

External Stress Corrosion Cracking of In-Situ Carbon Steel Pipelines

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ABSTRACT

There has been multiple reported and documented external stress corrosion cracking (SCC) of above-ground carbon steel pipelines within the past 5 years for a number of in-situ oilsands operators. Majority of these failures were on pipeline carbon steel grades API 5L or Z245.1 with specified minimum yield strength (SMYS) 52 ksi or higher, but there were also reports of external SCC on A106 Gr B and A234 WPB steel grades. All the cracks manifested on the bare (uncoated) Outside Diameter (OD) surface of the pipe, and all were associated with wet mineral wool insulation. Common features include operating temperature between 70°C and 160°C, intergranular cracking morphology, and exposed to wet mineral wool insulation with vintage post 2005.

Previously, SCC of carbon steel pipelines has been commonly reported and investigated for buried pipelines. There is limited information in the industry however on SCC of above ground carbon steel pipelines. Extensive field and lab tests were performed to understand the mechanism, in conjunction with technical studies/ literature reviews. This paper provides a summary aimed at increasing the awareness of the industry with this new damage mechanism, and improve public safety.

Key words: Stress Corrosion Cracking (SCC), pipelines, in-situ, mineral wool insulation

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INTRODUCTION

There are hundreds of kilometers of above-ground carbon steel pipelines located in 32 in-situ oilsands facilities operated by 18 producers in Alberta Canada, with a total thermal oilsands capacity (operating) of 1.8 million barrels per day ^[1]. A typical in-situ oilsands operation is for recovering bitumen located 75 meters or more below the surface, by the injection of steam. See figure 1.

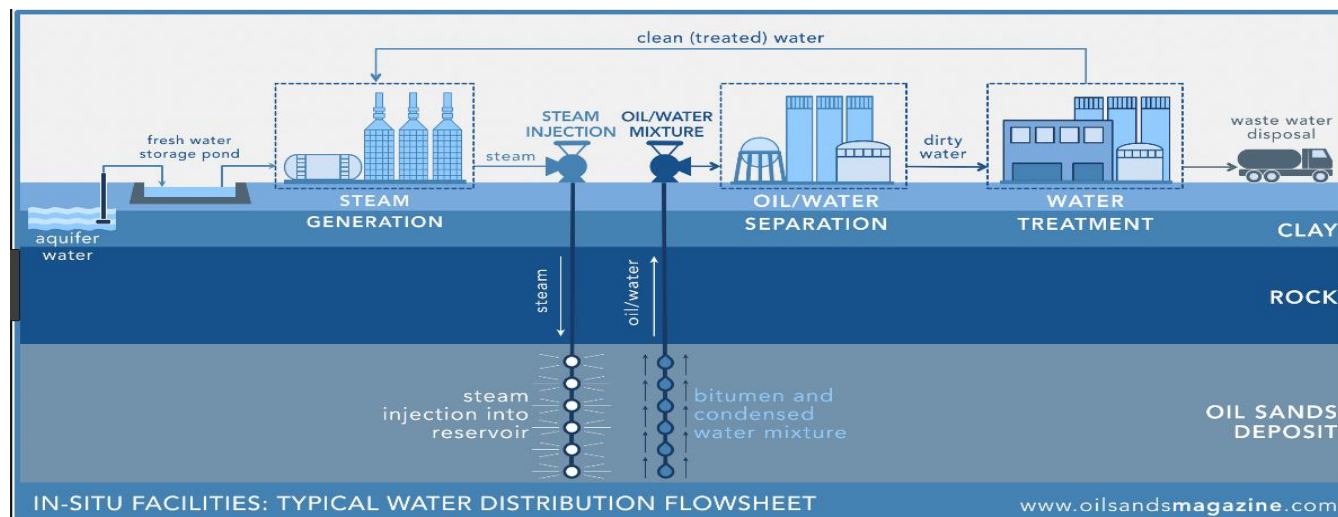


Figure 1: Typical in-situ oilsands facility (source: OilsandsMagazine.com)

The first in-situ oilsands operations were commissioned in 1985 in Cold Lake, Alberta. Until recently, there were no reported cases of external SCC of above ground carbon steel pipelines. The first documented external intergranular SCC associated with wet mineral wool was in 2015 for an A234 WPB fitting installed in 2009.

Stress corrosion cracking (SCC) mechanism occurs when a 1) susceptible material is exposed to 2) the right environment, and 3) stress.

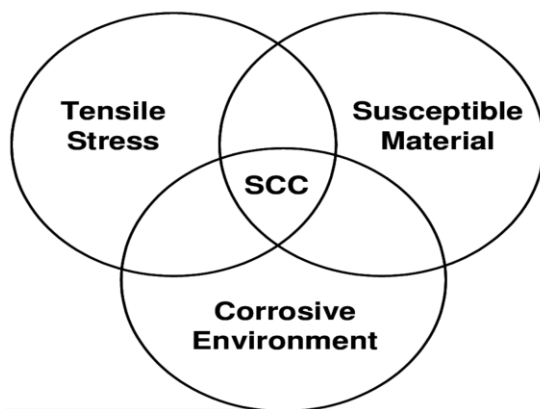


Figure 2 : Representation of the necessary conditions for SCC

External intergranular SCC have been reported for carbon steel grades API 5L or Z245.1 with specified minimum yield strength (SMYS) 52 ksi or higher, A106 Gr B and A234 WPB steel grades. This is currently the list of confirmed susceptible material to this mechanism.

Based on the reported failures to date, the environment present where intergranular SCC occurred are:

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operating temperature between 70°C and 160°C, exposure to wet mineral wool insulation, and the insulation vintage is post 2005.

It is inferred that there may have been changes to the mineral wool binder chemistry over the years, that explains why this SCC mechanism was not observed for older in-situ pipelines.

It is also inferred that the compounds causing SCC originates from the leachate in the mineral wool binder – either the direct leachate compounds from the binder, or that new compounds are being formed as the leachate breaks down at temperature in the presence of water and ambient air.

There is not a lot of information available with regards to the stress levels of the pipelines that cracked. However, majority of the cracks were found on and around suspected high-residual stress areas, i.e. induction bends, formed fittings, fillet welds on pipe shoes, longitudinal seam and girth welds. Majority of these cracks were also found along the lower half of the pipe, where moisture is expected to collect.

The focus of the extensive investigation contained in this paper is to understand more:

- 1) the role of environment, i.e. pH, leachate chemistry, exposure time, polarization potential, and field open circuit potential, vintage of mineral wool
- 2) the role of stress, i.e. residual stress measurements, pipeline combined stress

The paper also discusses the screening and inspection technologies and strategies used for the optimal detection and sizing of SCC.

What is not covered in this paper is the role of material. It is recommended that further study is performed to understanding the threshold strength of steel and various grades outside of the reported ones, but are more commonly used in the oil and gas industry, e.g. A 516 Gr 70 carbon steel, and low alloy steel such as 1 ¼ Cr -0.5 Mo for pressure vessels, and G40.21-38W for storage tanks.

A substantial body of work investigating SCC under these circumstances has been discussed by Ralston et al. in two preceding papers ^[2,3,6]. The objective of this paper is to build upon the existing body of knowledge and provide additional guidance to operators on:

- 1) identifying where to look for suspected SCC locations
- 2) deploying the best detection and sizing inspection technologies and strategies
- 3) identify ways to mitigate SCC for existing assets, and prevent for new construction

EXPERIMENTAL PROCEDURE

The content of this paper includes both field and laboratory investigations. For laboratory investigations, leachates were prepared from samples of insulation and subsequently used to simulate the field environment during cyclic potentiodynamic polarization (CPP) and slow strain rates tests (SSRT). Pup spools of the pipeline found with stress corrosion cracking (SCC) were sectioned and sent to laboratory for metallographic analysis, mechanical testing, and for residual stress measurement.

In the field, moisture detection imaging (MDI) was used to screen the pipelines for the presence of water in the mineral wool (MW) insulation without having to remove the cladding. Eddy current array (ECA) was then used to inspect the pipe outside diameter (OD) for the detection and sizing of stress corrosion cracking (SCC). Field open circuit potentials (OCP) were measured at the pipe OD across different locations, notably around the locations SCC were found.

The procedures for each aspect of this investigation are provided below.

A. Laboratory Testing

A1. Leachate Preparation and Chemical Analysis

Insulation from multiple field locations were sampled and sent to a laboratory for analysis. Both mineral wool insulation and aerogel insulation were tested as part of this study; however, the vast majority of samples and the primary focus of this study was mineral wool insulation. Samples were received with varying degrees of moisture content and were dried in a laboratory oven at 40 °C for a period of 3 days to ensure a consistent basis for subsequent leachate preparation. The inner surface of mineral wool samples (the surface in contact with piping) was brownish in color and loosely bound, whereas the remainder of the sample was lighter green and of similar appearance and quality to new mineral wool insulation. Material from the inner most and outer most layer from each sample of insulation were separated, taking approximately 1 cm of material from each side. No gradient in color or mechanical properties were apparent for the aerogel samples and no separation was performed prior to leachate preparation for this material.

Insulation was then combined with deionized water at a ratio of 40 g dry insulation to 1 L of deionized water. The resultant mixtures were shredded by processing in a blender for 5 minutes at high speed and then boiled for a period of 30 minutes. After boiling, the liquid was decanted and the solids were pressed to release as much liquid as possible. The liquid was then filtered to remove any remaining mineral wool fibers and concentrated by a factor of 5 by further boiling. The concentrated leachate was allowed to cool and stored in well-sealed container with minimal headspace prior to use in subsequent investigations, which would typically commence the following day.

The pH of all concentrated leachates was measured at room temperature on the day they were produced, and again prior to use in subsequent tests. A subsample of leachates was stored in containers open to air and monitored for changes in pH for a period extending up to 40 days.

Select leachates also underwent chemical analysis including inductively coupled plasma mass spectroscopy (ICP-MS), ion chromatography (IC) and titration for alkalinity.

A2. Cyclic Potentiodynamic Polarization

Cyclic potentiodynamic polarization (CPP) tests were performed using a Gamry Reference 600+ potentiostat and a 4 L autoclave constructed from alloy C276. The electrochemical cell consisted of a working electrode, counter electrode, reference electrode, and electrolyte (leachate). Working electrodes were machined from CSA Z245.1 Grade 359 cat 2 pipe to dimensions shown in Figure 3. A new working electrode was used for each CPP test. The counter electrode used for this work was a platinized niobium cylinder of the same dimensions as the working electrode. The reference electrode used was a high temperature silver/silver chloride (Ag/AgCl) reference electrode supplied by Cortest. A polytetrafluoroethylene (PTFE) cylinder was placed in the bottom of the autoclave, reducing the autoclave volume by 2 L, so that less leachate was required to fully submerge the working, counter and reference electrodes. Each test utilized 700 mL of concentrated leachate.

All CPP tests in this investigation were performed at 125 °C. Prior to heating, the autoclave was purged with nitrogen at a rate of 5 standard liters per minute for a duration of 75 minutes. CPP scans were conducted with a starting voltage of -0.1 V versus the open circuit potential (OCP) and a scan rate of 0.167 mV/s. The scan was reversed once current density reached 1 mA/cm².

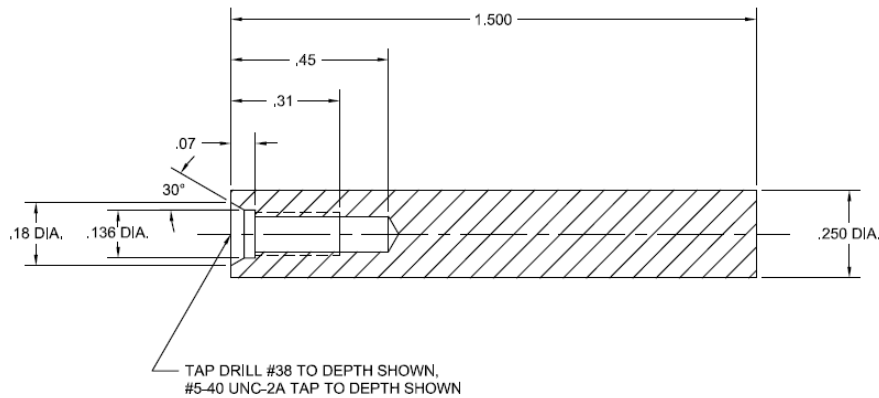


Figure 3: Dimensions of CPP working electrode in inches

A3. Slow Strain Rate Testing

Slow strain rate tests (SSRT) were performed using a tensile frame, a pull through autoclave constructed from alloy C276, and a Gamry Reference 600+ potentiostat. Within the pull through autoclave, the electrochemical cell consisted of a working electrode, counter electrode, reference electrode, and electrolyte (leachate). Working electrodes were fabricated from CSA Z245.1 Grade 359 cat 2 pipe that was cut out from an area where IGSCC cracking was observed. Blanks for the working electrodes were extracted from the pipe carcass using water jet to avoid heat input during cutting. All blanks were extracted a minimum of 2 inches away from the longitudinal weld seam. Working electrodes were then machined on a CNC lathe, taking care to avoid overheating and cold working the gauge section. The final two passes on the lathe removed no more than 0.002 inches of material and produced a gauge diameter of 0.149 inches. Each working electrode was then manually polished with progressively finer emery paper (wetted), ending with 1200 grit and a final gauge diameter of 0.145 inch. Specimens were not notched. Detailed dimensions of the SSRT working electrode are shown in Figure 4. Working electrodes were connected to the tensile frame using threaded Nitronic 50 fittings and were electrically isolated from the autoclave body using polymeric sliding seals (Bal Seal). Exposed surfaces of the Nitronic 50 fittings were also tightly wrapped in PTFE tape. The counter electrode used for this work was a platinized niobium cylinder, of the same dimensions as used for CPP tests. The reference electrode used was a high temperature silver/silver chloride (Ag/AgCl) reference electrode supplied by Cortest. 550mL of leachate was used for all tests, which was sufficient to fully submerge the exposed surfaces of the working electrode, the counter electrode and reference electrode.

All slow strain rate tests in this investigation were performed at 125 °C. Prior to heating, the electrolyte was purged with nitrogen at a rate of 2.3 standard liters per minute for 75 minutes. Once at temperature, potentiostatic polarization was applied to the working electrode, and the working electrode was progressively strained in stages, as summarized below. Depending on the test objective, the polarization potential was selected to correspond with the active passive transition (APT) from corresponding CPP data or field OCP measurements. In theory, the potential at and around APT leads to the initiation of SCC. Actual field OCP were also used as polarization potential in SSRT to simulate the real field condition and determine the response of the steel sample with respect to SCC.

After stage 2, the working electrode was removed from the autoclave to inspect for cracking. The working electrode was then returned to the tensile frame and further strained in air to open any cracks that may have formed during stages 1 and 2.

- Stage 1: Strain rate of 0.914 mm/hr (based on cross head displacement) until stress in working electrode reached 287 MPa (80 % SMYS)
- Stage 2: Strain rate of 0.007 mm/hr for 115 hours
- Remove working electrode from test environment---
- Stage 3: Strain rate of 0.914 mm/hr, until 3 mm crosshead displacement

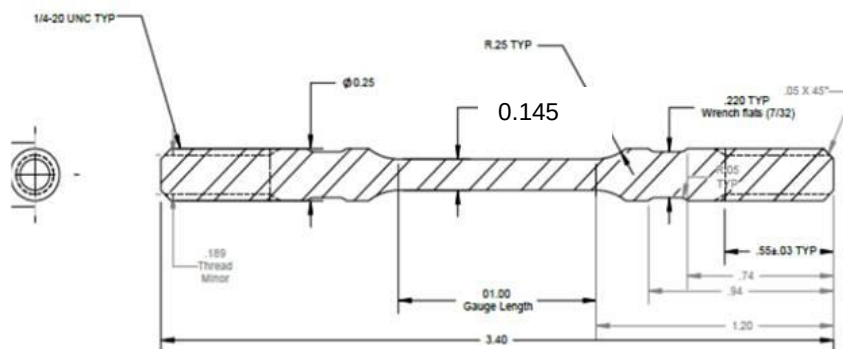


Figure 4: Dimensions of SSRT working electrode in inches

B. Mechanical and Metallographic Analysis

B1. Residual Stress Measurement

A pipe sample containing a suspected SCC was sent for mechanical and metallographic testing. The pipe sample was a 12.75 inch OD section of an emulsion pipeline of 0.25 inch thickness, with specification CSA Z245.1 Grade 359 Category II. It normally operated between 90-140 C.

Residual stress measurements were taken near 3 crack tip locations using the blind-hole (BHD) method^[4], with strain gauge rosettes and a custom milling guide/drill, in accordance with ASTM E837. This was carried out by installing specialized strain gauge rosette at points of interest and balancing the gauge outputs to zero. A small flat-bottomed hole was then drilled into the center of the strain gauge incrementally using a precision milling high speed pneumatic drill. At each increment the resulting change in strain was recorded and plotted against the hole depth. The residual stress of the pipe prior to the drilling of the hole was then calculated based on these strain measurements.

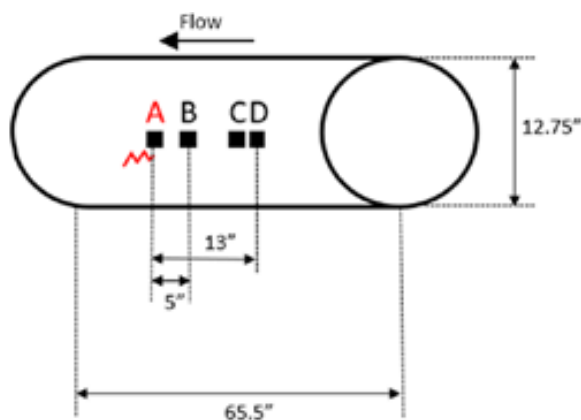


Figure 5: Residual Stress Measurement Locations and Photo of Location A