The CEPA Report on Circumferential Stress Corrosion Cracking

Robert L. Sutherby, M.Sc., P.Eng
NOVA Gas Transmission Ltd.
Calgary, Alberta, Canada

ABSTRACT

According to the NEB Report of the recent inquiry on pipeline stress corrosion cracking (NEB Order No. MH-2-95), six of the Canadian failures to that time had been leaks resulting from circumferentially-oriented cracks. A review has been made of the five CEPA leaks; two leaks from non-CEPA companies; and a case of non-leaking circumferential SCC, also from CEPA. All of the Canadian cases occurred in regions of west and central Alberta.

Circumferential stress corrosion cracking is a rare cause of pipeline leakage. Canadian cases have occurred in very specific conditions that exist in only a small proportion of the regions where pipelines operate. All cases of circumferential SCC, to date, have occurred under either polyethylene tape or a polyethylene backed shrink sleeve. The SCC appears to have been of the neutral-pH form and initiated and grew in response to high axial stresses generated by soil creep and/or localized pipe bending on slopes of 10° or greater. In this sense, circumferential SCC is a manifestation of a geotechnical instability in an area of SCC susceptibility. It would be prudent for operators of susceptible pipelines to consider the potential risks of such failures and to manage those risks accordingly.

Management of circumferential SCC may be largely achieved by effective management of geotechnical concerns on slopes. Geotechnical programs directed toward preventing soil movement or pipe loading could have benefit with respect to preventing circumferential SCC in susceptible areas. Other management approaches, involving in-line inspection tools, may also be found to have benefit.

Given that circumferential SCC (C-SCC) is driven by geotechnical instability, a significant research effort directed specifically toward C-SCC is not considered warranted at this time. Rather, geotechnical research will augment SCC research in progress to provide insight and capabilities to manage the concern.

To assist pipeline operators, CEPA will issue, in 1998, a revision of the SCC Recommended Practices providing guidance to manage this concern.

INTRODUCTION

CEPA recognizes stress corrosion cracking (SCC) as a major challenge facing the pipeline industry. As a consequence, in 1994, CEPA established its SCC Working Group to share SCC experience and create a proactive program to investigate, mitigate and prevent SCC on Canadian pipelines.

When the NEB Inquiry was announced in 1995, CEPA participated by preparing a detailed technical submission, and by participating in the April 1996 proceedings, held in Calgary. CEPA brought to the Inquiry extensive insight on the detection and mitigation of the problem obtained through member company inspection and maintenance activities and by extensive research conducted over many years.

According to information in the Submission and the NEB Report on the Inquiry, SCC has been found in both longitudinal and circumferential orientations. Due to the potential for rupture in the case of longitudinally-oriented SCC, such cracks were the principle focus of the CEPA submission and the Inquiry. Of the leaks that had occurred up to the Inquiry, however, six were reported as resulting from circumferentially-oriented SCC, an example of which is shown in Figure 1.
Figure 1: Circumferentially-Oriented Stress Corrosion Cracking

Failure by circumferential SCC has been a rare event. In Canada only six leaks, by this cause, have been recorded in the twenty years since 1977. Elsewhere, circumferentially-oriented SCC was reported, in 1974, in regard to drip branch connections in the United States and more recently on gas lines in Italy. In all these cases, leaks have occurred without fire or personal injury.

Circumferential SCC is understood to occur by similar mechanisms as longitudinal SCC and, consequently, to require the simultaneous presence of conditions conducive to cracking:
- material susceptible to cracking
- tensile stress
- cracking environment

Whereas in most cases of SCC, cracks initiate and grow along the longitudinal axis of the pipe in response to the operating hoop stress in the pipe, in the case of circumferential SCC, cracks develop in response to maximum stresses aligned parallel to the axis of the pipe.

This report will review the current state of knowledge of circumferentially-oriented SCC on the basis of available information on eight cases: six from within CEPA, five of which have been reported leaks, one leak on the Federated Pipe Lines system, and one from the SNAM pipeline system in Italy. These cases are reviewed and analyzed to determine if a pattern exists, in terms of the conditions associated with the initiation and growth of the SCC, the characteristics of the cracking, and the potential for management approaches.

CIRCUMFERENTIAL SCC EXPERIENCE

Information has been obtained for the circumferential SCC (C-SCC) leaks that have occurred in Canada, on the NOVA Gas Transmission Limited (NGTL), Northwestern Utilities Limited (NUL), and Federated Pipe Lines systems, and from SNAM for such a leak on its system in Italy. In addition to leaks, one case of non-leaking C-SCC has been identified, also in the NGTL system. A brief description of each case follows. A compilation of pertinent conditions associated with each of the eight cases is presented in Table 1.

NOVA Gas Transmission Ltd.

NGTL has experienced two leaks and has located a single sub-critical case of C-SCC. No corrosion was associated with any of these cases. Furthermore, none of the leaks resulted in fire or personal injury.

The first recorded SCC failure in Canada in 1977 involved C-SCC on an NPS 36 x 8.74 mm W.T. Gr. 5LX65 pipeline in a remote, unpopulated area of west-central Alberta, NGTL-1 in Table 1. The pipeline was constructed in 1969 and was coated with polyethylene tape over primer with an outer wrap of unbonded asphalt impregnated fibreglass. The failure occurred on a slope that displayed indications of soil instability and recent movement. While the cause of the movement was not positively identified, the presence of low shear-strength bentonite, groundwater, and a slope of 25° - 30° were considered risk factors for slope movement and geotechnical pipe loading. The failure involved the leakage of sweet natural gas.

Case NGTL-2, in 1990, involved a polyethylene tape-coated NPS 6 x 3.96 mm W.T. Gr. 5LX42 pipeline constructed in 1969 in a remote area of west-central Alberta. Two leaks resulted from through-wall cracks on the bottom of the pipe at sites separated from each other by less than five meters. The cracks followed the edge of the tape helix. The leaks occurred in the vicinity of an overbend at the crest of 10° - 20° slope to a river crossing. Indications of slope instability were noted adjacent to the right-of-way, and within six years the right-of-way slope failed catastrophically. Surficial deposits consisted of clay till and clay deposits of glacial
and glaciolacustrine origin. The toe of the slope was coincident with the edge of the river, on the outside of a meander loop, and displayed minor river bank erosion. The failure involved the leakage of sweet natural gas.

Case NGTL-3 was discovered when a NPS 30 x 12.70 mm W.T. Gr. 5LX52 pipeline was being prepared for a metal loss in-line inspection. Pipe sections containing 10% dents were removed from two sides of a river crossing and sent for SCC inspection. Cracks, C-SCC, were detected from only one of the two slopes: the longer, steeper of the two with a slope of 16°. The dent was located on the bottom of the pipe where the pipe had rested on a large rock. The C-SCC was located on top of the pipe, adjacent to the ERW long-seam weld, 5.5 m upslope of the dent. The polyethylene tape coating displayed extensive circumferential wrinkling, indicative of relative, axial movement between the soil and the pipe. Details of the soil were not reported.

Following the detection of C-SCC in this latter case, an inspection excavation was conducted for C-SCC on a similar slope on the same line; none was detected.

Northwestern Utilities Limited

Three NUL leaks were detected in 1989-90 on a single, polyethylene tape-coated NPS 8 x 3.6 mm W.T. Gr 317 pipeline located in a remote area of west-central Alberta. No corrosion was associated with the crack locations. Furthermore, none of the leaks resulted in fire or personal injury.

NUL-1 was discovered by a hunter and involved three separate leaks within 9 m of one another toward the crest of a long 15° slope. The leak at the highest elevation was located on top of the pipe; the downslope leaks occurred on the bottom. Magnetic particle inspection (MPI) revealed the leaking cracks to be located in colonies of circumferentially-oriented SCC. Some of the cracks were associated with the tape helix. Axial tension on the pipe was evidenced when, upon the cutting the pipe, the cut sides separated by 75 mm. The failure involved the leakage of sweet natural gas.

NUL-2 was detected by a leak patrol and occurred toward the toe of a 20° slope on top of the pipe directly over a large rock which had dented the pipe. The cracking was circumferential and followed the helical edge of the tape. The failure involved the leakage of sweet natural gas; no fire or injuries occurred.

Few details are available concerning NUL-3. The leak occurred on a 20° - 30° slope. The pipe, at the location of the leak was bent and the cracks were located on the tension side of the bend.

Following the three leak incidents a series of ten inspection excavations were conducted on the line for C-SCC. Five 2-5 m excavations were made on slopes of either similar grade or ones that displayed indications of movement. No C-SCC was detected. In 1996, following leak repairs on the same line, further inspections for SCC were conducted; none was detected, and no further C-SCC leaks have occurred to date.

Federated Pipe Lines Ltd

A single leak of NGL was reported in 1993 on the Federated Pipe Lines system in the Judy Creek area of central Alberta. The extruded polyethylene-coated NPS 16 x 6.35 mm W.T. Gr. X52 line was constructed in 1970 and used shrink sleeves at the girth welds. SCC reportedly occurred in association with corrosion under a girth weld shrink sleeve. The leak occurred in high moisture content silt/clay soil near the middle of a 20° slope. Indications of ground movement, localized corrosion, and an improperly applied shrink sleeve were suggested to have contributed to the leak. No fire or personal injury resulted from the leak.

SNAM, Italy

The only documented cases of circumferential SCC outside Canada have occurred in Italy. Such a case was reported for a NPS 16 x 7.92 mm W.T. Gr. 5LX52 pipeline in the SNAM system. During a survey in 1991 a leak was detected near the top of a 10° slope. The location of the leak was a section of pipe that had been field bent with a radius of about 40 times the pipe diameter. Damaged coal tar coating was covered with polyethylene tape after bending. The leaking crack was located at the 9 o'clock position, while colonies of cracks were mainly found on the bottom of the pipe between the 4 - 8 o'clock positions. That a significant tensile load was acting on the pipe became apparent when, during torch cutting, the pipe suddenly broke and the opposing ends displaced by about 16 cm. The torch had cut around 45 cm, and the ductile fracture occurred over 82 cm of circumference.

Over a length of 50 m other colonies of C-SCC were detected, all associated with tape repairs over coal tar at bends, weld joints or at tape repairs to localized coal tar damage.

Soil at the leak contained clay with rock fragments. Strain gauging of the pipe after repair indicated that the pipe was being strained by geotechnical loading at an average strain rate of approximately 10^-11 s^-1.

No corrosion was associated with the failure. No fire or personal injury resulted from the leakage.

Other details are presented in Table 1.

ANALYSIS

To determine if a pattern exists for this problem the eight cases were considered in terms of the broad conditions necessary for the SCC. On the basis of the foregoing, however, a number of very clear similarities exist:

- Susceptible Materials: All eight cases were associated with some form of polyethylene coating; tape or a shrink sleeve; all pipelines were constructed during the period 1965-71;
- Tensile Stress: All eight were located on slopes of 10° or greater; several slopes displayed indications of soil movement and local pipe bending;
• Environment: All seven Canadian cases were located in Alberta in similar conditions of undulating terrain.

Susceptible Materials

Susceptible materials consist of the coatings involved, and the pipe and its constituent components.

The Coating. In seven of the eight cases, polyethylene tape was involved at the cracking site. In the case of the SNAM leak, tape was applied over coal tar that had been damaged during construction.

Two forms of tape disbondment were associated with the C-SCC: the tape helix and wrinkles. The tape helix is essentially an area of tape tenting, as illustrated in Figure 3.

Figure 3: Polyethylene-Tape Helical Tent

As the tape was applied, successive wraps overlapped the previous. As illustrated, a narrow tented area would be created at the edge of the previous wrap under the successive wrap. Normally this gap is dry. However, where damage to the coating occurs, water can gain entry.

Two patterns of tape wrinkles have been observed: longitudinal and circumferential. Longitudinal wrinkles are presumed to be a result of soil settlement in the trench. Relative movement between the pipe and the soil stretches the tape, causing it to "bunch up" or wrinkle toward the bottom of the pipe. Circumferential wrinkles are seen on slopes and likely occur when coating adhesion fails in response to relative axial displacement between the pipe and the soil.

One of the eight leaks involved a shrink sleeve. In 1970, when this line was constructed, shrink sleeves in Canada were of either tube or wrap-around configurations. In each case, the sleeve consisted of an adhesive against the pipe, for example a rubberized asphalt, and a polyethylene backing on the outside. An improperly applied sleeve could result in a channel for water ingress beneath the polyethylene backing, a situation similar to the case of a disbondment beneath polyethylene tape coating.

The Pipe. The pipeline leaks occurred on lines constructed over a narrow range of years and involved pipe manufactured by both ERW and DSAW methods. No pattern was observed in terms of the pipe steel grades involved, 290 to 448 MPa, or in terms of pipe diameters which ranged from 168 - 914 mm (NPS 6 - 36).

Weld Metallurgy. In two cases, C-SCC were located across or in proximity to the long seam SCC weld. In the case of NGTL-3, cracks appear to have initiated both at the edge of the ERW weld and within the heat affected zone. In this case, the heat affected zone was reported to consist of fine, equiaxed bainite. As the cracking occurred in the top quadrant of the pipe in proximity to a rock bearing against the bottom of the pipe, it is not clear whether the HAZ microstructure was particularly susceptible to SCC initiation, as in some cases of longitudinal SCC, or if the HAZ was merely situated at the point of maximum tensile bending stress. In this regard, it is noted in the case of the SNAM leak, that the C-SCC correlated with sites where PE tape had been used to repair damaged coal tar as well as at girth welds and cold field bends. This suggests that welds and cold field bends were not sufficient, of themselves, to result in C-SCC.

Tensile Stress

Stress corrosion cracks develop perpendicular to the axis of the maximum stress. Longitudinal SCC develops in response to hoop stress; circumferential SCC develops in response to axial stress.

Common to all eight of these cases is the development of the C-SCC on a slope of 10° or greater. Axial loading has resulted from tension on the pipe as a result of relative settlement between the soil and the pipe, or by localized bending, eg. over a rock on the slope.

In the case of NUL-1 three leaks occurred near the crest of the slope, on top and bottom of the pipe. Local pipe bending was not apparent. When the pipe was cut for repairs the two sides of the cut separated by 75 mm. These observations indicate that loading on the pipe was pure tension and may have resulted from movement of the soil on the slope. Examination of photographs of the site suggest that the soil was comprised largely of clay. NGTL-2 is similar in that two leaks occurred at the crest, local pipe bending was not apparent, and the slope soils consisted of clay. In this case, there were indications of soil movement in the slope, and a number of years later the slope containing the pipeline failed catastrophically.

The SNAM failure is also similar, in that no local bending stress appears to have been present, and clays were present in the slope. In this case, when the pipe was being torch cut, a remaining ligament fractured and the opposing cut surfaces displaced axially. Based on the size of the fracture ligament and the displacement that occurred an axial stress of in excess of 360 MPa was estimated to have existed during operation of the line. It
is, therefore, apparent that during operation an axial stress in excess of 100% SMYS was being applied by soil movement.

In each of these cases, axial loading on the pipe resulted from continuous, slow movement of the slope soils, as opposed to catastrophic land slides. In the case of the SNAM leak, strain gages were applied to the pipe after repair. Over the following three year period the axial strain on the pipe was monitored. During this period the maximum strain increased by up to 600 microstrain and an average strain rate of $7 \times 10^{-12} \text{ s}^{-1}$ was recorded. Periodic, rapid increases in strain during winter months were hypothesized to be due to winter rains causing increases in the soil movement rate. Soil moisture and pore pressures are factors of known significance in terms of soil movement on slopes.

In four of the eight cases, a local tensile stress also resulted from a geometry change and/or bending of the pipe. NGTL-1 occurred on top of the pipe above a buckle presumably caused by slope movement and bending of the pipe. Constraint by the soil was indicated when, as the overburden was removed, the pipe rebounded 46 cm laterally and 20 cm vertically. NGTL-3, NUL-2, and NUL-3 occurred in association with localized bending, which in two cases also resulted in dents on the bottom of the pipe.

These latter cases indicate that not all C-SCC leaks will have a geotechnical component. Localized bending may also result in circumferential crack initiation.

Environment

The environments to which the pipes were exposed can be considered in terms of the physical terrain factors as well as the chemical conditions in contact with the pipe.

Topography, Drainage and Soil. In terms of terrain parameters a trend is apparent. C-SCC sites have been slopes where clay-textured soil had been in contact with the pipe. In three of the eight cases, seepage at pipe depth had brought water to the pipe. Both clays and water are known to play roles in soil movement on slopes.

The Canadian cases all occurred in Alberta in two physiographic regions: the Lower and Upper Boreal-Cordilleran regions. Both these regions are described as uplands of undulating and rolling topography. Also worthy of note from the slope instability perspective, is the pattern of precipitation: these two regions have the highest summer precipitation in the Province, July being the wettest month with ranges as follows:

<table>
<thead>
<tr>
<th>Region</th>
<th>Summer Precipitation</th>
<th>Average Summer Precipitation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(mm)</td>
<td>(mm)</td>
</tr>
<tr>
<td>Lower Boreal</td>
<td>182 - 444</td>
<td>295</td>
</tr>
<tr>
<td>Cordilleran</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Upper Boreal</td>
<td>206 - 504</td>
<td>340</td>
</tr>
<tr>
<td>Cordilleran</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

DISCUSSION

Circumferential stress corrosion cracking is a rare cause of pipeline leakage requiring specific conditions that exist in only a small proportion of the regions where Canadian pipelines operate. The C-SCC observed to date occurred on pipe coated with polyethylene, in the form of either tape or a shrink sleeve. In all cases, C-SCC developed at slope locations in undulating terrain; in all cases slopes are known to have been of 10° or greater. In most cases the SCC appears to have been of the neutral-pH form and, in all cases, resulted in leaks, at worst. The SCC occurred on the body of the pipe. Cracks developed and leaks occurred on DSAW and ERW pipes ranging in diameter from 168 - 914 mm (NPS 6 - 36) and of grades 290 to 448 MPa.

The C-SCC initiated and grew under conditions of high axial stress generated by slow, continuous soil movement and/or localized pipe bending in the vicinity of rocks and dents on slopes. Despite the high levels of

Chemical Environment. SNAM provides the only insight into the chemical nature of the groundwater and the moisture in contact with the pipe. SNAM reports a groundwater pH of 8.2 to 8.9 with a low resistivity of 20 - 90 $\Omega$m. Moisture in contact with the pipe was a slightly acidic, pH 6.3 - 6.8, bicarbonate solution similar to the electrolyte found associated with neutral-pH SCC in Canada.

SCC Type

Cracking reportedly occurred by both neutral-pH and high-pH SCC. Part of the reason for the two identifiable forms may be a function of when the leaks occurred relative to when details of neutral-pH SCC became widely known. Differentiation of the two SCC forms has evolved since the low-pH form was first encountered in 1985. Currently, discrimination of the type of SCC is made on the basis of key differences between the two types, such as shown in Table 2. According to the observations made, the leaks resemble more the near-neutral form of SCC than the high-pH form. Generally, the more characteristics that can be confirmed, the greater the confidence in the classification. As integrity management for the two forms are different, it is important that the form of the SCC be correctly identified.

Growth Rates

Growth rates were calculated for six of the eight leaks based on the maximum depths of cracks. Time averaged growth rates calculated from the year of construction range from $1.4 \times 10^{-6}$ to a low of $3.2 \times 10^{-9}$ mm/s, with an average of $5.9 \times 10^{-9}$ mm/s. These rates are consistent with the range observed for neutral-pH SCC both in the laboratory as well as in operation. The average growth rate is consistent with several cases of operating and hydrostatic test leaks by neutral-pH SCC.
axial stress, crack growth rates compare closely in terms of both the range and average rates observed for longitudinal neutral-pH SCC.

The soil movements associated with these cases of C-SCC can be termed as creep movements, as opposed to catastrophic landslides. These slow and continuous movements can be difficult to recognize in the field but, as evidenced by strain measurements, can with time generate stresses in excess of SMYS on the pipe. Clay soils and moisture on and in slopes can be risk factors for soil creep. Periodic increases in axial tension on the pipe may be a result of seasonal rain. Canadian sites of C-SCC consisted of undulating terrain with high rainfall.

Besides contributing to axial loading of the pipeline, soil creep could also contribute to disbondment of polyethylene tape.

The soil conditions that contributed to pipe loading and coating disbondment may also have played a role in SCC initiation and growth. According to the CEPA SCC Recommended Practices, Section 5, clay soils, moisture and undulating topography all correlate to locations of SCC initiation and growth.

In all documented cases of C-SCC, to date, whether in Canada or Italy the end result has been leakage, at worst. This is consistent with the orientation of the cracks and the generation of axial pipe stress by soil creep or localized bending stress; the likelihood of a guillotine rupture by C-SCC is low. In the case of very slow soil creep, if C-SCC develops and leaks occur, it is likely that the leaks would be detected prior to cracks growing to produce a guillotine rupture. In the bending situation, the stress and the driving force for crack growth would likely diminish as cracks grow. This is not to suggest that guillotine rupture could not occur, however, it is much more likely to be a result of catastrophic slope failures.

With seven of the eight C-SCC cases having been on natural gas pipelines, the leak on the Federated NGL line serves to indicate that the problem is a concern to any pipeline operating in conditions conducive to C-SCC. Where pipelines constructed using polyethylene tape or shrink sleeves traverse SCC-susceptible terrain, as described by the Recommended Practices, and where the potential for soil creep or localized pipe bending exists, it would be prudent to consider the potential risks of failure (potential for cracking and potential failure consequences) by C-SCC and to manage those risks accordingly.

On the basis of the cases reviewed here, it appears that C-SCC management may be largely addressed by effectively managing geotechnical concerns on slopes. In Alberta, susceptibility appears to be highest in portions of the Lower and Upper Boreal-Cordilleran regions. Susceptibility, however, may not be exclusive to slopes in these areas. Programs directed toward preventing soil movement, reducing the loading on the pipe, for example by strain relief, or relocating pipelines could all have benefit with respect to preventing C-SCC in susceptible areas.

Other management approaches that might also be considered and evaluated involve the use of in-line inspection tools. During the SCC Inquiry, British Gas testified that their magnetic flux inspection tool, normally used to detect metal loss, had demonstrated some capability to detect circumferential cracks in girth welds. Depending on the tightness of the cracks in the circumferential direction, it may be possible to apply magnetic flux leakage to identify C-SCC in the pipe body. Companies conducting metal loss inspections in areas with potential susceptibility to C-SCC might consider the use of the inspection data to locate circumferential cracks in the pipe body.

A second in-line inspection method might involve the use of the BJ Pipeline Inspection Services 'Geopig' to locate the position of the pipe and the size and position of dents. By conducting a series of inspections it may be possible to identify areas of pipe movement and hence areas where geotechnical forces may be acting on the pipe. It must be noted, however, that the Geopig may only identify one parameter of the three that must coexist in order for SCC to occur. Even though the stress regime may indicate that initiation of SCC is possible, the complementary conditions of a susceptible steel and the appropriate environment must also be present, and these contributors would not be detected by the Geopig technology alone.

To assist pipeline operators to manage this concern, it would be appropriate for CEPA to issue a revision to the SCC Recommended Practices concerning C-SCC.

Clearly, further information on C-SCC is needed to develop predictive or prioritization models, and management capabilities. Information on the presence or absence of C-SCC and the conditions for its initiation and growth could be obtained by inspecting pipe removed from slopes or geotechnically active areas, and by inspecting for circumferential cracks whenever SCC inspections are performed, particularly where bending is an issue.

Given that C-SCC is a case of SCC where localized loading is predominantly geotechnical in nature, additional SCC-directed research is not warranted at this time. SCC research in progress will provide insight into the processes at play, rates of growth, means of detection, etc. Geotechnical research in progress will provide insight into locations where axial pipe loading could occur, the magnitudes of the loads, and the rates of load and stress rise on the pipe. Examples of recent and current industry-sponsored geotechnical research are given in Table 4.

As such geotechnical research goes forward and matures it would be appropriate to consider circumferential SCC as one of the effects of pipe loading and to consider the research results in terms of SCC management. These two areas of SCC and geotechnical research will, therefore augment one-another in regard to C-SCC to provide insight and capabilities to manage the problem.

CONCLUSIONS

1. Circumferential stress corrosion cracking is a rare cause of pipeline leakage requiring very specific
conditions that exist in only a small proportion of the regions where Canadian pipelines operate.

2. Circumferential SCC has occurred in Canada and in Italy. In Canada, all known cases have occurred in Alberta.

3. To date, circumferential SCC in Canada has resulted in pipeline leaks at worst.

4. All known cases of C-SCC have occurred on slopes greater than 10° in undulating terrain where pipe loading resulted from soil creep or localized bending.

5. C-SCC will occur at the slope location where the axial tensile stress is highest. Localized bending from rocks, etc. may occur at any point on the slope; buckling may result in cracking near the toe; pure tension on the pipe may be greatest toward the crest.

6. One case of non-leaking C-SCC was detected in the vicinity of a dent removed from service prior to an in-line inspection.

ACKNOWLEDGEMENTS

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REFERENCES

1. Canadian Energy Pipeline Association Submission to the National Energy Board, Public Inquiry Concerning Stress Corrosion Cracking (SCC) on Canadian Oil and Gas Pipelines, Proceeding MH-2-95, Volume 1, Table 1.1


7. Transcript of the Public Inquiry Concerning Stress Corrosion Cracking (SCC) on Canadian Oil and Gas Pipelines, Order No. MH-2-95, April 19, 1996, p. 577
Table 1: Pertinent details of Circumferential SCC cases being reviewed

<table>
<thead>
<tr>
<th>Leak</th>
<th>NoTL</th>
<th>ML</th>
<th>FED</th>
<th>SNAM</th>
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<td>Natural Gas</td>
<td>Natural Gas</td>
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<td>762 x 12.7</td>
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<td>ERW</td>
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<td>ERW</td>
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<td>Longitudinal wrinkles and tape helix</td>
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<td>PE Tape</td>
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<td>Location of SCC</td>
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<td>Bottom</td>
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<td>Source of Stress</td>
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<td>rock caused 10%</td>
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<td>West-central Alberta</td>
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<td>Resembled Clay</td>
<td>Silty Clay</td>
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<td>Clay</td>
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<td>Near-Neutral SCC</td>
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<tr>
<td>----------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td></td>
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<tr>
<td>Location</td>
<td>• Typically within 20 km downstream of compressor</td>
<td>• SCC associated with specific terrain conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Number of failures falls markedly with increased distance from compressor and lower pipe temperature</td>
<td>• No correlation with distance downstream of compressor stations.</td>
<td></td>
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</tr>
<tr>
<td>Temperature</td>
<td>• Growth rate decays exponentially with temperature</td>
<td>• No apparent correlation with temperature</td>
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<td>Associated Electrolyte</td>
<td>• Concentrated carbonate-bicarbonate solution with an alkaline pH greater than 9.3</td>
<td>• Dilute bicarbonate solution with a neutral pH in the range of 6 to 8</td>
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</tr>
<tr>
<td>Electrochemical Potential</td>
<td>• -600 to -750 mV (Cu/CuSO₄)</td>
<td>• At free corrosion potential: -760 to -790 mV (Cu/CuSO₄)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• Cathodic protection is effective to achieve these potentials</td>
<td>• Cathodic protection is ineffective at SCC sites</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crack Path and Morphology</td>
<td>• Intergranular (around the steel grains)</td>
<td>• Transgranular (through the steel grains)</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>• Narrow, tight cracks with little evidence of secondary corrosion</td>
<td>• Wide cracks with evidence of substantial side-wall corrosion</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 3: Comparison Of Circumferential SCC Cases In Terms Of SCC Forms

<table>
<thead>
<tr>
<th>Reported Form</th>
<th>Leake Year</th>
<th>NGTL-1</th>
<th>NGTL-2</th>
<th>NGTL-3</th>
<th>NUL-1</th>
<th>NUL-2</th>
<th>NUL-3</th>
<th>FED</th>
<th>BNAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crack Morphology</td>
<td>Main crack typically straight Branched Transgranular or Mixed Inter and Transgranular Wide with Corroded Side Walls</td>
<td>Highly branched Intergranular</td>
<td>branch cracks discontinuous Combined inter and transgranular</td>
<td>limited branching mixed inter and transgranular</td>
<td>straight branched discontinuous intergranular</td>
<td>mixed inter and transgranular</td>
<td>branched crack tips suspected intergranular</td>
<td>straight</td>
<td>Macroscopic branching transgranular</td>
</tr>
<tr>
<td>Electrolyte pH</td>
<td>6.8</td>
<td>&gt; 9.3</td>
<td>6.3 - 6.8</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electrolyte Composition</td>
<td>Dilute bicarbonate Concentrated carbonate bicarbonate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance Downstream from Compressor</td>
<td>Indefinite</td>
<td>Typically within 20 km downstream of compressor</td>
<td>9.5 km</td>
<td>37 km</td>
<td>38 km</td>
<td>45 km downstream of gas plant</td>
<td>45 km downstream of gas plant</td>
<td>60 km downstream of gas plant</td>
<td>(30°C)</td>
</tr>
</tbody>
</table>
Table 4: Examples Of Recent And Current Geotechnical Research Of Relevance To Circumferential SCC

<table>
<thead>
<tr>
<th>Project Title</th>
<th>Participants</th>
<th>Potential Relevance to C-SCC Management</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipeline-Soil Interaction (multi-year project)</td>
<td>British Gas, Gaz de France, Italgas, Tokyo Gas, NGTL, Geological Survey of Canada</td>
<td>Capability to estimate pipe loads and deflections caused by soil movement</td>
</tr>
<tr>
<td>Surface Load Hazards</td>
<td>PRCI</td>
<td>Assess formulations to predict pipeline response to external surface loads and develop preliminary design guidelines</td>
</tr>
<tr>
<td>Demonstration Study of Digital Image Acquisition and Processing for Monitoring Ground Movements over Large Areas</td>
<td>NGTL/ SNAM &amp; PRCI</td>
<td>Capability to identify presently unmonitored unstable slope locations</td>
</tr>
<tr>
<td>Analysis of Geotechnical Hazards with Respect to Pipeline Integrity</td>
<td>NGTL</td>
<td>Capability to model pipeline performance in situations involving ground movement</td>
</tr>
<tr>
<td>Pipe Buckling During Upheaval in Areas with Temperature</td>
<td>IPL/NSERC</td>
<td>Capability to identify sites of pipe bending and buckling</td>
</tr>
<tr>
<td>Slope Movement Monitoring</td>
<td>Numerous</td>
<td>Understanding of conditions and kinetics of slope movement</td>
</tr>
</tbody>
</table>