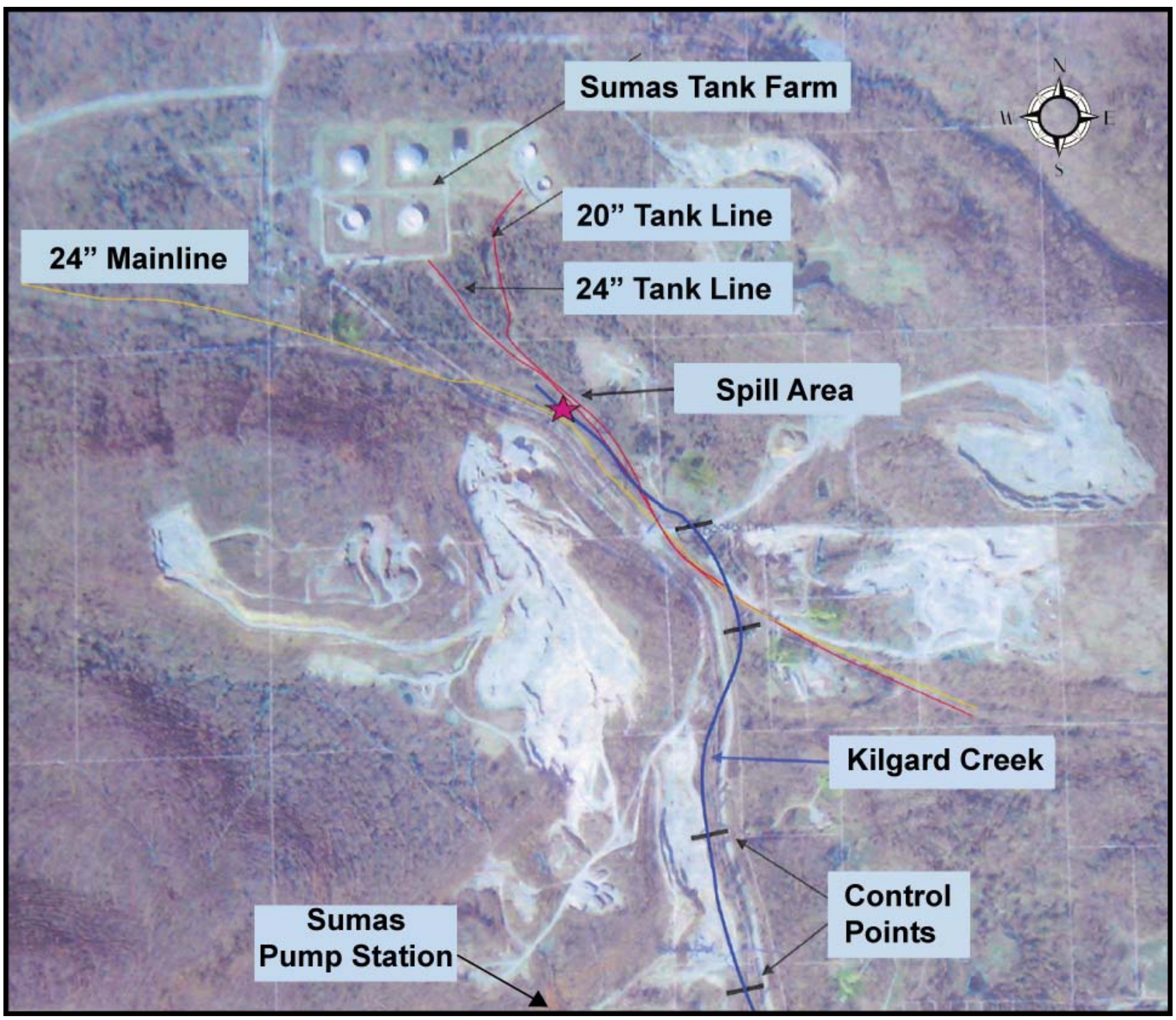

Figure 1. Terasen's mainline pipeline system between the Sumas Pump Station and the Sumas Tank Farm

At 1130 mountain daylight time[1] on July 8, the CCC received an odour complaint from a local resident. The CCO used Terasen's Odour Complaint Form to record the details, then notified the company's Burnaby operator, who investigated the odour complaint around 1400. The operator could detect crude oil odours, but could not determine the source.

At 2138 and 2355, the CCO received further odour complaints from local residents in the same vicinity. After completing an Odour Complaint Form, the CCO contacted Burnaby to dispatch a Terasen operations employee to investigate. On 08 July 2005, around midnight, the operations employee proceeded to Ward Road. While crude oil odours were apparent near Ward Road, he did not discover crude oil.

During the week leading up to the discovery of the location of the rupture, Terasen received five odour complaints from the area immediately south of the Sumas Tank Farm. Each complaint was investigated by a Burnaby operations employee without determining the cause of the odours.

On July 15 at 1030, a Terasen employee discovered crude oil in Kilgard Creek at the intersection of Ward Road and Upper Sumas Mountain Road. Because the vegetation along the right-of-way (ROW) and over the ditch and creek was very dense and 2 m tall, the employee did not walk the ROW to locate the source of the crude oil leak. The company had scheduled this section of the ROW for annual vegetation cutting during October. The Terasen employee was wearing basic personal protective equipment (PPE): safety glasses, boots, and Nomex coveralls. However, he was not equipped with the additional PPE appropriate for the hazards associated with this occurrence, such as a respirator or self-contained breathing apparatus, and a benzene detector or any other type of volatile organic detector.

The CCO, the Environmental Coordinator, and the Burnaby Pipeline Maintenance group were contacted immediately. The CCO immediately shut down deliveries from the Sumas Tank Farm to the United States and initiated Terasen's emergency response plan.

The Environmental Coordinator reported the incident to the British Columbia Provincial Emergency Program. Terasen's Pipeline Maintenance (PLM) Division began mobilizing personnel and equipment. The Incident Command System was implemented and, in accordance with the emergency response plan, an On-Site Commander was appointed.

At 1110, the City of Abbotsford (COA) Police and Fire Rescue Service (FRS) personnel arrived on site. At 1120, Terasen's Environmental Coordinator arrived on site. To enable the FRS to mitigate incidents involving any hazardous products, Terasen's first responders needed to identify the hazardous properties of the spilled product. However, the Terasen representative did not immediately identify the spilled product as containing hazardous by-properties. The FRS personnel, believing that there were no imminent hazards, began searching the ROW to determine the source of the leak. Once identified, they marked the source of the leak. Then, they erected inverted weirs and began to contain the crude oil spill and inhibit further migration of product downstream of Ward Road. At 1140, vacuum trucks were dispatched to Ward Road. They arrived on site at 1440.

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1 All times are mountain standard time (Coordinated Universal Time minus five hours).

At 1200, Burnaby's PLM Supervisor arrived and was designated the On-Site Commander.

At 1210, the CCO initiated procedures to shut down the Terasen mainline pipeline system and close the Hope Pump Station block valve, to isolate the crude oil downstream of the Hope Pump Station. By 1220, the Terasen mainline pipeline system had been shut down and the Hope mainline block valve had been closed. The CCO also initiated procedures to drain the 508 mm (20-inch "A" header) line and the 610 mm line (24-inch "B" header) tank lines between the Sumas Tank Farm and the Sumas Pump Station. These procedures were completed by 1430.

At approximately 1310, the Terasen representative informed the FRS personnel that the crude oil contained benzene. The FRS personnel retreated to a safe area until a benzene detector could be located and delivered to the occurrence site.

At 1340, the Royal Canadian Mounted Police (RCMP) arrived to cordon off the area and evacuate local residents.

Excavation of the pipeline identified three adjacent buckles on the 508 mm pipeline oriented about a vertical axis. Numerous cracks were observed to be associated with the buckles and wrinkles, and were located on the compression side of the buckles. One major 50 mm crack was identified as being through-wall. No other mechanical damage was found near the buckle. There was minor surface damage to the exterior concrete coating of the 610 mm line.

Environmental Impact

Approximately 210 cubic metres (m^3) of crude oil was released into the surrounding environment, affecting a main area covering approximately 5755 square metres (m^2). The total area requiring remediation was 14 300 m^2. The crude oil entered a watercourse, upstream of Ward Road, which supplies flow and nutrients to downstream fish-bearing waters. The wetlands upstream of Ward Road support amphibians, shrews, deer, garter snakes, and various birds. Approximately 5150 m^3 of organic soil (peat) was removed from the wetland area during the remediation activities. Post-accident soil and water samples indicate that the site had been substantially remediated.

Weather

Environment Canada weather reports indicated that the Abbotsford area had had an above average amount of rain in the first six months of 2005 when compared to the average amount of rain measured five and ten years ago.

Community Relations

The general public along Terasen's pipeline ROW had been encouraged to report any unusual crude oil odours and any sightings of crude oil to the CCO or to any other Terasen employee, or to a Terasen pipeline facility. There has been a history of odour complaints from the surrounding area of the Sumas Tank Farm, due mainly to vapour emissions emanating from the operation of the floating roof tanks. Terasen instituted a tank odour abatement program at this site to reduce the loss of petroleum crude vapours from the floating roofs during normal operations, which reduced the number of odour complaints.

Supervisory Control and Data Acquisition System and Leak Detection System

Day-to-day pipeline operations are controlled by Terasen's CCO using a SCADA system and leak detection system with the main control centre at Edmonton, Alberta. The CCO uses the SCADA system to manage and control all pipeline operations on the system such as delivering product into and out of the system, opening and closing valves, ensuring that the pipeline operates within prescribed pressure limits, and shutting down immediately during an emergency.

In addition to the SCADA system, the company has developed a real-time transient leak detection system that meets current industry standards and expectations. This system continuously receives SCADA data across most of the entire pipeline system to determine if a leak or rupture has occurred anywhere in the system. Given the elevation changes and the environmentally sensitive areas that the pipeline traverses, the real-time transient leak detection system provides the lowest detectable threshold values achievable.

However, the two pipeline sections between the Sumas Tank Farm and the Sumas Pump Station were not part of the SCADA system and leak detection system. Instead, Terasen depended upon deviation alarms, which are set at the Sumas tanks to monitor any volume changes that may occur in the tanks or the transfer lines when crude oil is not being delivered on either of the two Sumas pipelines.

Complaint Procedure

When any complaint, including an odour complaint, is received by the CCC, it is the responsibility of the CCO to document the calls ensuring that the complaint is recorded on Terasen's Odour Complaint Form. Once recorded, the CCO gives the appropriate pipeline station operator the relevant information. The CCO also tells the pipeline station operator if the complainant wants a call back about any complaint findings. If the operator or supervisor cannot be reached, then the Regional Manager is contacted.

Completed Odour Complaint Forms are faxed to the Regional Office for distribution to the Regional Manager, Station Supervisor, Environmental Coordinator, Environment, Health and Safety Supervisor, and Quality Control and Measurement official for action.

When responding, the pipeline station operator follows the Terasen Safety Manual, which has a written procedure for investigating an odour complaint: "519 Investigate Odour Complaint."

A TSB review of completed Odour Complaint Forms found that they were not being completed consistently; that is, information was missing (such as the street location, address, and general description of the area). Further, at the time of the occurrence, Terasen did not have a follow-up procedure to record follow-up actions taken or required as a result of the odour complaint.

Failed Pipe Replacement

On 21 July 2005, the failed pipe section was replaced. During the field phase of cutting out the failed section, it was observed that the pipe ends closed tightly together when the first cut was made, indicating that the pipeline section was under a significant amount of compressive stress. A second cut on the other side of the buckle also resulted in similar binding, indicating that the pipeline was still under compressive stress. With the removal of the damaged pipeline section, it was observed that the end of the pipe closest to the Sumas Tank Farm had shifted approximately 0.60 m towards the west and slightly upwards, while the end of the pipe closest to the Sumas Pump Station had shifted approximately 0.25 m towards the west. No significant rotation of the pipeline was noted. The failed section was replaced by a section of pre-tested pipe of a similar specification.

Integrity Management Program

As part of normal pipeline operations, Terasen has had a formalized Integrity Management Program (IMP) since 1996. The IMP describes sub-components of the overall integrity program such as in-line inspection (ILI), excavation programs, aerial patrols, and leak detection. The IMP meets the requirements of both the Canadian Standards Association (CSA) standard CAN/CSA Z662, *Oil and Gas Pipeline Systems* (CSA Z662), and the National Energy Board (NEB) *Onshore Pipeline Regulations* (OPR-99).

Since 1974, Terasen has had an active ILI program that forms the basis of the company's Anomaly Investigation and Pipeline Repair programs. Terasen's pipeline system is 100 per cent compatible with ILI tools. The tools it commonly uses include magnetic flux leakage (MFL), ultrasonic (UT), and internal caliper types. Depending on the type of tool selected, the ILI program provides Terasen with a detailed listing of anomalies on the inspected pipelines such as metal loss (corrosion, gouges, grooves), metal addition (weld fill-ins, fittings), manufacturing defects (inclusions, laminations), and weld defects, cracks, and deformations (dents, wrinkles, buckles). From the analysis of the data collected, a dig list is created and provided to the PLM crews who are responsible for excavating, analyzing, and repairing the pipeline at identified locations.

The ILI frequency for each pipeline depends on risk factors such as anticipated or known defect type(s) and severity, consequences (population and environmental sensitivity), and pipeline operating pressures and stress levels. Following an ILI, a pipeline repair program is instituted. Defects that fail to meet the criteria of Terasen or CSA Z662 are scheduled for investigation and repaired, when required. Various repair techniques are employed according to Terasen's standards, and as permitted by CSA Z662.

Based upon their specific characteristics, the two Sumas pipelines were scheduled for an ILI tool run every 10 years. The two pipelines were last inspected in October 1995. The 1995 ILI logs found no mechanical or other anomalies near the occurrence site. Following the occurrence, Terasen contracted to have the two pipelines re-inspected in September 2005 with an MFL inspection tool. An excavation program for this inspection was prepared to address identified anomalies.

Following the 1995 ILI of the two Sumas pipelines, an extensive excavation and repair program was conducted. A total of 46 anomaly investigations were conducted on the 3.7 km-long, 508 mm tank line. Fourteen defects were removed by cut-out, and two defects were repaired in 1998. A review of the anomalies identified in 1995 and of the subsequent repair program shows that Terasen had a high standard of repair. Most anomalies were excavated, assessed, and repaired by cut-out if required. The anomaly program exceeded the current requirements of CSA Z662.

Terasen's Pipeline Network

Originating in Edmonton, Alberta, and terminating in Burnaby, British Columbia (0 to 1146 km), Terasen's pipeline network traverses the Canadian Rocky Mountains and Jasper National Park. The pipeline traverses numerous geotechnical and hydrotechnical hazards, as well as integrity hazards associated with drainage ditches and navigable rivers.

Geotechnical hazards include processes such as landslides, debris flows, ground settlement, subsidence, and soil heave. Common triggers include high-intensity or long-duration precipitation events, changes in groundwater conditions, erosion and over-steepening of slopes, earthquakes, thawing of ice-rich soils, and freezing of frost-susceptible soils.

Hydrotechnical hazards are associated with stream and river processes and include scour, channel degradation, bank erosion, encroachment, channel avulsion, and debris impact on aerial crossings. Hydrotechnical hazards usually occur during flood events (involving small streams) and are often triggered by local precipitation cells. Disturbances to stream channels, including the effects of landslides, change in forest cover, degradation of ice rich soils, or the presence of poorly designed river control structures, can also increase the hazard potential.

Because of this challenging terrain, the company has developed a Natural Hazards Management Database to keep track of the potential hazards on the system including information on crossing details, field assessment data, and any mitigating actions taken. Developed in 1998, the database contains hazards information on all its pipeline facilities and is part of a formalized, semi-quantitative system to manage hydrotechnical and geotechnical hazards effectively.

Although the two Sumas pipelines follow the same route as the Terasen mainline pipeline system, they were not included in this program. In the case of any hazard analysis work being conducted on the mainline, it would have considered the two Sumas pipelines since the three pipelines follow portions of similar routing. While the natural hazards program includes information on water crossings and some seismic areas, the program does not include information on other potential natural hazards arising from swamps and peat bogs.

Vegetation Along the Right-of-Way

At the time of the incident, the vegetation on the ROW was approximately 2 m (approximately 6 feet) high. Therefore, during daylight, the presence of oil on the ROW would not have been readily apparent. The situation was even more difficult for employees responding at night, as was the case on 08 July 2005.

Vegetation clearing along the Terasen pipeline system ROW is performed by outside contractors. The frequency of the ROW clearing operations depends on the rate of growth of the vegetation and any government restrictions. Until 2000, the ROW in the area of the occurrence was cleared twice a year in May and October. After 2000, clearing was reduced to an annual October cutting. Because the occurrence site is located in a wet peat bog, the vegetation (primarily grass and bulrushes) grows very high.

Third-Party Encroachment

Third-party encroachment is considered a serious threat to pipeline integrity by Canada's pipeline industry. Terasen has a number of programs to minimize accidental third-party damage. In addition, Terasen has a land group whose sole responsibility is to manage ROW matters and third-party issues. The programs include:

- An Integrated Public Awareness Program designed to inform the public regarding pipeline safety, damage prevention, emergency preparedness, and maintenance projects.
- A Signage Program to ensure that the ROW is clearly marked with signs (in accordance with CSA Z662) that specifically identify the hazard as a liquid petroleum pipeline and provide an emergency response contact number.
- A Right-of-Way Surveillance Program with aerial patrols of the ROW to check for any signs of encroachments or other visible threats to pipeline integrity. All sightings are recorded in a patrol sighting report and filed in the appropriate Regional Office for any follow-up action. For the section from Kamloops to Burnaby, the pipeline ROW is patrolled weekly all year. In addition to the aerial surveillance, Terasen staff conducts day-to-day routine surveillance of the ROW as part of their regular duties.
- A Crossings Program designed to ensure that all crossing requests are processed by the Right-of-Way and Crossings Coordinator for the region involved.

Adjacent Landfill Operations

A local landowner contacted Terasen before placing landfill material adjacent to the ROW and in the immediate vicinity of the occurrence site. Terasen's local PLM technician met the landfill contractor, conducted a detailed review of the proposal, and then endorsed an approved Abbotsford Temporary Soil Removal and Placement Permit (COA permit). This permit specified that the landfill material was not to encroach on the ROW and that any mechanical excavation activities within 30 m of the ROW required prior approval. The Terasen maintenance technician placed a handwritten note on the permit that stated that landfill material should not be placed closer than 25 m to the pipeline ROW. The note also requested that the contractor contact Terasen if they needed to go any closer. The filling contractor did not place fill or complete any mechanical excavations within the 25 m separation approved by Terasen.

The COA permit specified that Terasen required one week's notice before the fill operation began to delineate the separation zone by placing flags. These flagging activities were carried out before the landfill material was placed near Ward Road.

The landowner requested time extensions of the COA permit several times between early 2000 and late 2005. The following approvals were granted:

- The original permit was issued 30 March 2000 and expired 30 July 2000.
- Time extension 2 was issued 02 July 2003 and expired 15 September 2003.
- Time extension 3 was issued 23 July 2004 and expired 15 September 2004.
- Time extension 4 was issued 15 September 2004 and expired 15 March 2005.
- Time extension 5 was issued 15 March 2005 and expired 15 September 2005.

While the COA permit specified the duration of the permit, it did not note what volume of landfill the landowner was authorized to place on the site, nor did it specify how the landowner was to report the actual volume of landfill accepted. Further, the COA permit did not describe any way to verify the accuracy of landfill volume accepted. The final volume of material accepted by the landowner was approximately 54 160 m^3.

While the original COA permit of March 2000 did not identify a volume of landfill material in the original soil deposit application, it did state that landfill material would be only 3 m deep. The COA Soil Deposit Application form, completed by the landowner, provides for an estimated volume. This volume is used to evaluate the fill proposal and to collect soil fees. On the soil deposit extension application of June 2003, the estimated volume listed was 20 000 m^3 (see Appendix B).

Sumas Tank Farm Operations

The Sumas Pump Station and Tank Farm are the hand-over point for crude oils destined to the United States. Referred to as "swings," the Sumas Tank Farm is used predominately to assemble batches of crude oil from Terasen's mainline pipeline system. The batches are then held for delivery to Washington refineries on an as required basis. This permits deliveries of crude oil to the Burnaby Terminal to progress, while providing delivery flexibility for the United States refineries.

Terasen typically uses the 508 mm pipeline to flow product up to the Sumas Tank Farm from the Terasen mainline pipeline system via the Sumas Pump Station and uses the 610 mm pipeline to deliver crude oil from the Sumas Tank Farm to United States markets, allowing the highest pipeline pressure for gravity-induced deliveries to United States refineries. One of the safety features for the tank transfer lines is a pressure relief valve at the Sumas Tank Farm that is set for 1000 kPa, approximately 29 per cent of the maximum operating pressure of the pipe.

Metallurgical Analysis

During the original construction of the pipeline in 1957, the 508 mm pipe was exterior coated with a coal tar epoxy material that was overlaid with a paper wrap containing asbestos fibres. It was found to be in relatively good condition. When the coating was removed during a surface cleaning operation, the coating was determined to be well adhered to the pipe surface. Visual inspection of the cleaned surface found no indication of any external corrosion.

The 508 mm pipe had a pre-existing cold bend that was formed in the field during initial construction of the pipeline. From a visual inspection of the failed pipe, a significant buckle was present, generally in the centre of this cold bend. A metallurgical analysis indicated that, although some transverse wrinkles were present along the length of this cold bend, the dimensions of the bend may not have met the specifications in place at the time of pipe installation or met the current CSA Z662 standards. The analysis further noted that the measurement techniques may not be accurate enough to definitely state whether the bend radius met the past or current standard.

In addition, a number of cracks were visually observed on the contours of the buckle. After breaking them open in the laboratory, four cracks were confirmed to be through-wall. Most of the crack surfaces appeared to exhibit ductile fracture with coarse striations indicating probable fatigue, which is a typical driving force for ductile cracks. Two of these cracks contained some mechanical damage, which indicates that the two crack surfaces had rubbed against each other before failure.

The metallurgical examination concluded that the buckle formed as a result of a significant bending stress imposed on the pipe at this location. The cracks associated with the buckle subsequently grew as a result of cyclic stresses imposed on the pipe during normal pipeline operations. It is believed that the stresses responsible for the formation of the buckle, and the subsequent initiation and growth of the cracks, were relatively uniform. It was also estimated that at least 40 stress cycles were required for the cracks to initiate and grow once the buckle had formed.

No evidence was found to suggest that corrosion, stress corrosion cracking, or substandard material contributed to the failure. There was no evidence of any mechanical damage other than the buckle and wrinkles present on the section of pipe examined. The metallurgical analysis determined that the source of the leak was located in four through-wall cracks in wrinkles associated with the buckle located in the middle of the pre-existing cold bend. However, the analysis could not fully explain the origin of the forces necessary to produce the buckle.

Study of the Origin of the Buckles and Associated Cracks

Mechanical damage in the form of buckles, dents, and gouges has emerged as a key safety concern for North American pipelines. Mechanical damage and/or ground movement are common precursors of pipeline buckles. The buckle could have existed at the occurrence site since the original construction of the 508 mm pipeline in 1957 and slowly fatigued to failure. No mechanical damage was identified on the surface of the pipe, and Terasen had successfully run an ILI tool (MFL) in 1995 with no indication of this buckle or cracks.

The first evidence that ground movement played a role in the development of the buckle was the lateral displacements of both the 508 mm and 610 mm lines towards the southwest and north of the pre-existing cold bends. A post-failure survey by Terasen of both transfer lines was conducted 150 m upstream and downstream of the occurrence site. This survey confirmed the presence of lateral deformation, from a straight line, northwest of the two cold bends. Peak deviation from a straight line was found to be 1.5 m and 0.95 m for the 508 mm and 610 mm lines, respectively.

The survey illustrated that both transfer lines showed evidence of being bowed-out, but the 508 mm line was more bowed-out than the 610 mm line. Since the pipe cross-section for the 610 mm line had approximately twice as much bending stiffness as the 508 mm line, the 610 mm line would have resisted movement much better than the 508 mm line. The post-failure survey illustrated that, towards the southeast, and away from the cold bends, both transfer lines were relatively straight.

Terasen and a consultant conducted an extensive geotechnical assessment to determine if pipe buckling was related to geotechnical movement. Both pipelines are located in a highly compressible layer of organic peat. Attention was given to the stockpiling of imported landfill material, located approximately 25 to 50 m northeast of the edge of the ROW, as a possible trigger for movement in the peat.

The landfill material that had been brought in by the landowner between early 2000 and mid-2005 was the only significant change in the vicinity of the occurrence site. Visual inspection of the landfill site highlighted tension cracks that ran parallel to the pipelines. Coring and cone penetration testing determined that the landfill material ranged from 3 to 8 m deep. This did not conform to the conditions of the 2000 COA permit, which had established a maximum landfill material depth of 3 m. The coring determined that a compressed layer of peat, followed by layers of silt, sand/gravel, and a till base underlay the landfill material. The silt, part of the Fort Langley Formation, has low strength when saturated and disturbed. Successive borehole excavations established a dip of the silt and sand/gravel layers to the southwest.

Slope inclinometers were installed in the ground, between the 610 mm line and the landfill material. The inclinometers measure soil displacement along their burial depth, thus providing a measure of potential movements of the various soil layers. Readings taken between September and November 2005 showed progressive and accelerating soil movement to the southwest and towards the pipelines. The largest displacements were located at points where the two transfer lines were closest to the landfill material and the occurrence site. These measurements confirmed that creep was occurring in the peat and silt layers.

Strain gauges were affixed to both transfer lines. The 508 mm line strain gauges were installed approximately one week after the pipeline was repaired to represent a near zero absolute strain condition. Any strain deviations from the zero condition are representative of absolute strain. Since installation, observed strain in the pipe has fluctuated at low levels due to site conditions such as rain, excavation activities, and pumping. Absolute strain values have fluctuated in the range of 100 micro-strains ($\mu\varepsilon$) to 400 $\mu\varepsilon$ as compared with the 2340 $\mu\varepsilon$ to 3750 $\mu\varepsilon$ required to plastically deform the pipe.

The strain readings taken on the 610 mm line were largely from an unexcavated line. In August 2005, peak strains were in the order of 600 με to 1000 με, which is less than the 5000 με to 7000 με required for the pipe to yield plastically. It was noted that, at the 90-degree position, the strain gauge was in tension, while at the 270-degree position, the strain gauge was in compression. This confirms that a bending moment about the cold bend in the pipeline was pushing the pipeline to the southwest because of ground movement. This movement was further confirmed by aerial photography, which illustrated the shift in the pipeline when observed from north of the occurrence site.

To better define the origin of the buckling on the 508 mm line, a finite element model of the occurrence pipeline was constructed. The analysis determined the buckling loads for the 508 mm pipe, and found that, when the model was loaded to the point where it formed a 17-degree angle, it formed a buckle whose appearance was consistent with the shape of the observed buckling damage. A parametric study was performed to determine the sensitivity of the analysis to variables such as initial surface imperfections, internal pressure, and temperature differential. A further analysis was conducted to study the cyclic stresses on the pipeline. The parametric study determined that external cyclic loading stresses caused by varying the applied curvature had the greatest effect, whereas those caused by temperature cycling had a moderate effect, and those caused by internal pressure cycling had a lesser effect. Additional analysis determined that the sweeping bends caused by soil movement resulted in bending moments that were sufficiently high to cause a buckle.

The finite element report concluded that the buckle was caused by soil movements associated with the formation of the sweeping bends adjacent to the failure. Once the buckle had formed, low cycle fatigue cracks grew within the buckle due to cyclic loads experienced in service. The study determined that, to obtain a buckle of the magnitude found at the occurrence site, a bending moment of approximately 450 kilonewton-metres (kNm) was required. The largest contributor to the bending moment in the pipe was the lateral displacement of the pipe caused by soil movement north of the pre-existing cold bend location (the occurrence site).

The study determined that, for the occurrence site, the displacement of the pipe laterally to the southwest created significant bending moments. Soil–pipe interaction modelling was conducted, which showed that, by displacing the pipeline 1.5 m towards the southwest, over a 60 m length, as was observed from the pipe survey, a bending moment in excess of 550 kNm was generated at the occurrence site. This action, by itself, would have been sufficient to create and grow the buckle in the cold bend to the point that any minor load cycling (from pressure or temperature) would create the fatigue cracks that ultimately led to the occurrence on the 508 mm line. The study also determined that very few cycles would have been required to fail this pipe.

Blasting in the Immediate Vicinity of the Pipeline

The immediate vicinity of the occurrence site is a mixture of residential and industrial establishments. There are several large rock quarries on either side of the pipeline that have been active for several decades. A common feature of these quarry operations is the regularity of heavy industrial blasting. Shockwaves from blasting in the vicinity of the pipeline can result in direct and indirect effects that, under certain conditions, may lead to the development of buckles. The closest quarry where blasting occurs is at Sumas Shale Inc., which is located between 300 and 600 m from the occurrence site on top of a high rock hill. The closest blasting to the pipeline was 70 m from the pipeline, but several hundred metres upstream of the occurrence site.

Terasen has a standard for reviewing blasting adjacent to the ROW: Terasen Engineering Standards and Practices—MP 3120C. This standard specifies that the maximum horizontal peak particle velocity and maximum amplitude resulting from blasting should be less than 50 millimetres per second (mm/s), which is a more conservative standard than the 60 mm/s standard set by the British Columbia Ministry of Energy, Mines and Petroleum Resources. This standard was initially intended to address blasting works related to the construction of a facility, such as a roadway or buried service, across and/or in proximity to a pipeline and ROW.

Terasen's blasting standard does not permit any blasting within the ROW and requires the company to review blasting plans for any blasting within 100 m of the ROW. It may also require a review for blasting within 300 m of the ROW. Although blasting at the local quarries occurred, on average, once every six days for the six months preceding the occurrence, the Terasen Crossings Specialist did not have any blasting records for the previous few years for the Sumas Mountain area.

A review of the quarry company's blasting records from January 2005 until the occurrence shows that the amount of charge could reach 3.5 tons of charge for a single blast. The quarry company's blasting records had no information on the peak particle velocities associated with blasting.

Terasen indicated that the blasting did not contribute to the failure in any meaningful manner. However, it could not determine whether regular blasting contributed to

- the landfill material settling deeper into the peat;
- the migration of the landfill material; or
- the migration of the underlying compressed peat material in the direction of the pipeline.

Analysis

The analysis will focus on events leading up to the buckle, third-party encroachment, identification of the location of the leak, the SCADA system and leak detection system, the initial response and first responders, the Natural Hazards Management Database, and the management of blasting issues.

Events Leading up to the Buckle

Evidence collected during the borehole excavations and cone penetration testing strongly suggests that the application of the landfill material disturbed the state of equilibrium of the native peat, silt, and sand/gravel layers. The increased loading caused by the imported dense landfill material resulted in the compression of the peat layer, along with consolidation of the soft silt layer. This, combined with heavy rains, and the regional dip of the competent soil below (sand/gravel and till), created a situation of creep in the layers above the competent soil.

The highly compressible peat surrounding the pipelines gave little lateral support, thus allowing the pipelines to be moved in a southwesterly direction, away from the area affected by the landfill operation. Evidence to confirm this movement was obtained from the metallurgical testing, the finite element analysis work, and detailed field testing. As a result of a significant bending stress imposed on a pre-existing cold bend, the buckle and associated cracks formed in the cold bend and, subsequently, grew as a result of imposed cyclic stresses causing the pipeline to fail.

Third-Party Encroachment

Since threats to the security and integrity of pipelines are critical issues in North America's pipeline industry, Terasen's land department is charged with managing all matters related to pipeline ROW integrity issues, especially those that could result in damage to the pipeline. Encroachment issues that can have an impact on pipeline integrity and security were not fully addressed by Terasen. Although Terasen was aware of the landowner's landfill operations, it did not verify that the landowner was adhering to the conditions set out in the COA permit.

Similarly, the COA was responsible for reviewing and issuing a landfill permit, and reviewing any subsequent revisions, but did not systematically review the permit to ensure compliance with its conditions. The final responsibility for adherence to conditions in the COA permit rested with the landowner. However, the land owner accepted excess volumes of landfill without verifying the consequences with either Terasen or the COA. During the landfill operations, there was limited dialogue between the landowner, Terasen, and the COA regarding the potential impact of the landfill on the pipeline.

Identification of the Location of the Leak

Terasen's response and identification of the location of the leak was delayed by a number of factors that were within the company's capacity to manage and remediate. Vegetation along the ROW was dense. Vegetation clearing had been changed from twice to once a year and was not scheduled until October. Deploying a single Terasen operations employee at midnight did not lend itself to easy and early detection of product loss at the occurrence site because of both overgrown vegetation and darkness.

Terasen employees responding to the odour complaints would have found walking the ROW difficult, with wet, soft footing, and dense, tall vegetation hampering visibility. The employee that discovered the release was not equipped with the PPE and gas detection equipment required by company procedures, although they were available. The employees were not well equipped to perform a thorough investigation of the ROW to find the source of the odour.

Unlike PLM employees, the Burnaby operations employees had limited knowledge of PPE and of the location of the pipelines in the ROW. Because no Odour Complaint Follow-Up Form was available from previous visits to the same location, responding operations employees were handicapped with respect to specific knowledge of the ROW and the location of the pipeline. This lack of follow-up did not permit employees on subsequent complaint investigations in the same area to explore other avenues. Because of the extensive history of previous odour complaints related to the Sumas Tank Farm, Burnaby operations employees may have underestimated the issue and were therefore reluctant to call for local PLM technical assistance. This incomplete response to the odour complaints led to delays in identifying the occurrence and to an increased impact of the leak on the surrounding environment.

Supervisory Control and Data Acquisition and Leak Detection Systems

The management of day-to-day pipeline operations is accomplished through Terasen's highly sophisticated SCADA system. Combined with the company's leak detection system, this provides a very effective method for early detection of pipeline leaks. However, the two Sumas pipeline sections were not covered by the leak detection system. Instead, Terasen depended upon a less efficient system that depends on deviation alarms set at the Sumas tanks to monitor any volume changes that might occur in the tanks and transfer lines when the two Sumas pipelines were idle.

However, the release of crude oil occurred when it was being delivered to and from the Sumas Pump Station. From the time of the first odour complaint, the deviation alarm system failed to detect the loss of product over a seven-day period. The leak of product occurred outside of the scope of this type of detection system. There were no apparent technical reasons for excluding the two Sumas pipelines from the overall framework of the leak detection system.

Initial Response and First Responders

Within four hours of arriving on site, the majority of the initial response, including locating the source of the leak, determining the extent of migration of the crude oil, and initiating containment (constructing three weirs) was completed by the FRS. Once assembled on site, Terasen's PLM response team added additional weirs, and began the clean-up and removal of spilled oil and contaminated soils. Terasen's response was handled efficiently and effectively by the initial PLM response group and later by the larger team controlled by the Incident Command System. The released oil was cleaned up quickly and contaminated soils were removed to a controlled area for disposal. Site restoration work is ongoing. Further monitoring is required to assess longer-term issues at and near the occurrence site.

First responders, such as police and fire departments, are charged with responding to emergency situations efficiently and effectively to protect life, property, and the environment. The initial response of FRS personnel was very effective, but because they had not been adequately informed by Terasen of the potential hazards of the products released from the pipeline, they lacked proper detection equipment to protect against potential occupational safety and health issues. The National Energy Board's *Onshore Pipeline Regulations* require that the company inform local emergency measures, fire department, and first responder personnel along the pipeline route of the location of the pipeline and the nature of the products being shipped. Terasen had not informed FRS personnel of the hazards or of the need for special types of equipment when responding to pipeline emergencies.

Natural Hazards Management Database

The Terasen mainline pipeline system from Edmonton to Burnaby traverses a wide variety of terrains, each with potential hydrotechnical and geotechnical hazards to the structural integrity of the pipeline. In response to these hazards, the company developed its Natural Hazards Management Database to track and address potential hazards on the pipeline system. However, the two Sumas pipelines were not included in this database. In addition, although Terasen indicated that a hazard analysis of the mainline would have considered the two Sumas pipelines, the database does not include information on natural or man-made hazards arising from swamps, peat bogs, or landfill activities.

Management of Blasting Issues

In its blasting management, Terasen did not fully address blasting issues that could affect pipeline integrity and security. Although it has a blasting standard, which includes maximum acceptable peak particle velocities, the Terasen Crossings Specialist did not maintain records. While the Terasen standard specified recording peak particle velocities, the quarry company did not record this information. The lack of recorded information on peak particle velocities could have impeded Terasen's ability to determine any effects on blasting on the pipeline and the landfill material.

Findings as to Causes and Contributing Factors

1. As a result of a significant bending stress imposed on a pre-existing cold bend, a buckle and associated cracks formed in the cold bend and subsequently grew as a result of imposed cyclic stresses; consequently, the pipeline failed.

2. Migration of the compressed peat layer and consolidation of the soft silt layer, created by the application of landfill, disturbed the state of equilibrium of the native peat, silt, and sand/gravel layers and produced the bending forces sufficient to displace the 508 mm diameter pipeline.

3. The response to the leak was delayed because of a lack of an effective leak detection system and an effective response to odour complaints.

4. Because the frequency of vegetation clearing had been reduced, the Terasen Pipelines (Trans Mountain) Inc. employee responding to the complaints was impeded by dense growth on the right-of-way.

5. The delays in emergency response, as well as the time taken to identify the leak, increased the severity of the accident.

6. A lack of communications between the landfill site owner, the City of Abbotsford, and Terasen exposed the pipeline to a threat from excessive landfill operations.

Finding as to Risk

1. Employees and other responders who are not wearing the appropriate personal protective equipment are exposed to health and safety risks when operating in the vicinity of a leak.

Other Findings

1. While Terasen has a formal standard for reviewing blasting adjacent to the right-of-way, its Crossings Specialist did not have any blasting records for the past few years for the Sumas Mountain area. Neither Terasen nor the quarry company had a process for recording key peak velocity measurements and other pertinent information from ongoing blasting operations to ensure compliance with Terasen's blasting standard.

2. The two Sumas pipelines were only in-line-inspected every 10 years, and the detailed review of the October 1995 in-line-inspection logs did not reveal any mechanical or other anomalies.

Safety Action Taken

In response to this occurrence, Terasen Pipelines (Trans Mountain) Inc. (Terasen) undertook a number of initiatives to address the deficiencies it identified during the response to and subsequent review of the occurrence.

A. The odour complaint procedure was revised to improve the recording of complaint details.

- If the source of an odour complaint cannot be attributed to a known operating condition, the Regional Manager should be notified, and this notification should be recorded on the Odour Complaint Form.

- The odour complaint procedure was revised to require that response actions taken are recorded on the form and that odour complaint management is communicated between changing shifts for responsible operations crews.

- The closing of an Odour Complaint Form will require sign off by the Regional Manager.

- Technicians responding to odour complaints will follow the appropriate odour complaint investigation procedures, including assurance that the required personal protective equipment is on hand.

B. Terasen's Integrity Management Program and pipeline maintenance procedures have been revised to improve the effectiveness of these programs.

- Identify all pipeline locations with soils such as peat bogs and swamps, and extend the Natural Hazards Management Program and the associated geotechnical database to include these areas.

- Issue a Technical Services Bulletin warning of the dangers of changes due to soil loading around peat bogs and swamps. The bulletin was addressed to Terasen's Operations groups including Pipeline Maintenance (PLM) groups, Aerial Patrol, One-Call System and Crossings groups on all pipeline systems.

- Revise the existing crossing approval procedure for known areas with vulnerable soils to require the approval of the Crossings and/or PLM groups as well as Technical Services for any third-party activity in these areas.

- Review in-line inspection data and perform strain calculations on pipe segments in areas of vulnerable soils, particularly those with pre-existing cold bends.

- Provide the resources to control very high-growth vegetation areas along the pipeline right-of-way as required by the Canadian Standards Association (CSA) standard CAN/CSA Z662, *Oil and Gas Pipeline Systems* (CAN Z662).

- Update the pipeline integrity management programs to include these changes.

- Write a technical paper describing this occurrence for presentation at a conference in order to alert industry to this type of scenario.

- The re-inspection of the two pipelines during September 2005 prompted the company to address anomalies identified on the two pipelines.

C. Terasen's leak detection system will be modified to include the two pipeline sections between the Sumas Tank Farm and the Sumas Pump Station into the overall leak detection system.

D. In 2005/2006, Terasen developed a detailed restoration plan to reconstruct the affected watercourse and replace the removed organic soil, and it was forwarded to government regulators for approval. The pipelines are in the final stages of being backfilled with organic peat to restore the site according to plan. Terasen has an ongoing monitoring program that includes measuring pipeline strain, as well as soil displacements at the occurrence site.

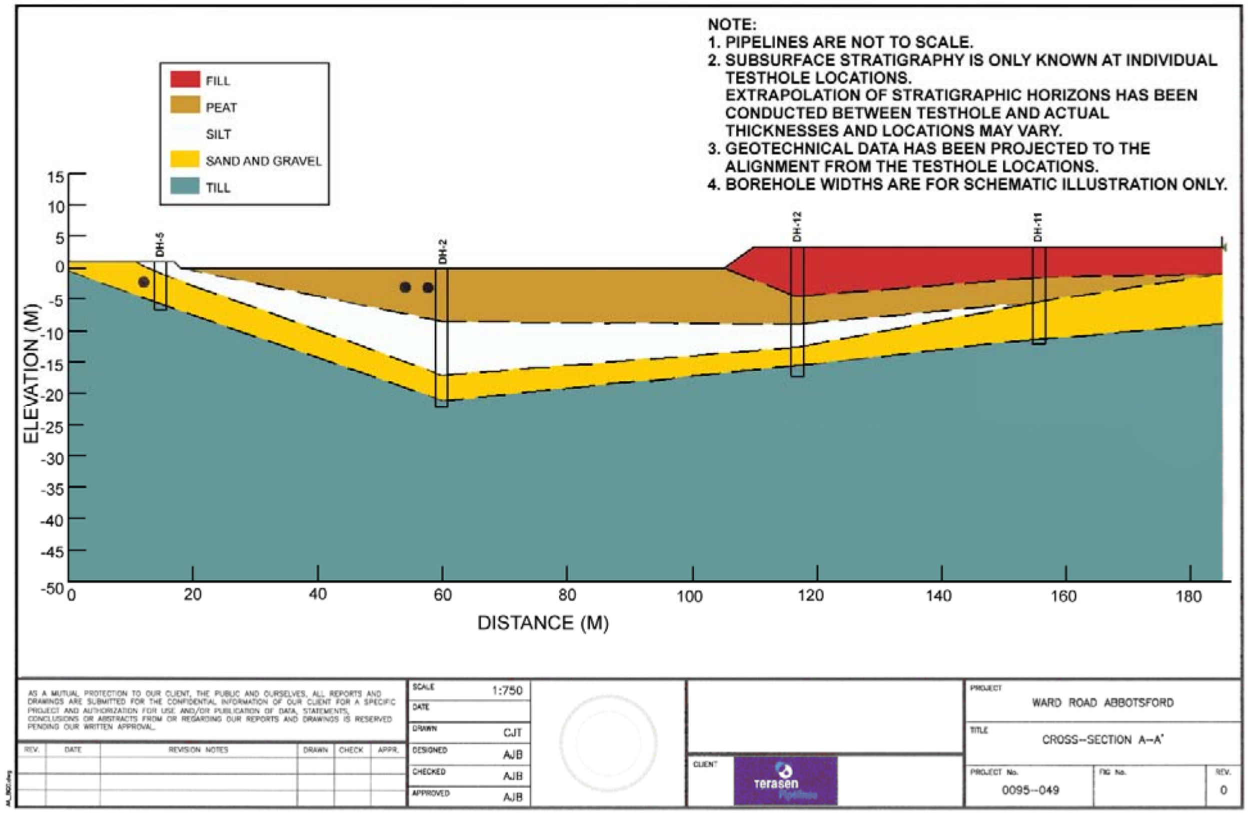
E. Terasen is currently evaluating and revising procedures and record keeping regarding blasting activities in the vicinity of Sumas Mountain and the two transfer lines.

This report concludes the Transportation Safety Board's investigation into this occurrence. Consequently, the Board authorized the release of this report on 07 February 2007.

*Visit the Transportation Safety Board's Web site (**www.tsb.gc.ca**) for information about the Transportation Safety Board and its products and services. There you will also find links to other safety organizations and related sites.*

Appendix A – Reference System Schematic

Appendix B – Cross-Section of Ward Road



Appendix C – Glossary

CCC	company control centre
CCO	control centre operator
COA	City of Abbotsford
CSA	Canadian Standards Association
CSA Z662	Canadian Standards Association standard CAN/CSA Z662, *Oil and Gas Pipeline Systems*
FRS	Fire Rescue Service
ILI	in-line inspection
IMP	Integrity Management Program
km	kilometres
kNm	kilonewton-metres
m	metres
m^2	square metres
m^3	cubic metres
mm	millimetres
mm/s	millimetres per second
MFL	magnetic flux leakage
NEB	National Energy Board
OPR	*Onshore Pipeline Regulations*
PLM	Pipeline Maintenance
PPE	personal protective equipment
RCMP	Royal Canadian Mounted Police
ROW	right-of-way
SCADA	Supervisory Control and Data Acquisition
Terasen	Terasen Pipelines (Trans Mountain) Inc.
TSB	Transportation Safety Board of Canada
UT	ultrasonic
$\mu\varepsilon$	micro-strains