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External Stress Corrosion Cracking of Underground Pipelines

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Foreword

The purpose of this technical committee report is to provide useful information on stress corrosion cracking (SCC) for engineers, designers, consultants, and others involved in the design, maintenance, and rehabilitation of underground petroleum (including gas, crude oil, and refinery products) pipelines. This technical committee report contains information obtained from a survey of the open literature on the subject.

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Introduction

SCC is one form of environmentally assisted cracking (EAC). EAC is a generic term that describes all types of cracking in materials in which the environment and stress act together to reduce the strength or load-carrying capacity of the material. Other forms of EAC include hydrogen embrittlement, sulfide stress cracking, and corrosion fatigue. EAC is an ongoing integrity concern for many industries including oil and gas, nuclear power, and chemical process. It affects most common construction materials including carbon steels, stainless steels, and copper-based alloys.

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(1) National Energy Board (NEB), 444 Seventh Avenue SW, Calgary, AB T2P 0X8 Canada.

The first reported incident of external SCC on natural gas pipelines occurred in the mid-1960s, and numerous failures have occurred since that time.[2] SCC failures have also been reported on liquid pipelines, and SCC continues to be an integrity concern. It is now recognized that there are two forms of external SCC on underground pipelines: high-pH SCC (also referred to as classical SCC) and near-neutral-pH SCC (also referred to as low-pH SCC). A characteristic of both forms of SCC is the development of colonies of up to thousands of longitudinal surface cracks in the body of the pipe that link up to form long, shallow flaws. In some cases, growth and interlinking of the stress corrosion cracks produce flaws that are of sufficient size to cause leaks or ruptures of pipelines.

The high-pH form of SCC is intergranular, and there is usually little evidence of general corrosion associated with the cracking. A concentrated carbonate-bicarbonate (CO_3-HCO_3) solution was identified as the most probable environment responsible for this form of cracking.[3] The near-neutral-pH form of SCC is transgranular and is associated with corrosion of the crack faces, and in some cases with corrosion of the external surface of the pipe as well. This form of cracking occurs in near-neutral-pH ($6 < pH < 8$) dilute carbon dioxide (CO_2)-containing electrolytes and was first observed beneath polyethylene-tape coatings on TransCanada PipeLines Limited's (TCPL's)[(2)] system in the 1980s.[4,5]

Stages of SCC

Figure 1 shows a "life" model for a pipeline containing stress corrosion cracks.[1] The model consists of four stages. In Stage 1, the conditions for the initiation of SCC develop at the pipe surface. The coating disbonds, a cracking electrolyte develops at the pipe surface, and the pipe surface may become pitted or modified in other ways as a result of the presence of the electrolyte. Cracks begin to initiate in Stage 2, and continued initiation, growth, and crack coalescence occur in Stage 3. In Stage 4, large cracks coalesce and final failure occurs. The model was developed for high-pH SCC; it may be relevant to near-neutral-pH SCC, but its applicability to that form of SCC has not been demonstrated. In particular, the observation that some cracks become dormant over time is not included in the model.

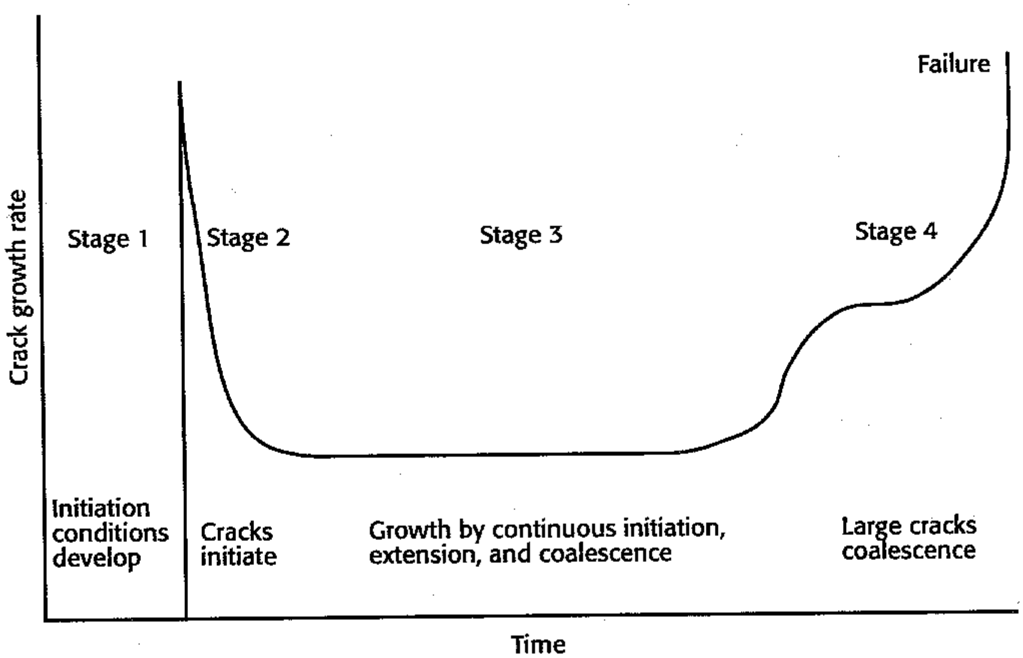

Figure 1: Life Model for a Stress Corrosion Crack

The coalescence of individual stress corrosion cracks helps to determine whether a colony of cracks is an integrity concern. If cracks nucleate in close proximity to one another, crack growth may be dominated by the coalescence of collinear cracks. Coalescence can occur throughout the SCC life cycle. Depending on the size of the crack, either environmental or mechanical forces can cause the cracks to grow during Stage 3. In Stage 4 of growth, coalescence may occur primarily by tearing, when mechanical loading has a stronger effect in producing crack growth.

(2) TransCanada PipeLines Limited (TCPL), 450 1 Street SW, Calgary, AB T2P 5H1 Canada.

Research on near-neutral-pH SCC has shown that the geometry of the SCC colony is important in determining whether cracks coalesce and grow to failure.[1] Colonies of cracks that are long in the longitudinal direction but narrow in the circumferential direction present more of a threat to pipeline integrity than colonies of cracks that are about as long as they are wide. In long, narrow colonies, individual cracks that are aligned head-to-tail can link up and lead to rupture, but in colonies of cracks that are equally long and wide, growth occurs primarily at the edge of the colony. Cracks located deep within these colonies tend to shield each other from stress and become dormant.

The circumferential spacing between cracks within a colony varies. Leis used a circumferential spacing equal to 20% of the wall thickness between cracks as the distinguishing criterion between sparse and dense cracks.[6] Cracks circumferentially spaced closer than 20% of the wall thickness tend to go dormant, whereas cracks spaced farther apart (at distances greater than 20% of the wall thickness) can continue to grow. This behavior suggests that crack coalescence is a possible influence on crack growth.

Three conditions are inherent for SCC initiation and propagation in Stages 2 and 3 to occur. These conditions generally differ for the two types of cracking:

- A potent environment develops at the pipe surface,
- The pipe steel is susceptible to SCC, and
- A tensile stress of sufficient magnitude is present.

This concept is shown graphically in Figure 2. SCC is often mitigated if any one of these conditions is eliminated. For example, enhancement of the cathodic protection (CP) system may alter the conditions at the pipe surface such that a potent environment is no longer present. Further discussion of these three conditions for high-pH and near-neutral-pH SCC is given below.

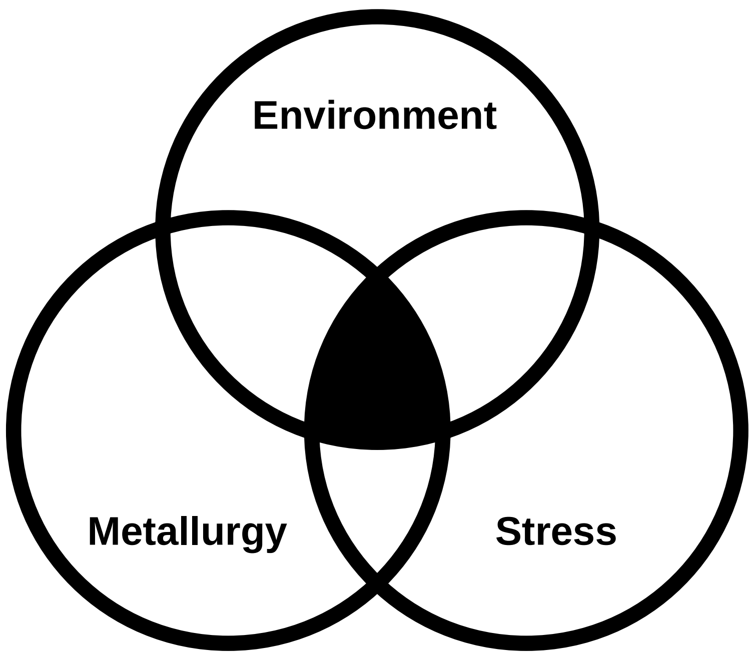

Figure 2: Three Conditions Necessary for SCC

Conditions for SCC

Potent Environment

As described above, the two forms of external SCC are associated with two distinct types of environments that develop at the surface of underground pipelines. In the case of near-neutral-pH SCC, the cracking environment appears to be a dilute groundwater containing dissolved CO_2. The source of the CO_2 is typically the decay of organic matter and geochemical reactions in the soil. This form of cracking occurs under conditions in which there is little if any CP current reaching the pipe surface, either because of the presence of a shielding coating, a high-resistivity soil, or inadequate CP design.[7] In the case of high-pH SCC, CO_2 is also involved. CP causes the pH of the electrolyte beneath disbonded coatings to increase, and the CO_2 readily dissolves in the elevated-pH electrolyte, resulting in the generation of a concentrated CO_3-HCO_3 electrolyte.[2] Four factors determine whether either of these potent environments can develop at the pipe surface: coating, soil, CP, and temperature.