Incident Investigation Report – 2018-001
April 27, 2018

Butane Leak

Irving Oil Terminals and Pipelines G. P.
59 Pipeway, Saint John, NB
January 8, 2018
1. Incident Summary

On January 8, 2018 at approximately 10:35am during a routine patrol on the 59 Pipeway, owned by Irving Oil Terminals and Pipelines G.P. (Irving Oil), a 3rd party inspector hired by Irving Oil discovered a leak on the NPS\(^1\) 4 liquid butane pipeline near Bayside Drive in the City of Saint John (figure 1). The leak was verified and 911 was dialed at 10:48. The Energy and Utilities Board (Board) was notified at 11:05. The Saint John Fire Department (SJFD) arrived on site at 11:10 and Bayside Drive was closed to traffic at that time. A precautionary voluntary evacuation was conducted by the SJFD initially for a 120 m radius. Three teams of three persons with representation from SJFD, Saint John Water Dept., and Irving Oil conducted hourly gas monitoring at 27 sites. The evacuation area was subsequently increased to include approximately 4 residential blocks (50 homes). The Hampton Inn and a Red Cross reception area were set up in support of the 84 residents who were evacuated.

At 11:50 a vent connection was established to the existing refinery flare system and venting of the pipeline began. At 13:00 a plan was developed to purge the pipeline from the East Saint John (ESJ) location with nitrogen. Irving Oil procured the necessary nitrogen and equipment from third party suppliers in Halifax and Moncton. The nitrogen and equipment arrived on site and the purge began at 14:50 on Jan 9, 2018. On January 11, while purging of the pipeline continued, the Lower Explosive Limit (LEL) levels in the area of the leak dropped to a level which allowed safe access to the site and the installation of a clamp which sealed the leak at 22:30. The purging was completed and the pipeline was isolated with the installation of blinds at both the ESJ and refinery ends at 15:00 on January 13. Also on January 13, all evacuees were allowed back home and the Saint John Emergency Measures Organization deactivated by 22:00.

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\(^1\) Nominal Pipe Size is a standard pipe size designation based on inches.
2. **Scope of Investigation**

The scope of a pipeline incident investigation is provided by section 50(2) of the Pipeline Act, 2005 (Act) which states;

> The Board may inquire into any accident involving a pipeline and may, at the conclusion of the inquiry, make

(a) findings about the cause of the accident or factors contributing to it,

(b) recommendations for preventing future similar accidents, or

(c) any decision or order that the Board can make.
3. **Site Examination**

Once the LEL levels at the area of the leak dropped to a safe level on January 11, Board inspectors performed a site examination. The following observations were made:

Nitrogen that was earlier introduced into the pipeline was escaping through a small opening at the bottom of the butane pipeline directly adjacent to a 2”x2” piece of angle iron that was welded directly on the bottom of the pipe. The opposite end of the angle iron was pointed downwards. The pipe in the area of the break was touching or partially submerged in a pool of water approximately 6” deep and the surrounding area was covered in ice and snow (figure 2). The pool of water did not appear to have any hydrocarbons present nor were any strong odours detected.

Due to the close proximity of the water it was difficult to examine the area of the break so more sandbags were placed to control the intrusion of water and pumps were brought into remove the water around the break. Once the water was removed it could be seen that the other end of the angle iron was partially embedded in ice and was not perpendicular to the surface of the pipeline (figure 3).
4. **59 Pipeway**

The 59 pipeway runs from the refinery to the ESJ terminal, is approximately 1800 m long and consists of 10 aboveground pipelines ranging from NPS 4 to 30 carrying liquid hydrocarbons (gasoline, diesel, jet fuel, butane, hot oil, bunker C, and crude) and one NPS 30 pipeline carrying ballast (water). The pipe supports consist of concrete piers and steel frames on concrete foundations. The pipelines are used for batch loading and unloading of product and are idle between these times.

The NPS 4 butane pipeline was built in 1959 and was constructed in accordance with the Standard ANSI/ASME B31 - 1955 - Pressure Piping and was fabricated from butt welded NPS 4 schedule 40 A53 grade B pipe. In 1974, additional lines were installed in the pipeway. Also during this time, new concrete supports were installed on the NPS 4 butane pipeline from Little River to Bayside Drive.

The line was modified in 1988 when the underground section of pipeline running under Bayside Drive was abandoned. The line was rerouted above ground over the railway into the ESJ terminal where it was reconnected to the existing above ground section of piping. The new sections were constructed from NPS 4 schedule 40 A53 grade A pipe.

5. **Examination of Failed Component**

An analysis of the failed pipeline section was carried out by the New Brunswick Research and Productivity Council (RPC) in Fredericton, NB and the report was filed with the Board on March 28, 2018 (attached as Appendix A). The analysis concluded that the break was the result of a “ductile shear fracture from an overload situation in service” and that “there is no evidence of another cracking mechanism that pre-existed before the ductile fracture.” Further the report states “The entire ductile fracture likely occurred in a short time frame and could have occurred from a single load excursion on the pipe.” The report also concluded;
• The chemical analysis, microstructure and hardness readings of the failed pipeline are consistent with the chemical composition requirements and material properties of A53 pipe.

• The metallographic examination reveals no major material flaws in the failed pipeline that would indicate that the A53 steel is defective.

• The failure is considered to be solely related to service conditions at the time of the incident.

6. **Analysis**

No material deficiencies or operating issues were found as contributing to the failure of the pipeline. The analysis of the incident will focus on the pipe failure, leak detection and on incident response.

a) Incident

The leak occurred when butane was released from the NPS 4 butane pipeline through a small opening on a welded connection of a 2”x2” piece of angle iron used as a support on a pipeline and commonly referred to as a “pipe shoe” (figure 4). Pipe shoes are used as part of the support system on above ground pipelines and are designed to allow for pipe movement due to thermal expansion. An inspection of the pipeline showed that this was the only support of this particular design that was present on the pipeline or on other pipelines in 59 Pipeway. The design of this support provided a low bearing area on the pipe. The combination of insufficient drainage in the area of the leak and the length of the support perpendicular to the
pipeline allowed for water to accumulate and freeze around the support which created a constraint on the pipeline. The extreme ambient temperature changes and low temperatures that occurred during the few days leading up to the break and the constraint of this support created sufficient force due to thermal expansion to break the weld from the pipe and create the opening. The findings from the RPC analysis of the failed pipe section support this conclusion.

The design of the remaining pipe shoes used by the operator is typical of what is used in the industry today.

Figure 4

b) Discovery and Response

The leak was discovered during a routine patrol at approximately 10:35 on January 8, 2018 by a 3rd party inspector hired by Irving Oil. After discovery the liquid butane
continued to escape from the break for approximately 13 hours. Maximum daily ambient temperatures increased daily from 1°C on January 8 to 15°C on January 13. Butane’s boiling point is approximately -1°C so it is likely that most of the spilled liquid product vapourized during this time, however it is expected that remediation and monitoring will continue as a precaution until the ground thaws to ensure the area remains safe.

The time between the discovery of the leak and when a plan was in place to introduce nitrogen into the pipeline to control the flow of butane was approximately 2.5 hours and approximately another 26 hours before the necessary nitrogen and equipment arrived on site and was operating.

After approximately 55 hours the gas levels at the area of the leak dropped to a level which allowed personnel into the area to cut off the 2”x2” support and install a clamp to seal the break in the pipeline.

7. Findings

a) Pipeline Failure

The design of the support combined with inadequate drainage and the extreme weather period is found to be contributory to the failure of the pipeline.

b) Leak Detection

The leak detection system for the 59 Pipeway is comprised of a series of pipeline patrols and by periodic material balance measurements. The use of patrols and periodic material balance measurements are acceptable methods for leak detection.
on pipelines in accordance with the Pipeline Regulation (Regulation) 2006-2 under the Act and the governing standard, CSA Z662 Oil and Gas Pipeline Systems (Z662).

Pipeline surveillance in the form of pipeline patrols is a highly effective means of non-continuous leak detection especially when pipelines are short, above grade and in full view such as in the 59 Pipeway. Also pipeline patrols are equally effective regardless of the size of a leak and whether the pipeline is in a flow or non-flow condition.

The frequency requirement of patrols is not stipulated in the Z662; only that the frequency shall be determined by considering such factors as:

- operating pressure;
- pipeline size;
- population density;
- service fluid;
- terrain;
- weather; and
- agricultural and other land use.

Since the incident the pipeline patrols have been increased from twice daily to 3 times daily and four additional patrol checkpoint locations were added throughout the 59 Pipeway.

Material balance measurements are primarily used for leak detection of continuous flowing buried transmission pipeline systems where daily patrols or other forms of external leak detection are not practical due to the length of the pipeline. While the use of material balance measurements is effective during flow conditions for detecting large leaks, such as complete severance of a pipeline, the measurement
accuracy is low and therefore limited in detecting small leaks such as the one that occurred on the butane pipeline. The area of the break in the pipe was approximately 0.20 in² or about 1.60% of the area had a complete severance of the pipeline occurred.

While Annex E of the Z662 provides guidelines for material balance calculation intervals this is a non-mandatory annex and the only requirement is that periodic material balance calculations are completed. While periodic material balance measurements are completed this system appears to be used more for the refinery process than for leak detection and no calculations were completed for the last butane unloading operation. Material balance calculations are however completed for each ship loading operation for both custody transfer and leak detection.

Periodic material balance measurements on the NPS 4 butane pipeline for railcar unloading operations are calculated via a series of meters on multiple pipelines that measure flow to and from the refinery butane sphere and a radar and differential pressure gauge to determine product level in the sphere.

The Z662 commentary states that it is impractical to perform material balance calculations on multiple metered branches because of the difficulty of identifying the source of shortage — be it a leak, measurement device failure or false reading. Further the Z662 states that material balance calculations are not intended to exclude other, equally-effective leak detection methods.

Section 36 of the Regulation requires that a leak detection system “be adequate to and reflect the level of complexity of the pipeline”, and shall “be adequate to the pipeline location and to the products transported”. Section 4.20 of the Z662 requires that liquid hydrocarbon pipeline systems “be designed to provide appropriate leak detection capability”.

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The pipeline patrol frequency as part of the leak detection system in place at the time leading up to the discovery of the leak was effective, however because it is a non-continuous method it does not provide for the earliest detection. Early detection of a leak is paramount in reducing the risk to the safety of the public and company employees, as well as the protection of property and the environment.

The use of material balance measurements has limited accuracy for detecting small leaks, especially for use on a multiple metered system, and is also a non-continuous method.

Since the pipelines are used for batch loading and unloading of product and are idle between these times and the present methods used for leak detection are both non-continuous it was determined that leak detection should be enhanced to:

i. provide for continuous (24/7) leak detection
ii. be capable of detecting a broader size range of leaks
iii. be capable of detecting leaks during both flow and non-flow conditions
iv. be capable of detecting leaks on all the pipelines in 59 Pipeway.

c) Time of Incident and Release Volume

The exact time of the leak occurrence and the amount of product spilled was not known at the time of discovery and can only be estimated at this time.

The last butane unloading operation was completed at approximately 16:30 on January 7 therefore the butane pipeline was idle (non-flowing) at the time of discovery. At 01:00 on January 8, 2018 an operator was conducting an inspection as part of the start-up procedures for another pipeline and was in the immediate area where the leak occurred. Due to the close proximity of this operator to where the
break occurred it is likely that if the pipeline was leaking it would have been discovered at that time. The last pipeline patrol was conducted at 03:42; approximately 6 hours prior to the discovery of the leak. Based on these times it is likely the earliest the leak started was between 01:00 and 10:35 on January 8.

A graphical review of the error curve calculated from meter readings shows an anomaly at approximately 06:30 or approximately 4 hours before the leak was discovered. This disruption or anomaly in the curve indicates that it is probable that the leak occurred at this time.

Regardless of the time the leak occurred, the minimum amount of product lost was calculated using a volume survey based on the observed height of pooled butane in relation to the pipe at the time of discovery. This volume was calculated to be approximately 106 bbl\(^2\).

The maximum amount of product lost was determined by calculating the rate of flow based on the pipeline pressure and the size of the break in the pipe multiplied by the time between 01:00 and 10:35. To this amount must be added the contents between the highest elevation of the pipeline and the location of the leak. This amount is calculated to be approximately 465 bbl. If the leak did occur at 06:30 then this maximum amount is approximately 216 bbl.

If the pipeline had been isolated from the sphere after the last unloading operation the amount spilled would have further been reduced to approximately 38 bbl which is the contents between the highest elevation of the pipeline and the location of the leak. It is not however, a requirement under the Z662 to isolate a pipeline during non-flow conditions.

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\(^2\) 1 bbl (barrel) = 159.0 litres
d) Emergency Response

The lack of an early response plan that included the necessary equipment to control and stop the flow of butane contributed to the extended length of time required for gas levels to dissipate to a level where remediation of the pipeline break could be carried out safely. If the response plan to use nitrogen to purge the pipeline and the necessary nitrogen and equipment had been readily available the leak would have been controlled and sealed earlier. Further if the leak had been controlled and sealed earlier then the time for site remediation of the released product would also have been shorter which would have allowed the evacuation order to be lifted earlier.

8. Safety Actions

As a result of the preliminary investigation the Board directed Irving Oil to demonstrate that the pipeline can be operated safely before permission would be granted to resume operation. This was to include the installation of an enhanced leak detection and monitoring system. Irving Oil completed this work to the Board’s satisfaction and the pipeline was placed back into service on January 19, 2018. This work included;

a) Repairs to the pipeline which included raising a section of the pipeline so it was not susceptible to constraints due to icy conditions.

b) The necessary nitrogen and equipment needed for purging operations in the event of a leak is now located adjacent to the pipeline and is readily available.
c) Four additional patrol checkpoint locations were added throughout the 59 Pipeway and the patrol intervals have been increased from twice daily to 3 times daily.

d) The pipeline was thoroughly inspected to identify any deficiencies. This included;

   i. 554 circumferential UT thickness scans. All readings were found to exceed minimum code requirements.
   ii. Radiographs were completed at all low point areas to determine if any internal corrosion was present. All readings were found to exceed minimum code requirements.
   iii. A review of the pipeline supports was completed to identify any issues dealing with movement of the pipeline due to ambient temperatures

e) Irving Oil implemented and tested a new leak detection system capable of detecting butane and other hydrocarbons present along the 59 Pipeway.

The Board inspection of the leak detection system concluded that the system is a continuous (24/7) external leak detection and monitoring system. A demonstration of the system at the time of the inspection showed that the detection of hydrocarbons will trigger the system and cause an alarm (visual and auditory) at the refinery Control Panel.

The investigation findings of this report require the completion of further corrective actions as follows (note: A number of these further corrective actions have already been initiated by Irving Oil);
f) In addition to the newly installed leak detection described above, install and implement a leak detection system to continually monitor internal pressure of the pipelines in the 59 Pipeway. Upon the detection of a loss in pressure in one of the pipelines, the systems shall be capable to trigger an alarm (visual and auditory) at the refinery control panel.

g) Review the emergency response plan including the availability of any necessary equipment for controlling and stopping the flow of a leak, including purging operations, for the pipelines in 59 Pipeway. The procedures shall include the control and containment of lost product.

h) Liaise with emergency response agencies that responded to the January 8, 2018 incident and complete a debriefing exercise as outlined in CSA Standard Z731-03 Emergency Preparedness and Response.

i) Hazard identification, risk analysis and risk evaluation shall be conducted for the 59 Pipeway and include the review of methods and procedures to reduce the consequences associated with failure or damage incidents. This risk assessment shall be carried out as per the requirements and guidelines of the Z662. The following shall be considered in the assessment;
   i. Methods for early leak detection,
   ii. Methods to control and shutdown supply sources,
   iii. Methods to limit the amount of product released,
   iv. Methods of recovery and clean-up of product released,
   v. Improved emergency response procedures, and
   vi. Improved public awareness and education programs.

j) Consult with appropriate emergency response agencies when updating the emergency procedures manual.
k) All pipelines shall be isolated from supply sources during non-flow conditions, i.e. in-between shipments.

l) Ensure that adequate drainage is provided to protect the aboveground pipelines from ice and snow buildup.

m) All patrol personnel shall use the punch recording system as presently used by security and records are to be retained for a minimum of five years.

n) Review the leak detection systems and emergency response procedures to confirm their adequacy and effectiveness at least annually.

A corrective action plan (CAP) is required to be filed with the Board for review by July 1, 2018. The CAP is to include how the corrective actions are to be addressed and include any changes required to programs, processes and procedures to satisfy the actions items. The CAP must also include a schedule of implementation and completion for each item.

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FAILURE ANALYSIS OF BUTANE PIPELINE
8TH JANUARY 2018 INCIDENT

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RPC Report No.: MSD/18/J9581R1
Job No.: MSD-J9581
Date: 26 March 2018
1.0 INTRODUCTION

RPC was requested to perform a failure analysis on a section of 4 in. nominal diameter pipe that was removed from a liquid butane pipeline owned by Irving Oil Terminals & Pipelines, G.P. This pipeline section reportedly failed on or about the 8th of January 2018, resulting in the loss of liquid butane. At the time of the incident, the failed pipeline was noted to have fractured at the location of a welded-on 2 x 2 angle attachment, which was constrained in ice. As well, the city region was experiencing cold weather and significant temperature changes.

The actual age of the failed portion of the butane pipeline is not known at this time. The liquid butane pipeline was initially built in 1959 and reportedly fabricated from butt-welded 4 in. schedule 40 A53 Grade B pipe. Modifications to the pipeline were made in 1974 and again in 1988 when the pipeline was rerouted above ground. The new piping was reportedly fabricated from similar 4 in. schedule 40 A53 Grade A pipe. It is not known whether the failed section is part of the former pipeline or part of the modifications. The following report details our investigation.

2.0 METHOD

The present investigation included:

- Visual examination of the failed pipeline section and of the mating fracture faces to identify fractographic features that may establish fracture origin area(s), fracture propagation direction and fracture mode.
- Further detailed examination of the fracture faces using a scanning electron microscope (SEM) to identify microscopic features to verify fracture mode and identify any defects at origin area(s).
- Metallographic examination of a macro-section through the fracture to assess the condition of the pipe material and any possible material flaws.
- Chemical analysis and hardness testing of the pipe material to verify with ASTM A53 requirements
3.0 VISUAL INSPECTION

The failed pipeline section, approximately 4 feet (1.2 m) long, is shown in Figures 1 through 4. The pipe section measures 4.0 in. (102 mm) ID with a 0.237" (6 mm) wall thickness, which is consistent with 4 in. nominal pipe size (NPS) schedule 40 steel pipe. The pipeline section reveals a through-wall fracture that traveled closely along the toes (edges) of a fillet weld for attaching a 2 x 2 in. steel angle to the OD surface of the pipe. The fracture is roughly horseshoe-shaped about the contour of the fillet weld, measuring approximately 1½" (38 mm) long with approximately a ¼" (6 mm) wide gap.

A small amount of plastic deformation could be seen in the pipe at the fracture location. At the fracture, the attachment fillet weld and welded-on 2 x 2 angle remain relatively straight, while the pipe wall appears peeled outward. This outward peel is accompanied with a slight inward dent on the side of the attachment fillet weld opposite the fracture, leaving a shallow indent in the pipe wall. The plastic deformation can be seen in Figure 3.

The visible parts of the fracture faces were covered with rusty deposits likely from exposure to the weather after the incident. To further expose the mating fracture faces, the whole fillet weld was cut out and the remaining un-cracked portion of the pipeline was fractured in dry ice. The exposed fracture faces were cleaned initially by mild detergent followed later by 50% inhibited hydrochloric acid solution to remove the rusty deposits. After cleaning, the fracture faces were examined using a stereomicroscope at magnifications up to 40X. To aid in the following discussion, photographs of the fracture face are given in Figures 5, 6 and 7.

The fracture appears to start at the fillet weld, proceeding along or under the fillet weld toe and then travelling primarily through the pipe wall with the fracture plane approximately perpendicular to the OD. The fracture at the fillet weld has a silky appearance but is uneven. Most of the fracture is through the pipe wall and this portion
of the fracture face has a flat even profile and shows a smooth silky appearance with no
demarcation. The silky appearance is usually associated with ductile type fracture. No
distinctive propagation marks could be seen on the fracture face that are usually
associated with progressive crack growth and fatigue cracking.

The whole fracture face was prepared for detailed examination under a scanning
electron microscope (SEM), at magnification up to 3000X. In preparation, the above
cut-out section was slightly trimmed in order to make the piece fit within the SEM
chamber and cleaned in an ultrasonic bath using acetone. To aid in the following
discussion, electron photomicrographs from the SEM are given in Figures 8 through 11.

From the SEM examination, the fracture face shows distinct fractographic
features associated with ductile fracture. The fracture face at the toe of the fillet weld
reveals equiaxial dimples of different sizes. An example of the equiaxial dimples can be
seen in Figure 9. The dimpled appearance is from the coalescence of numerous micro-
voids. The micro-voids are created by the de-adhesion of the material under tension
and is highly characteristic of transgranular ductile fracture.

The fracture through the pipe wall reveals similar fractographic features
consisting mostly of elongated dimples of different sizes that are stretched
approximately flat. Examples of the elongated dimples can be seen in Figures 10 and
11. Like above, the dimpled appearance is from the coalescence of numerous
microvoids; however, under the action of a shear load, the dimples are typically
distorted to one side, elongated and crushed in the direction of shear. This is highly
characteristic of transgranular ductile fracture by shearing action. The elongated
dimples indicate that the ductile fracture propagated primarily from OD to ID.

Non-metallic inclusions (or precipitates) from the steel-making process are
frequently noted at the root of the dimples. This is common in ductile fracture, where
the inclusions act as initiation sites for the de-adhesion process. A number of shallow
smooth grooves are randomly scattered across the ductile fracture face. These grooves are believed to be created by the fracture intersecting longitudinal non-metallic inclusions or stringers in the steel and pulling the inclusions out.

4.0 CHEMICAL ANALYSIS

A small sample of the pipe material was submitted for ICP chemical analysis in accordance with ASTM D1976-12mod and ASTM E1019-11. The chemical analysis results given in Table 1 indicate that the pipe is made of plain low carbon steel with no significant amounts of the alloying elements chromium, nickel and molybdenum. Acceptable levels of phosphorus and sulfur impurities are present in the pipe material. The chemical composition is consistent with A53 Grade A and B steels, which are included in Table 1 for information purposes.

5.0 METALLOGRAPHIC EXAMINATION

A macro-section was prepared from the failed pipeline for metallographic examination under an optical microscope. The macro-section was taken through the fillet weld, intersecting the principal fracture at two locations. In preparation the macro-section was polished down to a 1-micron finish and etched using a 5% nital solution to reveal the microstructure of the weld, 2 x 2 angle and pipe material.

On the macro-section, the fillet weld is free of any cracks, free of any lack of fusion flaws between weld and pipe, and shows complete fusion to the weld root. The fracture initiated at or close to the weld toe. Shallow corrosion pitting and corrosion deposits could be seen at the weld toe. A photomacrograph of the macro-section is given in Figure 12.

The microstructure of the pipe material consists essentially of ferrite grains with a small amount of pearlite grains, which are in a somewhat banded formation. A small
The amount of non-metallic inclusions is present in the pipe material from the steel-making process; although not an excessive amount. This microstructure is consistent with low carbon steels in the hot-rolled (or hot-worked) condition. A photomicrograph showing the typical microstructure is given in Figure 13. No material or microstructural flaws are noted along the profile of the fracture. In essence, the metallographic examination reveals no major material flaws that would indicate that the A53 steel is defective.

The heat-affected zone (HAZ) adjacent to the weld consisted of two regions: (1) a coarse grain HAZ with a martensitic type microstructure and (2) a refined fine grain HAZ of ferrite and dissociated pearlite. The heat-affected zone can be seen in Figure 14. The coarse grain martensitic region near the fusion line is the result of rapid cooling during the welding process and would represent a hardened portion of the pipe material.

From the metallographic examination, the fracture propagates through the pipe wall in a jagged transgranular manner with very little branching. This is consistent with ductile-type cracking and a photomicrograph showing the typical fracture profile is given in Figure 15. Near where the fracture intersects the ID, the microstructure of the pipe material is deformed and elongated, as shown in Figure 16. This also indicates that the fracture propagated from OD to ID.

6.0 HARDNESS TESTING

Vickers’ hardness testing was carried out using a 10-kg load on the prepared metallographic sample. A total of twenty hardness readings were taken in the weld, heat-affected zone (HAZ) and pipe material. The location of the hardness indentations are shown in the Figure above Table 2 and the hardness readings are listed in Table 2. The pipe material has an average hardness of approximately 165 HV$_{10}$, which converts to approximately 165 HB on the Brinell hardness scale, following the Hardness Conversion Tables in ASTM Standard E140. There is a good correlation between hardness and tensile strength for plain low / medium carbon steels and low-alloy steels.
Based on a hardness of 165 HV, the pipe material is estimated to have a tensile strength of approximately 77,000 psi (531 MPa). The A53 pipe seems to have an acceptable tensile strength, which is greater than the minimum of 60,000 psi (414 MPa) for A53 Grade B steel and likewise, 48,000 psi (331 MPa) for A53 Grade A steel.

The fillet weld material has an average hardness of approximately 216 HV. Although the welding specifications, if any, are not known, this hardness value for the weld metal seems reasonable. The coarse grain martensitic region of the HAZ recorded the highest individual hardness reading of 290 HV.
7.0 DISCUSSION

Based on our examination, the failure of the liquid butane pipeline is considered to be the result of ductile shear fracture from an overload situation in service. Several indicators of ductile fracture are evident including the smooth silky appearance of the fracture face, plastic deformation of the pipe material associated with the fracture, the jagged fracture profile, and the presence of a dimpled fracture face from the coalescence of micro-voids. As mentioned earlier the micro-voids are created by the de-adhesion of the material under stress. There is no evidence of another cracking mechanism that pre-existed before the ductile fracture. As well, there is no evidence of any brittle type fracture in the pipeline from the cold weather.

It is believed that the ductile fracture initiated on the pipe OD at or close to the toe of the attachment fillet weld. No welding flaws were seen that might have been associated with fracture initiation. The toes of the fillet weld could be considered to represent the transfer point between the thicker cross-section of the attachment fillet weld and the thinner pipe wall and hence, act as an inherent stress raiser. No progressive propagation markings from gradual crack growth are present on the fracture face. The entire ductile fracture likely occurred in a short time frame and could have occurred from a single load excursion on the pipe.

Ductile fracture is caused by stresses in service, which are greater than the ultimate tensile strength of the material, resulting in plastic deformation and the tearing apart of the material. A53 pipe material is a ductile low-to-moderate strength plain carbon steel. Based on hardness test results, it appears that the pipe material has sufficient tensile strength to meet A53 tensile requirements. The pipeline failure is considered to be the result of an overload on the pipe where the service stresses exceed the tensile strength of the pipe material. The ductile fracture initiated by ductile tearing on the OD at or close to the fillet weld, creating more equiaxial dimples on the fracture face. Later, the fracture continued in a rapid manner through the rest of the pipe.
pipe wall by ductile shear, creating elongated and crushed dimples on the fracture face. The result is similar as a perpendicular cutting action through the pipe wall.

One would not expect significant service loads on the 2 x 2 angle attachment welded to the pipeline. One explanation for the overload is the constrained of this attachment in ice, which generated high local loads at the fillet weld from movement or thermal expansion of the pipe.

The chemical analysis, microstructure and hardness readings of the failed pipeline are consistent with the chemical composition requirements and material properties of A53 pipe. No distinguish is made between A53 Grade A and Grade B pipe. The metallographic examination reveals no major material flaws in the failed pipeline that would indicate that the A53 steel is defective. The failure is considered to be solely related to service conditions at the time of the incident.
8.0 CONCLUSIONS

- Based on our examination, the failure of the liquid butane pipeline is considered to be the result of ductile shear fracture from an overload situation in service.

- The ductile fracture initiated on the OD of the pipe at or close to the toes of the attachment fillet weld.

- The chemical analysis, microstructure and hardness readings of the failed pipeline are consistent with the chemical composition requirements and material properties of A53 pipe.

- The metallographic examination reveals no major material flaws in the failed pipeline that would indicate that the A53 steel is defective. The failure is considered to be solely related to service conditions at the time of the incident.
Table 1: Chemical Analysis - Pipe

<table>
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<th>Composition, wt%</th>
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</tbody>
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Notes: (a) The combination of copper, nickel, chromium, molybdenum and vanadium should not exceed 1.00 wt%
Table 2 - Vickers’ Hardness (HV$_{10}$) at Fracture Location

<table>
<thead>
<tr>
<th>ID</th>
<th>Location</th>
<th>Vickers’ Hardness, HV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fillet weld</td>
<td>215</td>
</tr>
<tr>
<td>2</td>
<td>Fillet weld</td>
<td>218</td>
</tr>
<tr>
<td>3</td>
<td>Fillet weld</td>
<td>216</td>
</tr>
<tr>
<td>4</td>
<td>Coarse-grain HAZ, near fusion line</td>
<td>259</td>
</tr>
<tr>
<td>5</td>
<td>Coarse-grain HAZ, near fusion line</td>
<td>256</td>
</tr>
<tr>
<td>6</td>
<td>Coarse-grain HAZ, near fusion line</td>
<td>264</td>
</tr>
<tr>
<td>7</td>
<td>Fine-grain HAZ</td>
<td>212</td>
</tr>
<tr>
<td>8</td>
<td>Fine-grain HAZ</td>
<td>217</td>
</tr>
<tr>
<td>9</td>
<td>HAZ</td>
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<td>Pipe material</td>
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</tr>
<tr>
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<td>Pipe material</td>
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<tr>
<td>14</td>
<td>Coarse-grain HAZ</td>
<td>258</td>
</tr>
<tr>
<td>15</td>
<td>Pipe material, away from weld</td>
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<tr>
<td>16</td>
<td>Pipe material, away from weld</td>
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<td>Pipe material, away from weld</td>
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<td>18</td>
<td>Coarse-grain HAZ, near fusion line</td>
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<td>Coarse-grain HAZ, near fusion line</td>
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<tr>
<td>20</td>
<td>Coarse-grain HAZ, near fusion line</td>
<td>265</td>
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Figure 1: Photographs of the failed pipeline section, as received. The fracture is located at the toes (edges) of a fillet weld attaching a 2 x 2 steel angle to the OD of the pipe. The fracture is roughly horseshoe-shaped about the contour of the fillet weld, measuring approximately 1½” (38 mm) long with approximately a ¼” (6 mm) wide gap. Ruler is graduated in millimeters.

Photos: J9581 pipe (2) copy.jpg and J9581 pipe (3) copy.jpg
Figure 2: Photographs of the failed pipeline section, as received. The fracture is located at the toe (edges) of a fillet weld attaching a 2 x 2 angle to the OD of the pipe. Ruler is graduated in millimeters.

Photos: J9581 pipe (8) copy.jpg and J9581 pipe (11) copy.jpg
Figure 3: Photographs of the failed pipeline section, as received (top) and cut-out of fracture (bottom). At the fracture location, the attachment fillet weld and welded-on 2 x 2 angle remain relatively straight, while the pipe wall appears peeled outward. This outward peel is accompanied with a slight inward dent on the side of the attachment fillet weld opposite the fracture, leaving a shallow indent in the pipe wall. Ruler is graduated in millimeters.

Photos: J9581 pipe (4) copy.jpg and J9581 pipe (15) copy.jpg
Figure 4: Photographs of the cut-out section from the failed pipeline section. The fracture is roughly horseshoe-shaped about the contour of the fillet weld, measuring approximately 1½” (38 mm) long, as can be seen on ID of pipe (top photo). To further expose the mating fracture faces, the whole fillet weld was cut out and the remaining un-cracked portion of the pipeline was fractured in dry ice (bottom photo). Ruler is graduated in millimeters.

Photos: J9581 pipe (20) copy.jpg and J9581 pipe (25) copy.jpg
Figure 5: Photograph of the cut-out section from the failed pipeline section, after cleaning the fracture faces. The fracture propagated approximately perpendicular to the pipe OD surface. Most of the fracture face has a flat even profile and shows a smooth silky appearance with no demarcation. No distinctive crack propagation marks could be seen on the fracture face. Ruler is graduated in millimeters.

Photos: J9581 pipe (42) copy.jpg
Figure 6: Photograph of the cut-out section from the failed pipeline section, after cleaning, showing a close-up view of the fracture face. Most of the fracture face has a flat even profile and shows a smooth silky appearance with no demarcation and no distinctive crack propagation markings from slow progressive crack growth. Ruler is graduated in millimeters.

Photos: J9581 fracture face (1) copy.jpg
Figure 7: Photograph of the cut-out section from the failed pipeline section, after cleaning, showing a close-up view of the fracture face. The fracture at the fillet weld has a silky appearance but is uneven. Most of the fracture is through the pipe wall and this portion of the fracture face has a flat even profile and shows a smooth silky appearance with no demarcation. Ruler is graduated in millimeters.

Photos: J9581 fracture face (4) copy.jpg
Figure 8: Electron photomicrograph from the scanning electron microscope (SEM) taken at the toe of the fillet weld. The fracture face shows distinct fractographic features that are associated with ductile fracture and closer views are given in Figures 9, 10 and 11.

Magnification of original image: 110X

Photo: J9581 b01 copy.jpg
Figure 9: Electron photomicrograph from the scanning electron microscope (SEM) of the fracture face close to the pipe OD and fillet weld. The fracture face at the toe of the fillet weld reveals equiaxial dimples of different sizes. The dimpled appearance is from the coalescence of numerous micro-voids, which are created by the de-adhesion of the material under tension. This is highly characteristic of transgranular ductile fracture.

Photo: J9581 b03 copy.jpg
Figure 10: Electron photomicrograph from the scanning electron microscope (SEM) of the fracture face, approximately mid-wall. The fracture through the pipe wall shows mostly elongated dimples of different sizes that are stretched approximately flat. The dimpled appearance is from the coalescence of numerous microvoids; however, under the action of a shear load, the dimples are distorted to one side, elongated and crushed in the direction of shear. This is highly characteristic of transgranular ductile fracture by shearing action. A number of shallow smooth groves are randomly scattered across the ductile fracture face believed to be created by the pull-out of inclusions in the steel.

Photo: J9581 a01 copy.jpg
Figure 11: Electron photomicrograph from the scanning electron microscope (SEM) of the fracture face, approximately mid-wall. This is from a different location than shown in Figures 8 through 10. The fracture through the pipe wall shows mostly elongated dimples of different sizes that are stretched approximately flat. This is highly characteristic of transgranular ductile fracture by shearing action.

Photo: J9581 d03 copy.jpg
Figure 12: Photomacrograph of the prepared metallographic sample showing the profile of the fillet weld and cross-section of the pipe wall. The macro-section intersects both sides of the horseshoe shaped fracture. The fillet weld is free of any cracks, free of any lack of fusion flaws between weld and pipe, and shows complete fusion to the weld root. The fracture initiated at or close to the weld toe.

Photo: J9581 macro (3) copy.jpg
Magnification of original image: 250X

**Figure 13:** Photomicrograph from the metallographic sample showing the typical microstructure of the failed pipe. The microstructure consists essentially of ferrite grains (F) with a small amount of pearlite (P) grains in a somewhat banded formation. This microstructure is consistent with low carbon steels in the hot-rolled (or hot-worked) condition.

Photo: J9581 micro (1) copy.jpg
Figure 14: Photomicrograph from the metallographic sample showing the microstructure from weld through the heat-affected zone (HAZ) to base metal (BM). The heat-affected zone (HAZ) adjacent to the weld consists of two regions: (1) a coarse grain HAZ with a martensitic type microstructure and (2) a refined fine grain HAZ of ferrite and dissociated pearlite.

Photo: J9581 micro (5) copy.jpg
Magnification of original image: 50X

**Figure 15:** Photomicrograph from the metallographic sample showing the profile of the fracture. The fracture propagates through the pipe wall in a jagged transgranular manner with very little branching. No material flaws are noted along the profile of the fracture.

Photo: J9581 micro (2) copy.jpg
Figure 16: Photomicrograph from the metallographic sample showing the profile of the fracture near the ID of the pipe. The fracture propagates through the pipe wall in a jagged transgranular manner with very little branching. Near where the fracture intersects the ID, the grains in the microstructure are deformed and elongated. This indicates that the fracture propagated from OD to ID.

Photo: J9581 micro (4) copy.jpg