Development of Guidelines for Identification of SCC Sites and Estimation of Re-inspection Intervals for SCC Direct Assessment

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TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABBREVIATIONS

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CEPA	Canadian Energy Pipeline Association
ILI	In-line Inspection
IMP	Integrity Management Plan
SCADA	Supervisory Control and Data Acquisition, the system used to acquire pressure-time data
SCC	Stress Corrosion Cracking
SCC DA	SCC Direct Assessment

ABSTRACT

This report describes the development of a series of guidelines for the identification of SCC sites and the estimation of re-inspection intervals. These SCC Guidelines are designed to complement and supplement existing SCC Direct Assessment protocols by drawing on information from past R&D studies. Guidelines are presented for the various mechanistic stages of both high-pH and near-neutral pH SCC, namely; susceptibility, initiation, early-stage crack growth and dormancy, and late-stage crack growth.

The guidelines are designed to be broadly applicable, and include discussion of both high-pH and near-neutral pH SCC, gas and (hydrocarbon) liquid pipelines, existing and future pipelines, on local and regional scales in North America and internationally. The guidelines are designed to be of use to pipeline operators with prior experience of SCC and to those for whom this is a new or unknown integrity threat.

The report also describes how these guidelines can be implemented by operating companies and provides a list of the analyses that need to be performed, the necessary input data, and how the resultant information can be used to identify SCC sites and estimate re-inspection intervals.

The main text is supported by four appendices where the interested reader can find much of the detailed background information.

EXECUTIVE SUMMARY

This report is a guidance document for identifying locations where external pipeline stress corrosion cracking (SCC) is most likely to exist and for estimating how frequently re-inspections should be performed. The guidance is provided by a series of "SCC Guidelines" that have been developed from the results of R&D studies performed over the last 30-40 years. These mechanistically based guidelines are designed to complement those developed on the basis of field experience. The major route for implementing these guidelines is through improvement of site selection as part of the SCC Direct Assessment (SCC DA) process.

The basis for the guidelines is a critical review of over 200 original R&D papers, articles, and reports available in the public domain. A set of 540 "R&D Guidelines" have been derived from these original works, 190 for high-pH SCC and 350 for near-neutral pH SCC. These R&D Guidelines have been combined into 109 SCC Guidelines that can be used for identifying SCC sites and estimating re-inspection intervals. These SCC Guidelines have been validated where possible against field data and observations.

The SCC Guidelines have been structured to reflect the various stages of the stress corrosion mechanism. In addition to a set of fundamental principles for each form of cracking, SCC Guidelines have been developed to determine the susceptibility of a pipeline segment to external SCC, to assess the possibility of crack initiation, of early-stage crack growth and dormancy, and of late-stage crack growth.

Pipeline operators will probably find Section 4 of the report of most use in implementing these guidelines. Here, the individual guidelines are structured in terms of various processes for the different stages of cracking. For each process, the nature of the analyses that pipeline companies need to perform is identified along with the required input data. A commentary is also provided describing how the resultant information can be used to either identify SCC locations or to estimate re-inspection intervals.

In addition to implementing the findings as part of a company integrity management plan, the guidelines developed here can be used to complement existing protocols developed by NACE, ASME, CEPA, and API. The existing methodologies are largely based on field experience, whereas the guidelines developed here are based on mechanistic information developed from R&D studies.

The main text is supported by four appendices which provide, for the interested reader, the detailed information underlying the SCC Guidelines. Appendix A is a compilation of one-page summaries for each of the original R&D studies that were critically reviewed. The R&D Guidelines derived from these reviews are listed in Appendix B and cross-referenced to the original studies. Appendix C describes the field data collected as part of this study and used to validate some of the guidelines. Finally, Appendix D describes how the individual R&D Guidelines were combined into the SCC Guidelines described in the main text.

1. INTRODUCTION

Since the first reported pipeline failure due to stress corrosion cracking (SCC) in the 1960's, a great deal of research and development (R&D) work has been performed. Some of the results of these R&D studies have been implemented, for example, in the way of improved pipeline coatings or the introduction of mitigation strategies such as the reduction of gas temperatures. However, many more studies remain to be implemented and it is the aim of this project to develop implementable guidelines based on the R&D conducted over the past 40 years.

This report describes a series of "SCC Guidelines" derived from the scientific and engineering R&D literature with the basic aim of identifying where and when SCC can be expected to occur on operating pipelines. The guidelines are designed to be applicable to:

- both high-pH and near-neutral pH SCC, the two forms of external SCC now recognized;
- all stages of the cracking process;
- gas and (hydrocarbon) liquid pipelines;
- existing and future pipelines;
- both local and regional scales;
- North America and internationally,
- and, both pipeline operators with prior experience of SCC and those for whom this is a new or unknown integrity threat.

These guidelines do not apply to:

- above-ground pipelines;
- internal SCC, such as that observed in ethanol or in sour service;
- forms of external cracking not covered by either the high-pH or near-neutral pH SCC mechanisms, such as hydrogen stress cracking; and
- materials other than C-Mn pipeline steels.

The current study deals with mechanistically focussed R&D. Thus, R&D directed towards the development of in-line inspection (ILI) technologies or specifically aimed at the development of improved coating formulations are excluded. Mechanistic R&D studies typically provide information that can be used to develop models for predicting where SCC might occur and how fast it will develop. Of the various methods for managing SCC, including ILI, hydrostatic testing, and Direct Assessment (DA), these models are most applicable to the DA process. (That is not to say, however, that the information presented here can not be used for prioritising pipelines for ILI or hydrotesting or the scheduling of same).

Current DA processes or, more generally, the selection of SCC sites are generally based on empirical information only. For example, a common approach is to identify operating conditions or particular environmental or site parameters associated with past incidents of SCC and to identify other, similar locations for further investigation. So-called soils or site-selection models are examples of this type of approach based on prior experience. Such models have found some success, but tend to be less successful when used in areas or on systems outside of that on which the model was developed.

Here, a different approach is taken. The R&D literature has been reviewed to identify mechanistic information that might be useful for identifying where SCC would be expected to occur or to estimate when and how fast cracks might grow. This approach ignores existing knowledge of where SCC has been found in the past and attempts to identify these locations based on a fundamental scientific and engineering understanding of the SCC mechanism(s). Wherever possible, the guidelines developed from the R&D literature have been validated against field data.

Many of the SCC Guidelines described here are quite technical in nature. This is, of course, a natural consequence of the fact that they are derived from detailed technical studies. Much of this technical detail has been retained in the description of the guidelines because it is believed that pipeline operators will be better able to manage SCC if they have some understanding of the mechanistic basis of the overall cracking process. Hopefully, users of these guidelines will still find them practical and that they offer some insights that a purely empirical approach has not in the past.

This report is arranged in the form of a main text supported by four appendices. The main text contains:

- a description of the process followed to develop the guidelines and the mechanistic stages into which they are divided (Section 2);
- a summary of the actual SCC Guidelines for both high-pH and near-neutral-pH SCC, again divided into each of the main mechanistic stages (Section 3);
- a discussion of how the guidelines can be implemented to identify SCC sites and to estimate re-inspection intervals, as well as a comparison with existing approaches in various consensus standards and a discussion of how pipeline operators can make best use of the guidelines (Section 4), and
- a discussion of the further development of the guidelines, both in terms of identified gaps in the existing R&D knowledge, as well as improvement of the guidelines themselves (Section 5).

The four appendices contain the detail on which the guidelines are based.

- Appendix A is a compilation of the 1-page summaries of each of the 200+ articles, papers, and reports critically reviewed for this project.
- Appendix B is a compilation of the 500+ "R&D Guidelines" that were derived from the R&D literature and which form the basis of the "SCC Guidelines" (see Section 2 for a description of the process that was followed).
- Appendix C contains a description of the field data that were collected as part of this project.

- Appendix D describes the development of the SCC Guidelines and the attempts to validate them against field data.

2. APPROACH TO THE DEVELOPMENT OF THE SCC GUIDELINES

2.1 GENERAL APPROACH

Figure 1 shows the overall process used to develop and validate the SCC Guidelines. The basis for the guidelines was a critical review of individual research papers, articles, and reports available in the public domain. Each of these papers was reviewed and summarized (Appendix A) and, depending upon the length and usefulness of the study, between zero and fifty so-called "Research Guidelines" were derived from each study (Appendix B). A Research Guideline is typically a relationship, an algorithm, equation, conclusion, etc. taken directly from the R&D study and can be highly technical and/or specific in nature. Examples of Research Guidelines include:

- "Overprotection at potentials more negative than -1.1 V_{SCE} can result in H_2 bubbles that block CP and shift the potential into the cracking range" (Research Guideline H010, Appendix B)
- "Cold work promotes cracking in near-neutral pH solutions" (Research Guideline N028)
- "There is no correlation between the microbial population and either the rate of hydrogen permeation or the rate of crack growth" (Research Guideline N246)

A total of 540 Research Guidelines were developed based on the review of 200 research articles. Of these 540 guidelines, 190 related to high-pH SCC and 350 to near-neutral pH SCC.

The majority of papers and reports that were reviewed directly addressed the SCC of underground pipelines. However, in some cases, articles from other areas or industries were reviewed where such studies provided useful information or insight; for example, the SCC of low-alloy steels in high-temperature water in nuclear reactors or the corrosion fatigue of high-strength steels used for aircraft landing gear.

In some cases, individual Research Guidelines were in a form suitable to be used directly to identify SCC sites or to estimate re-inspection intervals. In the majority of cases, however, two or more Research Guidelines were combined to form a potential SCC Guideline (Figure 1).

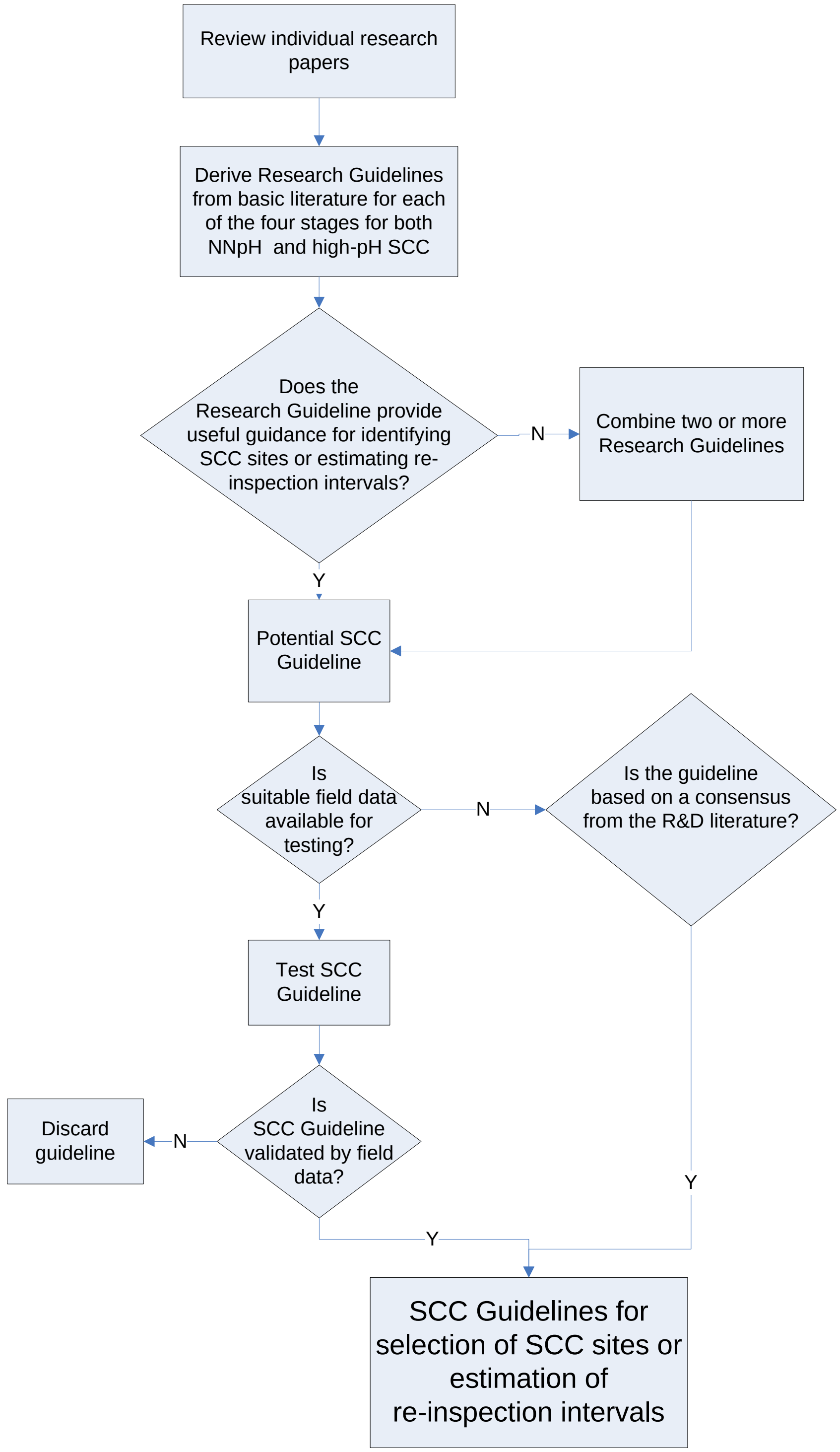

Figure 1: Flowchart Illustrating the Overall Process Used in the Development of the SCC Guidelines.

Where possible, these potential SCC Guidelines were validated against field data. The field data collected from operating pipeline companies and that publicly available from the literature are described in Appendix C. If appropriate field data were available for testing the guideline and if that validation was successful, then the SCC Guideline was retained. In the majority of cases, however, the guideline could not be validated because either the appropriate data were not provided in the survey of operating companies or because the guideline was such that the data necessary for validation are difficult to obtain. In those cases, provided the guideline represented a consensus from two or more R&D studies the guideline was retained. Therefore, the SCC Guidelines presented in Section 3 consist of both those that have been validated against field data and those that are un-validated but which represent a consensus of R&D opinion.

One of the main reasons why it has proven difficult to validate many of the SCC Guidelines against field data is the multivariate nature of SCC. Typically, an R&D study will be focussed on one of the many factors underlying the overall SCC process, for example, the effect of inclusions on the initiation of cracks on polished steel surfaces or the factors involved in the development of a high-pH environment under a simulated disbonded coating. However, the field data represent the consequences of all of the individual processes involved. Thus, the distribution of high-pH SCC failures as a function of distance downstream of the compressor station is the net result of:

- coating deterioration and disbondment,
- the development of a suitable environment due to the net effects of CP on the development of an elevated pH and suitable potential and the generation of CO_2 in the soil,
- the presence of steel susceptible to crack initiation,
- suitable cyclic loading characteristics,
- the coalescence of cracks and the re-activation of dormant cracks,
- the failure to detect cracks by ILI or hydrotesting,
- and many more individual processes.

Therefore, in the case of many of the SCC Guidelines, the available field data are not in a suitable format for validation purposes.

Partly because of the difficulty of validating these technically based guidelines, the approach has been taken to be as inclusive as possible in developing the SCC Guidelines. Thus, if a guideline is potentially useful for either locating SCC or estimating re-inspection intervals then it has been included in the lists in Section 3. In this respect, it should be remembered that these guidelines are only designed to provide guidance; they are not meant to be prescriptive rules. Therefore, users should expect that there will be exceptions to the guidelines when they are applied in the field.

An important aspect of the SCC Guidelines is that they have been designed to be useful for all pipeline operators. In particular, the guidelines are designed to be useful to both operators who have extensive experience of SCC and to those for whom this is a new phenomenon. Therefore, the guidelines exhibit different levels of sophistication, ranging from well-known observation that the severity of high-pH SCC increases with increasing temperature to the more esoteric guidance that "hydrogen plays a role in both crack initiation and propagation" for near-neutral pH SCC.

2.2 MECHANISTIC PHASES

Stress corrosion cracking comprises a number of phases or stages. Figure 2 shows the four stages for high-pH SCC defined by Parkins (1994), comprising an incubation period during which conditions for cracking develop (Stage 1), followed by a period of initiation and deceasing crack growth rate (Stage 2), a period of continued crack initiation and coalescence (Stage 3) and, finally, a period of more-rapid crack growth and eventual failure (Stage 4).

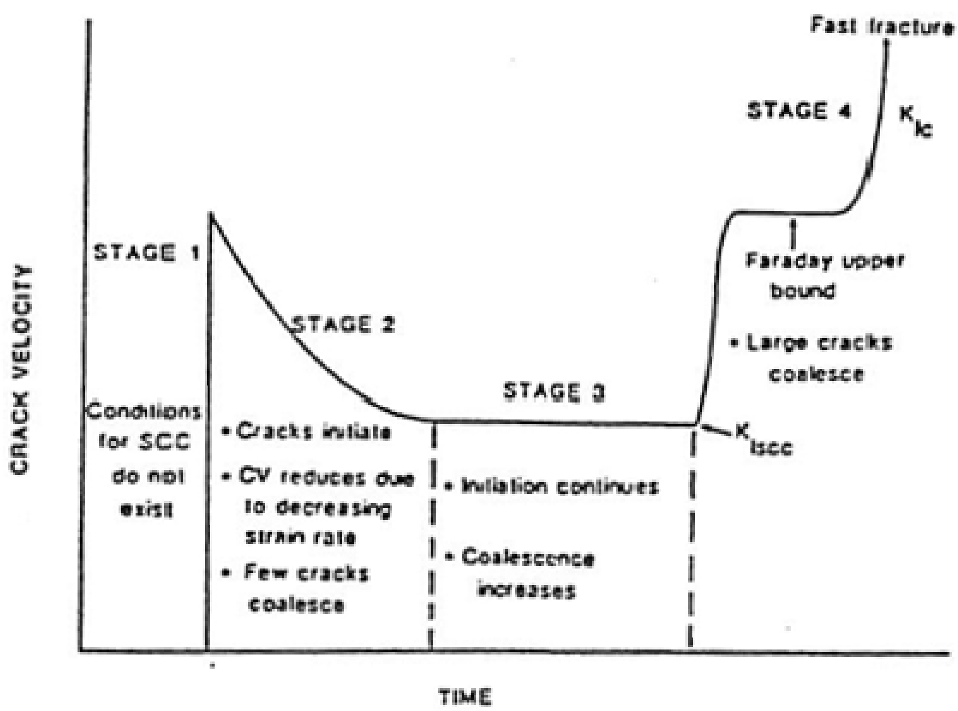

Figure 2: The Four Stages of High-pH SCC (Parkins 1994).

A similar mechanistic approach involving different stages is taken to the development of the SCC Guidelines in this study. Figure 3 shows the general structure of the SCC Guidelines and the four stages or steps into which they are divided. The first stage is termed "Susceptibility" and aims to answer the question of whether the pipeline is susceptible. The second stage concerns the initiation of cracks, which is taken here to refer to the development of crack-like features at least several grains in size up to a few tenths of a mm. The third stage, early-crack growth and dormancy, recognizes the fact that, once initiated, many cracks grow a limited extent and become dormant. Stage 4, late-stage crack growth, deals with cracks that continue

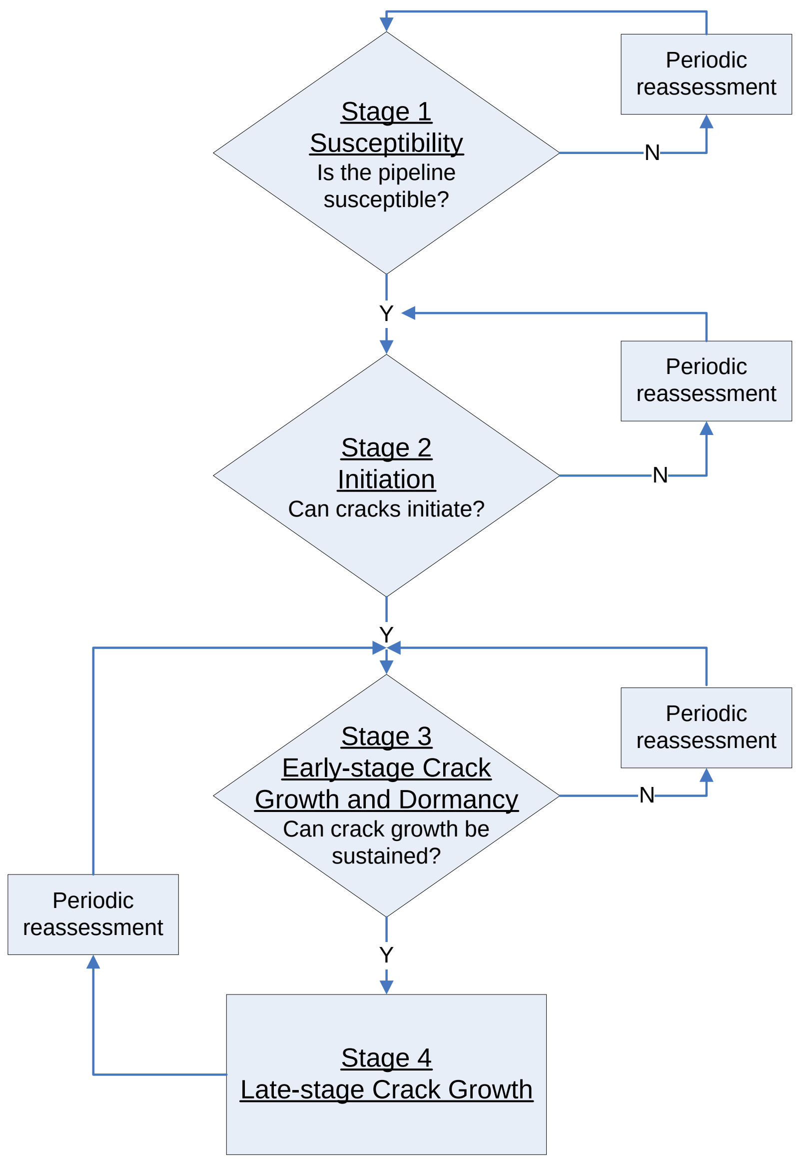

Figure 3: General Structure of the SCC Guidelines.

to grow and which may ultimately lead to failure. The crack size that distinguishes early-stage from late-stage crack growth is not clearly defined and differs for the two forms of cracking. However, in both cases, cracks in Stage 4 are generally more mechanically driven than those in Stage 3. This division of the guideline into these four stages is somewhat arbitrary but is useful for categorizing the guidelines.

3. SCC GUIDELINES FOR THE IDENTIFICATION OF SCC SITES AND THE ESTIMATION OF RE-INSPECTION INTERVALS

3.1 HIGH-pH SCC

High-pH SCC was first reported following the failure of a gas transmission pipeline in the US in the mid-1960's, although at that time there was no distinction between the two forms of cracking that are now recognized. Since that time, high-pH SCC has been reported in various countries, including Australia, Argentina, Iran, the former Soviet Union, Pakistan, and Canada (Parkins 1994).

High-pH SCC has been found to occur over a range of environmental and operating conditions The characteristics of high-pH SCC failures and the conditions under which failures have occurred include (Parkins 1994):

- NPS8 to NPS34 pipe
- wall thicknesses ranging from 4.6 mm to 12.7 mm
- on submerged arc, flash, and electric-resistance weld pipe, as well as seamless pipe
- as short as 6 years following the start of operation, to a maximum of 40 years, with an average of 15-20 years service
- 90% of failures have been within 10 miles (16 km) of the upstream compressor station as a result of the higher temperatures and more-severe loading conditions in this region
- gas temperatures at the time of failure have ranged from 10 to 60^{o}C with the majority >35^{o}C, although temperatures may have been hotter earlier in service
- 70% of failures initiated at the bottom of the pipe where coating damage is more likely
- there has generally been no correlation with soil characteristics, with one exception being the Moomba to Sydney pipeline where cracking occurred primarily in low conductivity wet clay pans
- failures have occurred in steels with a wide range of chemical compositions (0.07-0.35 C, 0.40-1.33 Mn, 0.006-0.062 S)
- failures have occurred at hoop stresses of 46-76% SMYS, with all but one occurring at >60% SMYS

- there is no evidence for any role of stress raisers, unlike near-neutral pH SCC, although high-pH SCC has occurred in dents
- the pipe-to-soil potential at the time of failure ranged from -0.85 to -2.0 V_{CSE}
- most failures have occurred on lines coated in the field with a combination of coal tar primer and a coal tar enamel/fiberglass felt, although some failures have occurred on asphalt- and tape-coated lines
- failures have also occurred on bare lines 1-17 years after the application of CP following a period of 9-16 years unprotected, during which a layer of corrosion product had built up
- field electrolytes are carbonate/bicarbonate based with concentration of the order of 0.1 mol/L (0.5-1 wt.%)

3.1.1 Fundamental Principles of High-pH SCC

These fundamental principles are overarching statements that either provide the user with a fundamental understanding of the overall process or apply to more than one stage in the cracking mechanism. A summary of these fundamental principles is provided in Table 1 and of the guidelines for the four mechanistic stages of SCC in Tables 2-5. For the sake of clarity, only a few references to the original literature are given in the main text. Interested readers can identify the original studies by identifying the R&D Guideline(s) associated with the given SCC Guideline from Appendix D, from which the reference to the original work (summarized in Appendix A) can be obtained from Appendix B.

Guideline H-0-1: High-pH SCC can be described by a slip dissolution mechanism.

Slip dissolution is also referred to as the film rupture-anodic dissolution mechanism. This mechanism implies that crack-tip strain, an environment in which the steel is marginally passive, and a potential within a certain cracking range are required for SCC. As discussed in more detail in below, these mechanistic requirements result in useful environmental and mechanical loading factors for identifying SCC sites and estimating re-inspection intervals.

Guideline H-0-2: Elevated temperature is a major contributing factor in many aspects of high-pH SCC.

Increasing temperature increases the rate of coating deterioration and disbondment, leads to the evaporative concentration of the trapped electrolyte, results in an increase in CO_2 generation rate in the soil, causes an increase in crack growth rate, shifts the potential at which the maximum crack growth rate occurs to a value closer to that for protected pipe, and increases the range of potential over which cracking is possible. Identifying locations of elevated temperature is a useful selection criterion for high-pH SCC sites.

Table 1: Fundamental Principles of High-pH SCC.

Number	Fundamental Principles of High-pH SCC
H-0-1	High-pH SCC can be described by a slip dissolution mechanism.
H-0-2	Elevated temperature is a major contributing factor in many aspects of high-pH SCC.
H-0-3	CO_2 is required to generate the concentrated carbonate-bicarbonate solution for cracking.
H-0-4	Coalescence of cracks is of fundamental importance to how high-pH SCC cracks grow.
H-0-5	The majority of the pipe lifetime is spent in Stages 1, 2, and 3 of the overall cracking process.
H-0-6	There is a continuum of cracking behaviour of pipeline steels in carbonate-bicarbonate environments.
H-0-7	Variability is inherent to many aspects of high-pH SCC.
H-0-8	There are two mechanistic approaches to lifetime prediction, one based on the micro-mechanical properties of the steel and the other on the kinetics of the slip dissolution mechanism.

Guideline H-0-3: CO_2 is required to generate the concentrated carbonate-bicarbonate solution for cracking.

Carbon dioxide is required to generate the high-pH environment responsible for passivation of the pipe surface. Any factor that affects the rate of CO_2 generation, such as the soil temperature and moisture content, is likely to affect the probability of high-pH SCC.

Guideline H-0-4: Coalescence of cracks is of fundamental importance to how high-pH SCC cracks grow.

Crack coalescence is responsible for the re-activation of dormant cracks and is a process that continues throughout much of the lifetime of the pipe. Prediction of re-inspection intervals should take into account the effects of coalescence.

Guideline H-0-5: The majority of the pipe lifetime is spent in Stages 1, 2, and 3 of the overall cracking process.

Based on the four stages of high-pH SCC illustrated in Figure 2, crack growth during Stage 4 is so fast that the effective pipeline lifetime is determined by the time required to reach the end of Stage 3. Therefore, pipeline operators should manage high-pH SCC by addressing issues that affect the rates of Stages 1, 2, and 3; namely: the development of the environment, crack initiation, and crack growth by continued initiation and crack coalescence, respectively.

Guideline H-0-6: There is a continuum of cracking behaviour of pipeline steels in carbonate-bicarbonate environments.

High-pH and near-neutral pH SCC are generally thought of as occurring under distinctly different environmental conditions. However, the intergranular cracking associated with high-pH SCC can occur over a much wider range of pH (pH 7-11) and potential than generally associated with this form of cracking.

Guideline H-0-7: Variability is inherent to many aspects of high-pH SCC.

Variation in soil and coating conditions affects the probability of developing a high-pH environment. Variation in loading conditions and micro-scale steel properties affect the probability of crack initiation and coalescence. These and other sources of variability result in a variation in effective crack growth rates. Variation in high-pH SCC behaviour in the field is to be expected and should be accounted for in any predictive model.

Guideline H-0-8: There are two mechanistic approaches to lifetime prediction, one based on the micro-mechanical properties of the steel and the other on the kinetics of the slip dissolution mechanism.

Existing models based on these approaches conservatively assume that the environmental conditions for high-pH SCC are present. The different methods require different types of input data, but both approaches can be used to predict re-inspection intervals or expected lifetimes.

3.1.2 Susceptibility

Guideline H-I-1: The probability of finding high-pH SCC increases with increasing temperature.

For gas pipelines, there is overwhelming field and R&D evidence that cracking severity is highest closet to the compressor station discharge, with most failures having occurred within 10 miles of the compressor station. Because they operate at lower temperatures, high-pH SCC is of little concern for conventional liquid lines, unless they are located in hotter climates or the product is heated to assist the flow characteristics.

Guideline H-1-2: The high-pH carbonate-bicarbonate environment can be generated by the evaporation of electrolyte on the hot pipe.

The evaporative concentration mechanism requires a soil-gas CO_2 concentration of between 0.1 and 5 vol.% to maintain the pH in the cracking range.

Guideline H-I-3: The application of CP is another major cause of the development of a high-pH carbonate-bicarbonate environment.

Formation of the high-pH environment via this mechanism requires a balance between the rate at which alkaline conditions are produced by the CP current and the rate at which these conditions can be transported away form the pipe surface through the permeable coating. This mechanism implies that the cracking environment will only form for certain combinations of CP current and coating quality that are likely to be line-specific.

Table 2: SCC Guidelines for High-pH SCC Susceptibility.

Number	High-pH SCC Guidelines - Susceptibility
H-I-1	The probability of finding high-pH SCC increases with increasing temperature.
H-I-2	The high-pH carbonate-bicarbonate environment can be generated by the evaporation of electrolyte on the hot pipe.
H-I-3	The application of CP is another major cause of the development of a high-pH carbonate-bicarbonate environment.
H-I-4	For cathodically protected pipe, the pipe must be inadequately protected for the potential to be within the range for cracking.
H-I-5	Maintenance of the high-pH carbonate-bicarbonate environment requires a sufficient and continuous source of CO_2.
H-I-6	Soils with high concentrations of sodium and potassium ions are required to support high-pH SCC.
H-I-7	Overprotection of the pipe can lead to the formation of H_2 bubbles that block the CP from reaching the pipe.
H-I-8	In general, the closer the off-potential is to -850 mV_{CSE} the more likely high-pH SCC becomes.
H-I-9	Under some circumstances, the -100 mV polarization criterion may not offer protection from high-pH SCC.
H-I-10	If CP is lost entirely, the potential can stay within the cracking range for periods of months.

continued …

Table 2: SCC Guidelines for High-pH SCC Susceptibility (concluded).

Number	High-pH SCC Guidelines - Susceptibility
H-I-11	The most important characteristics of the coating are the resistance to disbondment and the ability of CP to reach the pipe surface.
H-I-12	Seasonal or episodic changes in environmental and operating conditions can lead to changes in the cracking environment.
H-I-13	The different susceptibility of steels is associated with differences in their cyclic stress-strain behaviour.
H-I-14	Steels with uniform microstructures are less susceptible to high-pH SCC.
H-I-15	Pipes retaining the original surface finish are more susceptible than pipes that have a blasted surface.
H-I-16	The susceptibility to high-pH SCC increases with increasing cyclic loading.
H-I-17	There is a low probability of cracking at locations with mild cyclic loading.
H-I-18	Unlike near-neutral pH SCC, there is no evidence that stress raisers increase the probability of cracking.
H-I-19	High-pH SCC is unlikely to occur on liquid pipelines unless the fluid is heated or the line is located in a warmer region.

Guideline H-I-4: For cathodically protected pipe, the pipe must be inadequately protected for the potential to be within the range for cracking.

Adequate CP will shift the potential outside of the range for cracking. However, there are many mechanisms by which CP control can be partially or completely lost, including: iR drop in the coating due to the formation of H_2 bubbles or the precipitation of carbonate salts, periodic drying of the soil, or operational issues. Millscale can also polarize the pipe into the cracking range for certain CP current densities.

Guideline H-I-5: Maintenance of the high-pH carbonate-bicarbonate environment requires a sufficient and continuous source of CO_2.

Without a sufficient and continuous source of CO_2, the pH of the electrolyte will exceed the range for high-pH SCC. The rate of CO_2 formation increases with increasing soil temperature and moisture content, both of which may serve as indicators for high-pH SCC sites. Rapid transport of CO_2 to the pipe surface will occur in unsaturated, partially dry soils.

Guideline H-I-6: Soils with high concentrations of sodium and potassium ions are required to support high-pH SCC.

This guideline is a consequence of the fundamental chemical constraint that calcium and magnesium carbonates have limited solubility. The only means for developing a concentrated carbonate-bicarbonate solution is if Na and K are the dominant cations in the electrolyte. Soils with high (Na + K) concentrations are more likely to support high-pH SCC. The ratio of (Na + K) to (Ca + Mg) concentrations can also be a useful indicator, with higher ratios favouring high-pH SCC.

Guideline H-I-7: Overprotection of the pipe can lead to the formation of H_2 bubbles that block the CP from reaching the pipe.

Cathodic potentials more negative than -1.2 V_{CSE} can lead to the formation of H_2 bubbles that block the CP.

Guideline H-I-8: In general, the closer the off-potential is to -850 mV_{CSE} the more likely high-pH SCC becomes.

A potential of -850 mV_{CSE} is more negative than the range for cracking. As noted above, various factors can partially block the CP and shift the potential to within the cracking range. In addition, the cracking range shifts closer to -850 mV_{CSE} with increasing temperature.

Guideline H-I-9: Under some circumstances, the -100 mV polarization criterion may not offer protection from high-pH SCC.

The -100 mV polarization criterion may prevent high-pH SCC if the following conditions are met: FBE coating, a white or near-white surface finish, MAOP <40% SMYS, temperature of <35^{o}C, and a soil (Na + K) concentration of <0.01 mol/L. If all of these conditions are not met, then the possibility of high-pH SCC cannot be excluded.

Guideline H-I-10: If CP is lost entirely, the potential can stay within the cracking range for periods of months.

The native potential is more positive than the cracking range so the loss of CP should, theoretically, not result in cracking. However, upon interruption of the CP current, the potential slowly drifts through the cracking potential range and can be within the permissive range for periods of months.

Guideline H-I-11: The most important characteristics of the coating are the resistance to disbondment and the ability of CP to reach the pipe surface.

High-pH SCC is observed on all coating types, but is most commonly associated with asphalt and coal tar enamel, and, although it is generally considered to be shielding, PE tape. Properly applied FBE offers excellent resistance to disbondment and, as a consequence, to high-pH SCC.

Guideline H-I-12: Seasonal or episodic changes in environmental and operating conditions can lead to changes in the cracking environment.

Many locations exhibit seasonal or episodic variation in environmental conditions which may affect the nature of the pipe surface environment. Changes to operating conditions may also make cracking more or less likely. Therefore cracking may well not be continuous, a factor that should be taken into account when estimating re-inspection intervals.

Guideline H-I-13: The different susceptibility of steels is associated with differences in their cyclic stress-strain behaviour.

The cyclic stress-strain behaviour affects the probability of initation and the early-crack growth processes. Unfortunately, it is not possible to predict the cyclic stress-strain behaviour *a priori* but an industry database of material properties would help operators by summarizing data for different grades and vintages of steel from different manufacturers and even different mills.

Guideline H-I-14: Steels with uniform microstructures are less susceptible to high-pH SCC.

The uniform microstructures typical of modern TMCP produced steels appear to be less susceptible to high-pH SCC than mixed microstructure ferrite-pearlite steels. Coarser grain size also promotes cracking by promoting local microplasticity. Fine-grained weld material has also been found to be less susceptible to cracking.

Guideline H-I-15: Pipes retaining the original surface finish are more susceptible than pipes that have a blasted surface.

Millscale or rusted surfaces promote crack initation and help control the potential within the cracking range. This guideline implies that pipelines with over-the-ditch applied coatings are more susceptible to high-pH SCC than pipelines with mill-applied coating.

Guideline H-I-16: The susceptibility to high-pH SCC increases with increasing cyclic loading.

Both the magnitude and frequency of cyclic loading are of concern. Cyclic loading promotes cyclic softening and reduces the threshold stress for initiation. Even mild loading conditions, for example, a stress range of a few percent of the maximum load, can impact the cracking behaviour at sufficiently high stresses. High-pH SCC is more likely, therefore, closer to the compressor station where the maximum stress and stress range are higher and at any location with particularly aggressive cyclic loading.

Guideline H-I-17: There is a low probability of cracking at locations with mild cyclic loading.

Minimizing pressure fluctuations is one means to reduce the probability of cracking. It has been suggested that the probability of cracking is low for lines with a maximum stress of 72% SMYS and R values (the ratio of the minimum to maximum stress) of 0.90 or higher.

Guideline H-I-18: Unlike near-neutral pH SCC, there is no evidence that stress raisers increase the probability of cracking.

Whereas identifying the location of dents, gouges, and other sources of stress concentration can assist in locating near-neutral pH SCC, there is no evidence that these features are more prone to high-pH SCC than the pipe body.

Guideline H-I-19: High-pH SCC is unlikely to occur on liquid pipelines unless the fluid is heated or the line is located in a warmer region.

Because of the significant effect of elevated temperature on various aspects of the cracking process, high-pH SCC on liquid lines has historically been of limited concern.

3.1.3 Initiation

Guideline H-II-1: Cyclic loading promotes crack initiation.

Cyclic loading promotes microplastic deformation of the pipe surface and results in a decrease in the threshold stress for crack initation. Compared with the threshold stress under static loading, the threshold stress under cyclic loading decreases by 60-80 MPa for each 0.1 decrease in the stress ratio R. The threshold stress is independent of temperature and the electrolyte composition. A knowledge of the characteristics of cyclic loading allows operators to identify those locations where crack initiation is possible. Microscale variation in the mechanical properties of the steel leads to variation in the local threshold stress.

Guideline H-II-2: Under static loading, the threshold stress is approximately equal to the actual yield stress of the pipe.

Crack initiation is possible under static load, but requires some degree of plastic deformation and is only likely to occur in conjunction with high tensile residual stress and/or a stress raiser.

Guideline H-II-3: Higher operating pressures lead to a greater number of more-densely spaced cracks in a shorter time.

The propensity for crack initiation increases with increasing stress. Dense crack patches (defined as those with a circumferential crack spacing of less than 20% of the wall thickness) are a consequence of the extensive microplasticity at high stresses. However, many of these cracks may become dormant due to stress shielding by neighbouring cracks in dense crack patches.

Guideline H-II-4: The rate of crack initiation decreases with time.

The rate of crack initiation decreases with time due to stress shielding by existing cracks and work hardening associated with the cyclic loading. The number of initiated cracks, of course, continues to increase with time, albeit at a slower rate.

Table 3: SCC Guidelines for High-pH SCC Initiation.

Number	High-pH SCC Guidelines – Crack Initiation
H-II-1	Cyclic loading promotes crack initiation.
H-II-2	Under static loading, the threshold stress is approximately equal to the actual yield stress of the pipe.
H-II-3	Higher operating pressures lead to a greater number of more-densely spaced cracks in a shorter time.
H-II-4	The rate of crack initiation decreases with time.
H-II-5	Grit-blasted surfaces exhibit a higher threshold stress.

Guideline H-II-5: Grit-blasted surfaces exhibit a higher threshold stress.

The practical implication of this R&D finding is that pipelines with mill-applied coating should be less susceptible to crack initiation than pipelines coated in the field.

3.1.4 Early-stage Crack Growth and Dormancy

Guideline H-III-1: The crack growth rate decreases with time.

High-pH SCC cracks show a tendency to slow down with time. Cracks prefer to propagate in the near-surface layer because surface cracks are less constrained.

Guideline H-III-2: The maximum crack growth rate increases with strain rate.

Crack growth requires the rupture of the passive film at the crack tip and, in general, is a balance between the rate of film rupture and the rate of re-formation of this film. The faster the film is ruptured, the faster the crack grows, up to an upper limit at which point the crack tip is essentially permanently film free. On the other hand, at low strain rates, the film may re-form faster than it is ruptured and crack growth will effectively cease. It is difficult to relate the crack-tip strain rate to specific operating conditions. However, the slower the increase in pressure the slower the crack growth rate is likely to be. Locations with higher loading rates should exhibit faster crack growth.

Guideline H-III-3: The majority of cracks will become dormant at some stage in their growth.

Cracks may become dormant for a number of reasons, including stress shielding by neighbouring cracks, the rate of film formation exceeding the rate of film rupture, or the strain rate decreasing as the crack encounters stiffer material beneath the outer surface layer. Regardless, crack dormancy is a normal part of the growth of the crack and should be accounted for in models used to estimate re-inspection intervals.

Guideline H-III-4: Various factors can prevent cracks from becoming dormant.

Cracks in sparse crack patches (defined as areas of cracks where the circumferential crack spacing is greater than 20% of the wall thickness) are unlikely to experience stress shielding by their neighbours and will continue to grow. Unload/reload cycles can also prevent cracks from becoming dormant and could serve as an indicator of high-pH SCC sites.

Table 4: SCC Guidelines for High-pH SCC Early-stage Crack Growth and Dormancy.

Number	High-pH SCC Guidelines – Early-stage Crack Growth and Dormancy
H-III-1	The crack growth rate decreases with time.
H-III-2	The maximum crack growth rate increases with strain rate.
H-III-3	The majority of cracks will become dormant at some stage in their growth.
H-III-4	Various factors can prevent cracks from becoming dormant.
H-III-5	Dormant cracks can be reactivated.
H-III-6	Coalescence of cracks promotes continued crack growth.

Guideline H-III-5: Dormant cracks can be reactivated.

Just as dormancy is a normal part of crack growth, so too is reactivation of dormant cracks. The most common cause of reactivation is coalescence with a growing crack. In the case of dormant cracks in a dense crack patch, only those cracks around the periphery are likely to start growing as those in the centre will still be shielded by their close neighbours.

Guideline H-III-6: Coalescence of cracks promotes continued crack growth.

Coalescence is the major factor in continued crack growth and occurs when the tips of growing cracks, or one growing and one dormant crack, pass each other and are within a threshold circumferential spacing. That threshold spacing is 0.14 times the length of the crack and is determined by mechanical factors, rather than environmental or material-dependent properties.

3.1.5 Late-stage Crack Growth

Guideline H-IV-1: Beyond a certain threshold, cracks enter Stage 4 of the overall cracking process.

Beyond a threshold stress intensity factor of 20-25 MPa√m or a surface length of ~6 mm, cracks enter the fourth and final stage of the cracking process (Figure 2). Crack growth can be rapid in Stage 4 if the strain rate is high enough to maintain a film-free crack tip. Repassivation of the crack tip at slower strain rates will result in lower crack growth rates. However, management of cracks in Stage 4 is difficult because of the relatively rapid cracking.

Guideline H-IV-2: Cracking becomes more severe with increasing temperature.

Increasing temperature increases the crack growth rate, increases the range of potentials at which cracking is possible, and shifts the potential of maximum crack growth rate to more-negative values, i.e., closer to that for cathodically protected pipe. Therefore, the deepest cracks will be found at locations with elevated temperature, for example, close to the compressor station discharge.

Guideline H-IV-3: Cracking occurs in a range of potentials.

Cracking occurs within a range of potentials that is a function of temperature and electrolyte composition. The crack growth rate is zero outside this range. If the pipe surface potential is known or can be estimated based on CP information then it is possible to identify which parts of the line are susceptible to cracking. Account must be taken of the possibility of voltage drop through the coating or along the coating disbondment.

Table 5: SCC Guidelines for High-pH SCC Late-stage Crack Growth.

Number	High-pH SCC Guidelines – Late-stage Crack Growth
H-IV-1	Beyond a certain threshold, cracks enter Stage 4 of the overall cracking process.
H-IV-2	Cracking becomes more severe with increasing temperature.
H-IV-3	Cracking occurs in a range of potentials.
H-IV-4	The crack growth rate depends on the composition of the electrolyte.
H-IV-5	The crack growth rate in Stage 4 is independent of the pipeline steel properties.

Guideline H-IV-4: The crack growth rate depends on the composition of the electrolyte.

The peak crack growth rate increases with increasing electrolyte concentration and the potential corresponding to the maximum rate shifts to more-positive potentials. The cracking potential range shifts to more-negative values with increasing pH. It is unlikely that pipeline operators will know the electrolyte composition on the pipe surface, in which case the use of data from the literature based on a standard 1N-1N carbonate-bicarbonate solution is likely to be conservative. Field electrolytes tend to be more dilute than the standard laboratory solution.

Guideline H-IV-5: The crack growth rate in Stage 4 is independent of the pipeline steel properties.

The crack growth rate in Stage 4 is determined by environmental rather than material-related properties. As such, there is no effect of steel composition or microstructure on the corrosion rate.

3.2 NEAR-NEUTRAL pH SCC

Near-neutral pH SCC was first recognized as a separate form of external pipeline SCC in Canada in the 1970's and 1980's. Since that time it has been reported in many other countries, including the United States. The characteristics of near-neutral pH SCC include (NEB 1996):

- 65% of failures have occurred between the compressor station and first downstream valve (16-30 km), 12% between 1^{st} and 2^{nd} valves, 5% between 2^{nd} and 3^{rd} valves, and 18% downstream of 3^{rd} valve.
- SCC is associated with specific terrain conditions, alternating wet-dry soils, and soils that tend to disbond or damage coatings.
- There is no apparent correlation with temperature.
- The electrolyte under the disbonded coating is a dilute HCO_3^- solution with pH in the range 5.5 to 7.5.
- Cracking occurs at the free corrosion potential, -760 to -790 mV($Cu/CuSO_4$).
- CP does not reach the pipe because of the presence of a shielding coating or some other factor.
- The crack morphology is primarily transgranular, typically with wide cracks and substantial corrosion of crack walls.

3.2.1 Fundamental Principles of Near-neutral pH SCC

These fundamental principles are overarching statements that either provide the user with a fundamental understanding of the overall process or apply to more than one stage in the cracking mechanism. A summary of the guidelines is provided in Table 6 and those for the four mechanistic stages of SCC in Tables 7-10. For the sake of clarity, only a few references to the original literature are given in the main text. Interested readers can identify the original studies by identifying the R&D Guideline(s) associated with the given SCC Guideline from Appendix D, from which the reference to the original work (summarized in Appendix A) can be obtained from Appendix B.

Guideline N-0-1: Near-neutral pH SCC occurs at (or within 10-20 mV) of the native potential (also referred to as the corrosion, free-corrosion (FCP), or open-circuit (OCP) potential).

This guideline serves a number of purposes. First, it helps define near-neutral pH SCC and distinguishes it from other forms of cracking that might, on first inspection, appear to be similar. For example, transgranular cracking can also result from hydrogen-induced cracking due to cathodic over-protection, especially for CP-permeable coatings, such as asphalt and coal-tar enamel. It is important to distinguish these different mechanisms as their management approaches differ. Second, as noted below under SCC Susceptibility, it helps define a (range of) value(s) for the native potential which can be used to assess susceptibility to cracking.

Guideline N-0-2: Unlike high-pH SCC, there is no apparent effect of temperature for near-neutral pH SCC.

Although there is strong field evidence that the frequency of SCC failures on gas pipelines decreases with increasing distance downstream of the compressor station, there is no indication that this is a result of an effect of temperature on the cracking process. This is consistent with the occurrence of near-neutral pH SCC on both gas and liquid lines, unlike the high-pH form of cracking which is known to be temperature-dependent and which is virtually unknown on liquid lines. From a practical viewpoint, this guideline confirms that the selection of near-neutral pH SCC sites based on any temperature-related factor would be misleading.

Guideline N-0-3: Cyclic loading is important for all aspects of near-neutral pH SCC, including crack initiation, early-stage growth and dormancy, and late-stage crack growth.

The importance of cyclic loading is such that cracking should not be observed on lines that operate under static or near-static loading conditions. In general, the magnitude of the various effects of cyclic loading increase with increasing stress range (or decreasing R value, where R is the ratio of the minimum to maximum stress during the cycle), increasing maximum stress, and increasing cycle frequency.

Guideline N-0-4: Near-neutral pH SCC requires the presence of CO_2, but the occurrence of cracking is independent of the concentration of CO_2.

The overwhelming evidence from the R&D literature is that CO_2 is necessary for this form of cracking, but there is no evidence that the occurrence or severity of cracking is related to the concentration of CO_2. This observation has mechanistic implications (e.g., the most likely role of CO_2 is to buffer the pH of the trapped electrolyte and, possibly, that in the crack, but it does not participate directly in the cracking processes) and also has implications for site selection and the estimation of re-inspection intervals. For example, sites with higher rates of CO_2 generation (e.g., wetter sites or warmer sites on gas pipelines closer to the discharge of the compressor station) are no more likely to exhibit cracking than drier or cooler locations. In addition, such sites will not exhibit faster rates of cracking, although sites that periodically dry out could exhibit overall slower kinetics (or an increased probability of dormancy), considerations that could factor into the estimation of the re-inspection interval.

Table 6: Fundamental Principles of Near-neutral pH SCC.

Number	Fundamental Principles of Near-neutral pH SCC
N-0-1	Near-neutral pH SCC occurs at (or within 10-20 mV) of the native potential (also referred to as the corrosion, free-corrosion (FCP), or open-circuit (OCP) potential).
N-0-2	Unlike high-pH SCC, there is no apparent effect of temperature for near-neutral pH SCC.
N-0-3	Cyclic loading is important for all aspects of near-neutral pH SCC, including crack initiation, early-stage growth and dormancy, and late-stage crack growth.
N-0-4	Near-neutral pH SCC requires the presence of CO_2, but the occurrence of cracking is independent of the concentration of CO_2.
N-0-5	Near-neutral pH SCC is often found at locations where environmental conditions change with time, implying cracking need not be continuous.
N-0-6	The mechanism and management of SCC on gas and liquid lines may differ because of the difference in severity of cyclic loading.
N-0-7	On asphalt and coal-tar enamel coated lines, not all cases of transgranular cracking are necessarily near-neutral pH SCC.
N-0-8	Transition from near-neutral pH SCC to high-pH SCC is possible.
N-0-9	Hydrogen plays a role in both crack initiation and propagation.
N-0-10	The latter stages of crack growth are controlled by a corrosion fatigue mechanism.
N-0-11	All aspects of crack initiation and growth exhibit some degree of variability.

Guideline N-0-5: Near-neutral pH SCC is often found at locations where environmental conditions change with time, implying cracking need not be continuous.

This guideline is based on the results of an R&D study of environmental conditions at known near-neutral pH SCC field locations. It provides direct guidance for the selection of sites for investigative excavations on pipelines that are considered to be susceptible to cracking. Furthermore, because cracking may not occur during periods when the environmental conditions are unsuitable, predictions of the re-inspection interval based on the assumption of continuous crack growth will be conservative.

Guideline N-0-6: The mechanism and management of SCC on gas and liquid lines may differ because of the difference in severity of cyclic loading.

Liquid pipelines typically exhibit larger and more frequent pressure fluctuations than gas pipelines, both because of the difference in fluid compressibility and the tendency to operate some liquid lines in batch mode. As a consequence, mechanically driven crack growth is more-important for liquid lines. For gas lines, a greater fraction of crack growth is supported by environmental, rather than mechanical, factors. The growth characteristics of mechanically short (shallow) cracks is more important for gas lines. Therefore, although the control of pressure fluctuations is important regardless of the product being shipped, liquid operators should pay special attention to loading conditions, both for mitigating the severity of SCC and for identifying SCC DA sites and estimating re-inspection intervals.

Guideline N-0-7: On asphalt and coal-tar enamel coated lines, not all cases of transgranular cracking are necessarily near-neutral pH SCC.

As noted above, transgranular cracking on lines with CP-permeable coating may be due to hydrogen-induced cracking rather than near-neutral pH SCC. Recognition of the differences between these two forms of cracking is important since the two forms of cracking are managed differently.

Guideline N-0-8: Transition from near-neutral pH SCC to high-pH SCC is possible.

Although near-neutral pH and high-pH SCC cracking are thought of as different mechanisms, from an electrochemical point-of-view there is relatively little difference between the environments associated with the two forms of cracking. It is feasible that modest increases in CP levels could convert a near-neutral pH environment to a high-pH environment. This possibility has implications both for the management of the SCC threat and the identification of SCC sites.

Guideline N-0-9: Hydrogen plays a role in both crack initiation and propagation.

There is overwhelming evidence in the R&D literature for a primary role of absorbed hydrogen in the cracking mechanism. This observation is not just of academic interest. Through an understanding of the factors that lead to increased hydrogen absorption, such as the presence of sulphide species or SRB, excessive levels of CP, or high stress, operators can learn to identify sites of increased likelihood of crack initiation and growth or to avoid operating practices that lead to greater hydrogen absorption.

Guideline N-0-10: The latter stages of crack growth are controlled by a corrosion fatigue mechanism.

Mechanistic understanding is important so that conditions that could lead to more-rapid crack growth can be avoided. During the latter stages of crack growth, the magnitude of the stress range, the maximum stress, and the frequency of the pressure cycles all affect the rate of crack growth, with the former being the most important parameter. Identification of locations or pipelines with large, frequent pressure cycles can be used to identify possible SCC sites. Alternatively, avoidance of such conditions can be used to manage the cracking threat.

Guideline N-0-11: All aspects of crack initiation and growth exhibit some degree of variability.

An important consequence of this inherent variability of the cracking process is that a definitive crack growth rate or re-inspection interval is difficult to define. Predictions should take into account the inevitable variation in observed behaviour and be probabilistically based.

3.2.2 Susceptibility

Guideline N-I-1: The native potential must be below the H_2/H_2O equilibrium line which, for most soils, is in the range -670 to -790 mV_{CSE}.

This guideline is associated with the fundamental principle that hydrogen is involved in crack initiation and growth, since it defines the electrochemical potential below which hydrogen can be produced and absorbed by the steel. Comparison of native potentials to this threshold will indicate whether a particular pipeline, or which segments of the line, are susceptible. The native potential does not need to be below this threshold value continuously. In acidic soils the threshold potential is more positive than in alkaline soils (within the range of values given above).

Table 7: SCC Guidelines for Near-neutral pH SCC Susceptibility.

Number	Near-neutral pH SCC Guidelines – Susceptibility
N-I-1	The native potential must be below the H_2/H_2O equilibrium line which, for most soils, is in the range -670 to -790 mV_{CSE}.
N-I-2	No single soil species or property determines the overall SCC susceptibility.
N-I-3	Site selection should take into account multiple contributing factors rather than rely only on one or two indicative parameters.
N-I-4	On one particular line, no SCC was found at locations with a soil resistivity greater than 14,000 ohm·cm.
N-I-5	There is no conclusive proof that microbes play a role in near-neutral pH SCC.
N-I-6	The pH associated with near-neutral pH SCC is inconsistent with significant CP reaching the pipe surface.
N-I-7	Certain electrolytes maintain a sharp crack tip and promote crack growth.
N-I-8	The only coating that appears to offer resistance to near-neutral pH SCC is fusion bonded epoxy (FBE).
N-I-9	The presence of stress raisers promotes both crack initiation and growth.
N-I-10	On liquid lines, the occurrence of large amplitude, high-frequency pressure fluctuations promotes mechanically driven initiation and crack growth.
N-I-11	The incidence of near-neutral pH SCC correlates with areas of high tensile residual stress.
N-I-12	Dents lead to high local stresses and can promote near-neutral pH SCC.

continued ….

Table 7: SCC Guidelines for Near-neutral pH SCC Susceptibility (concluded).

Number	Near-neutral pH SCC Guidelines – Susceptibility
N-I-13	While cyclic loading in general promotes near-neutral pH SCC, certain loading patterns are particularly dangerous.
N-I-14	When selecting SCC sites based on stress considerations, all sources of stress need to be taken into account.
N-I-15	The presence of cold work promotes near-neutral pH SCC.
N-I-16	Modern steels appear to be less susceptible than older ferrite-pearlite steels.
N-I-17	All grades of older ferrite-pearlite steel appear to be susceptible to near-neutral pH SCC.
N-I-18	The presence of millscale on the pipe surface increases susceptibility to near-neutral pH SCC.
N-I-19	Electric resistance welded (ERW) pipe is particularly susceptible to near-neutral pH SCC.
N-I-20	Low-temperature creep is an important process in various stages of cracking.

Guideline N-I-2: No single soil species or property determines the overall SCC susceptibility.

Although it would be desirable to identify a major contributing factor that could be used to identify SCC sites, the R&D literature does not identify such a parameter. Furthermore, because of the multivariate nature of the cracking mechanism, it is highly unlikely that such a key parameter would exist.

Guideline N-I-3: Site selection should take into account multiple contributing factors rather than rely only on one or two indicative parameters.

In line with the previous guideline, site selection should be based on a consideration of all of the environmental, stress-related, and material-related parameters that contribute to crack initiation and growth.

Guideline N-I-4: On one particular line, no SCC was found at locations with a soil resistivity greater than 14,000 ohm·cm.

Notwithstanding the previous two guidelines, the only possible soil parameter that has been found to correlate, in this case, to the absence of SCC is soil resistivity. The exact value of the soil resistivity above which SCC does not occur may vary and there will be exceptions to the value quoted above. However, as a guiding principle, higher soil resistivity correlates with a lack of moisture to support the electrochemical processes involved in cracking.

Guideline N-I-5: There is no conclusive proof that microbes play a role in near-neutral pH SCC.

However, the requirement for CO_2 and the fact that sulphide promotes hydrogen entry suggest that microbial <u>activity</u> may be important. There is no correlation between the microbial <u>population</u> and SCC.

Guideline N-I-6: The pH associated with near-neutral pH SCC is inconsistent with significant CP reaching the pipe surface.

Where CP can penetrate under disbonded coating it is likely to suppress cracking, primarily because the pH will shift outside of the range for cracking.

Guideline N-I-7: Certain electrolytes maintain a sharp crack tip and promote crack growth.

For reasons that are not currently understood, certain electrolytes have been found to maintain a sharp crack tip and promote cracking. Additional R&D may identify the reason for this observation and help identify sites where such electrolytes exist.

Guideline N-I-8: The only coating that appears to offer resistance to near-neutral pH SCC is fusion bonded epoxy (FBE).

The superior resistance provided by FBE coating is both because it allows CP to penetrate to the pipe surface and because the surface preparation required for its application minimizes the probability of crack initiation.

Guideline N-I-9: The presence of stress raisers promotes both crack initiation and growth.

Many near-neutral pH SCC failures have been associated with features, such as dents, areas of corrosion, bends, wrinkles, etc., that cause an increase in stress. By identifying where such features are present and the degree to which they concentrate the stress, pipeline operators can improve the probability of identifying SCC sites.

Guideline N-I-10: On liquid lines, the occurrence of large amplitude, high-frequency pressure fluctuations promotes mechanically driven initiation and crack growth.

Control of such fluctuations could be used to manage SCC and a knowledge of their distribution on the system and their magnitude and frequency can be used to identify SCC sites and estimate the rate of crack growth, respectively.

Guideline N-I-11: The incidence of near-neutral pH SCC correlates with areas of high tensile residual stress.

Tensile residual stress promotes crack initiation and can counter the tendency for cracks to become dormant.

Guideline N-I-12: Dents lead to high local stresses and can promote near-neutral pH SCC.

Dents both impart residual stress and can act as a stress raiser due their geometry. In addition, rocks in constrained dents can shield CP and promote the formation of near-neutral pH SCC conditions.

Guideline N-I-13: While cyclic loading in general promotes near-neutral pH SCC, certain loading patterns are particularly dangerous.

Underload/reload, rapid loading, and variable loading cycles are more aggressive than uniform loading cycles of relatively constant frequency.

Guideline N-I-14: When selecting SCC sites based on stress considerations, all sources of stress need to be taken into account.

In addition to the hoop stress produced by the gas or liquid pressure, the magnitude and type of residual stress (tensile or compressive), external stresses (e.g., those due to unstable slopes), and the effect of stress raisers need to be considered.

Guideline N-I-15: The presence of cold work promotes near-neutral pH SCC.

Areas of cold work, such as may be introduced by mechanical damage during construction, will exhibit an increased susceptibility to cracking.

Guideline N-I-16: Modern steels appear to be less susceptible than older ferrite-pearlite steels.

There has been little direct comparison of the relative susceptibility of older and modern steels to near-neutral pH SCC, but what evidence is available seems to indicate a greater susceptibility for older steels. This lower susceptibility of newer steels is in addition to that resulting from the beneficial effects of surface preparation and the application of high-integrity coatings used on modern pipelines.

Guideline N-I-17: All grades of older ferrite-pearlite steel appear to be susceptible to near-neutral pH SCC.

Laboratory comparisons of the behaviour of different steels exhibit no systematic effect of steel chemistry on cracking. This is consistent with field observations that suggest all steel grades and compositions are susceptible.

Guideline N-I-18: The presence of millscale on the pipe surface increases susceptibility to near-neutral pH SCC.

Millscale has a number of possible effects, particularly on crack initiation. Laboratory tests invariably indicate that the original pipe surface is more susceptible than a polished surface.

Differences in the properties of millscale may explain why pipe from different sources but exposed to the same environmental conditions exhibit different susceptibility, although no definitive field data are available to support this suggestion.

Guideline N-I-19: Electric resistance welded (ERW) pipe is particularly susceptible to near-neutral pH SCC.

In laboratory studies, ERW pipe, especially samples taken from the weld heat-affected zone, have shown increased crack growth rates. ERW pipe also tends to exhibit lower fracture toughness.

Guideline N-I-20: Low-temperature creep is an important process in various stages of cracking.

Low-temperature creep of pipeline steels is promoted by cyclic loading. Creep has been suggested as a contributing factor to crack initiation, growth, and the onset of dormancy. Steels with different low-temperature creep properties would be expected to exhibit different cracking behaviour.

3.2.3 Initiation

Guideline N-II-1: Crack initiation requires some type of stress raiser.

Crack initiation appears to occur at stress levels equal to or greater than the specified minimum yield stress of the steel. Therefore, some form of stress raiser is required to initiate cracks under normal operating conditions and, possibly to induce localized plasticity. Such a stress raiser could result from a dent, wrinkle, bend, or other similar feature.

Guideline N-II-2: Cyclic loading, especially of higher frequency and larger amplitude, promotes initiation.

Cyclic loading may play several roles in the initiation of near-neutral pH SCC cracks. Given that a certain degree of cyclic loading occurs on all pipelines, the presence of cyclic loads is not necessarily a useful indicator of crack initiation, but it is apparent that the more severe the cyclic loading the more likely initiation is to occur.

Table 8: SCC Guidelines for Near-neutral pH SCC Initiation.

Number	Near-neutral pH SCC Guidelines – Crack Initiation
N-II-1	Crack initiation requires some type of stress raiser.
N-II-2	Cyclic loading, especially of higher frequency and larger amplitude, promotes initiation.
N-II-3	High levels of tensile residual stress promote crack initiation.
N-II-4	Pre-existing cracks influence crack initiation resulting in bands of cracks.
N-II-5	The probability of initiation is enhanced by the presence of millscale.
N-II-6	Steels with high inclusion content, especially manganese sulphide inclusions, are more susceptible to crack initiation.
N-II-7	The presence of martensite promotes crack initiation.
N-II-8	Crack initiation can occur near the edge of well-bonded coating.

Guideline N-II-3: High levels of tensile residual stress promote crack initiation.

Residual stress, added to the hoop stress from the gas or liquid pressure, can increase the total stress above the yield stress of the steel to promote the local plastic deformation that is a pre-requisite for crack initiation.

Guideline N-II-4: Pre-existing cracks influence crack initiation resulting in bands of cracks.

Crack initiation can be "directed" by existing cracks so that cracks form in bands. Directed initiation may result from preferential stress concentration just ahead of existing crack tips or from the local concentration of hydrogen produced by the growth of the existing crack.

Guideline N-II-5: The probability of initiation is enhanced by the presence of millscale.

Millscale promotes crack initiation via a number of mechanisms. Pipelines coated in the field will likely retain a millscale layer on the surface of the pipe, enhancing the probability of crack initiation. By inference, pipelines coated in the mill will be less susceptible to cracking.

Guideline N-II-6: Steels with high inclusion content, especially manganese sulphide inclusions, are more susceptible to crack initiation.

Cracks initiate preferentially at inclusions, especially MnS inclusions. The probability of crack initiation increases with increasing S content of the steel, although there is neither an absolute correlation between the S content and crack initiation nor a threshold S content above which cracking is more likely. However, it is clear from the evidence available, that pipeline steels with higher S contents are more likely to exhibit crack initiation.

Guideline N-II-7: The presence of martensite promotes crack initiation.

Areas of hardened martensitic microstructures are more sensitive to crack initiation. Hard spots introduced by mechanical damage or martensite introduced during improper welding procedures are possible areas of concern and should be identified when selecting sites for DA purposes.

Guideline N-II-8: Crack initiation can occur near the edge of well-bonded coating.

Although cracking is generally associated with disbonded coating, there is evidence that cracks can initiate under coating that is well bonded. Thus, provided there is a route by which electrolyte can reach the pipe surface, there is apparently no requirement for the coating to be physically disbonded from the pipe surface. In selecting sites for SCC DA, therefore, the degree of coating disbondment should be assigned a minimum weighting.

3.2.4 Early-stage Crack Growth and Dormancy

Guideline N-III-1: Factors that lead to higher absorbed hydrogen concentrations lead to an increase in crack growth rate.

This guideline is clearly mechanistically based and is directly related to the fundamental processes controlling crack growth. A wide range of factors, including the pH of the electrolyte, the stress level, the presence of a stress raiser, localized plastic strain, etc., can lead to increased hydrogen concentrations. Although it may be difficult for a pipeline operator to identify all of the factors that may lead to higher hydrogen concentrations, it is considered informative to provide this type of mechanistic understanding.

Guideline N-III-2: Unload/reload cycles can prevent dormancy, re-initiate dormant cracks, and accelerate active cracks.

Of the various types of loading to which a pipe may be exposed, unload/reload cycles are by far the most damaging. Although the number of such cycles is likely to be small and, hence, the accumulated extent of crack growth limited, such cycles can either prevent dormancy in the first place or cause dormant cracks to re-start. In either case, it is more likely that deeper cracks will be found in locations subject to a higher number of unload/reload cycles. Pipelines or pipe segments that experience more unload/reload cycles should be given priority for inspection over other lines and should be re-inspected more frequently.

Guideline N-III-3: The crack growth rate increases with increasing strain rate.

In addition to the number or amplitude of pressure cycles, there is evidence that the rate of pressure change also influences the rate of crack growth, especially for mechanically shorter (shallower) cracks. An understanding of the rate of pressure change can be used to identify lines or pipeline segments that may exhibit faster early-stage crack growth.

Guideline N-III-4: For deeper cracks and/or larger amplitude or higher frequency pressure fluctuations, crack growth is largely mechanically driven.

For liquid lines or for deep cracks on gas lines, the principle driving force for crack growth is the magnitude and frequency of pressure fluctuations. An analysis of SCADA pressure data can be used to prioritize pipelines for inspection and, if the variation in pressure fluctuations along the length of the pipe is known, be used to indicate specific locations of increased probability of crack growth.

Table 9: SCC Guidelines for Near-neutral pH SCC Early-stage Crack Growth and Dormancy.

Number	Near-neutral pH SCC Guidelines – Early-stage Crack Growth and Dormancy
N-III-1	Factors that lead to higher absorbed hydrogen concentrations lead to an increase in crack growth rate.
N-III-2	Unload/reload cycles can prevent dormancy, re-initiate dormant cracks, and accelerate active cracks.
N-III-3	The crack growth rate increases with increasing strain rate.
N-III-4	For deeper cracks and/or larger amplitude or higher frequency pressure fluctuations, crack growth is largely mechanically driven.
N-III-5	For mechanically shorter (shallower) cracks and/or smaller amplitude or lower frequency pressure fluctuations, crack growth is influenced more by the strain rate.
N-III-6	Environmental, rather than mechanical loading, conditions may determine the growth of mechanically short (shallow) cracks.
N-III-7	Mechanically short (shallow) cracks can grow below the threshold conditions for deeper cracks.
N-III-8	Factors that promote crack dormancy include: lower-amplitude, lower-frequency pressure fluctuations; the accumulation of corrosion products in cracks; changes in crack chemistry; an increase in the number of cracks; stress shielding due to dense crack spacing (defined as a circumferential spacing of less than 20% of the pipe wall thickness); crack-tip blunting by dissolution and/or creep; regions of compressive or reduced tensile residual stress; near-static loading; exhaustion of the supply of diffusible hydrogen; and harder pearlite grains.

continued …..

Table 9: SCC Guidelines for Near-neutral pH SCC Early-stage Crack Growth and Dormancy (concluded).

Number	Near-neutral pH SCC Guidelines – Early-stage Crack Growth and Dormancy
N-III-9	Factors that can re-activate dormant cracks include: unload/reload cycles, more-aggressive cyclic loading conditions, an increase in CO_2 level, an increase in the flux of diffusible hydrogen, or coalescence with growing cracks.
N-III-10	Environmental factors that promote early-stage crack growth include: the presence of sulphide or SRB activity, increased bicarbonate ion concentration, or increased CO_2.
N-III-11	Environmental factors that inhibit early-stage crack growth include: organics.
N-III-12	High tensile residual stress promotes crack growth and prevents dormancy.
N-III-13	Near-neutral pH SCC on gas transmission pipelines is likely to involve repeated cycles of crack growth and dormancy.
N-III-14	Cracks in sparse patches are more likely to continue to grow than densely spaced cracks.
N-III-15	Cracks coalesce if their circumferential spacing is less than 0.14 of their length.

Guideline N-III-5: For mechanically shorter (shallower) cracks and/or smaller amplitude or lower frequency pressure fluctuations, crack growth is influenced more by the strain rate.

The corollary to the previous guideline is that environmental factors are proportionately more important for the early-stage growth of mechanically short (shallow) cracks or for smaller amplitude or lower frequency pressure fluctuations. Consequently, when selecting SCC sites with suspected short (shallow) cracks, especially on gas lines, both environmental and mechanical loading conditions should be taken into account.

Guideline N-III-6: Environmental, rather than mechanical loading, conditions may determine the growth of mechanically short (shallow) cracks.

The nature of the environmental factors influencing short crack growth behaviour has not yet been investigated. However, there is evidence that mechanical loading conditions are not the only factor to consider in identifying SCC sites for short cracks.

Guideline N-III-7: Mechanically short (shallow) cracks can grow below the threshold conditions for deeper cracks.

Thresholds are useful for identifying conditions under which, in this case, crack growth does not occur. Although a threshold value has been established for the growth of deeper near-neutral pH SCC cracks, such a threshold does not apply to the mechanically short cracks of relevance during early-stage growth.

Guideline N-III-8: Factors that promote crack dormancy include: lower-amplitude, lower-frequency pressure fluctuations; the accumulation of corrosion products in cracks; changes in crack chemistry; an increase in the number of cracks; stress shielding due to dense crack spacing (defined as a circumferential spacing of less than 20% of the pipe wall thickness); crack-tip blunting by dissolution and/or creep; regions of compressive or reduced tensile residual stress; near-static loading; exhaustion of the supply of diffusible hydrogen; and harder pearlite grains.

Understanding the factors that promote dormancy is important for prioritizing pipelines or pipe segments for inspection and for estimating re-inspection intervals. Many of the factors that lead to dormancy are difficult to detect or identify. However, the tendency for cracks to become dormant is strongly related to the frequency and magnitude of the pressure fluctuations, with dormancy promoted by smaller amplitude, low-frequency loading.

Guideline N-III-9: Factors that can re-activate dormant cracks include: unload/reload cycles, more-aggressive cyclic loading conditions, an increase in CO_2 level, an increase in the flux of diffusible hydrogen, or coalescence with growing cracks.

Pipelines may not need to be re-inspected, or at least, not re-inspected as frequently, if cracks have been shown to be dormant. In such a case, however, it is important to understand what factors may re-activate the cracks. The most readily identifiable conditions that may lead to the re-activation of dormant cracks relate to the loading conditions, with unloading/reloading events of particular concern. Such events, especially if coupled with generally more-aggressive cyclic loading conditions, could require the re-establishment of an inspection program on a line on which cracks had previously been considered dormant.

Guideline N-III-10: Environmental factors that promote early-stage crack growth include: the presence of sulphide or SRB activity, increased bicarbonate ion concentration, or increased CO_2.

Identifying environmental factors at pipe depth from above-ground observations can be difficult. Consequently, although it is possible to identify environmental parameters that promote early-stage crack growth in the lab, it is not necessarily easy to identify such conditions in the field. Nevertheless, it is important to identify what conditions may be responsible for crack growth in case such detailed information is, or becomes, available to pipeline operators.

Guideline N-III-11: Environmental factors that inhibit early-stage crack growth include: organics.

Some organics have been shown to inhibit early-stage crack growth in laboratory tests. In other tests, either no effect or an accelerating effect has been observed, although on balance organics appear most likely to inhibit crack growth, especially if the pipe is surrounded by an organic soil layer.

Guideline N-III-12: High tensile residual stress promotes crack growth and prevents dormancy.

The incidence of SCC colonies has been associated with areas of high tensile residual stress, with measurements of the stress distribution showing tensile stresses down to depths of at least 2 mm. Such stresses (of the order of 200 MPa) appear to be sufficient to promote early-stage crack growth and prevent dormancy. Background knowledge of the level of residual stress could be a useful indicator of where to locate SCC.

Guideline N-III-13: Near-neutral pH SCC on gas transmission pipelines is likely to involve repeated cycles of crack growth and dormancy.

Pressure fluctuations on gas pipelines tend to exhibit high R values (small stress ranges) and low loading/unloading frequencies. Such conditions tend to promote dormancy. Consequently, it is likely that cracks propagate, become dormant, and are then re-activated. Identifying operating conditions that re-activate dormant cracks could be an effective way to locate near-neutral pH SCC.

Guideline N-III-14: Cracks in sparse patches are more likely to continue to grow than densely spaced cracks.

Closely spaced cracks shield neighbouring cracks from the effects of stress. More-widely spaced cracks, therefore, are more likely to grow. The division between dense and sparse spacing is taken to be a circumferential distance equivalent to 20% of the pipe wall thickness. If a prior direct examination has shown only dense crack patches then it might be reasonable to extend the time between re-inspections.

Guideline N-III-15: Cracks coalesce if their circumferential spacing is less than 0.14 of their length.

Crack coalescence is an important characteristic of both high-pH and near-neutral pH SCC. For near-neutral pH SCC coalescence can re-activate dormant cracks and affect the crack aspect ratio. Cracks will coalesce when their growing crack tips pass one another provided the circumferential spacing (y) is less than 0.14(2a), where 2a is the axial crack length. Knowledge of the crack spacing and the probability of coalescence from prior direct examinations will influence the estimation of the re-inspection interval.

3.2.5 Late-stage Crack Growth

Guideline N-IV-1: Stress raisers, such as dents, increase the crack growth rate.

Stress raisers increase the effective amplitude of the pressure cycles. Residual stress adds to the stress caused by the pressure in the pipe, whereas geometrical stress raisers, such as dents or areas of corrosion, multiply the level of stress. Locating areas of high residual stress or of geometrical defects will assist in identifying locations of deep cracking.

Guideline N-IV-2: On liquid lines, the greater number of large-amplitude, high-frequency pressure fluctuations enhance mechanically driven crack growth.

The incompressibility of liquids results in higher-frequency cycles and the nature of the fluid and mode of operation (e.g., batching) can lead to higher-amplitude fluctuations. Both of these factors have been shown to increase the growth rate of deeper cracks. Identifying lines subject to such loading conditions will help prioritize lines for inspection and, if local contributing factors can also be identified (e.g., location with respect to the pump station), could also be useful for site selection.

Guideline N-IV-3: On gas lines, the majority of damage is caused by a few high-amplitude pressure fluctuations.

For deeper cracks which are largely mechanically driven, the smaller number of high-amplitude cycles means that a relatively few cycles are responsible for the majority of damage. Identifying where these large fluctuations occur and when can assist in the prioritization of lines for inspection and the estimation of re-inspection intervals.

Guideline N-IV-4: Both the frequency and amplitude of pressure fluctuations are important in determining the rate of late-stage crack growth.

The corrosion fatigue mechanism thought to be responsible for the late-stage growth of near-neutral pH SCC is dependent on both the magnitude and frequency of cyclic loading. Therefore, the number and size of pressure fluctuations should be taken into account when selecting sites for inspection or estimating when to re-inspect a line.

Guideline N-IV-5: Variable amplitude cyclic loading is more damaging than relatively constant amplitude pressure cycles.

The mode of operation of a line may influence the late-stage crack growth rate. A line that experiences fluctuations of different magnitudes will exhibit a higher crack growth rate than a line that experiences relatively constant magnitude pressure fluctuations. Examination of pressure histories will indicate the nature of the pressure fluctuations and should be used in selecting lines or pipe segments for inspection.

Guideline N-IV-6: Unload/reload cycles promote crack growth.

Unloading and reloading cycles are particularly damaging, especially if the pressure is rapidly ramped. Lines experiencing such cycles should be inspected for SCC more frequently than lines that experience a relatively constant pressure regime.

Table 10: SCC Guidelines for Near-neutral pH SCC Late-stage Crack Growth.

Number	Near-neutral pH SCC Guidelines – Late-stage Crack Growth
N-IV-1	Stress raisers, such as dents, increase the crack growth rate.
N-IV-2	On liquid lines, the greater number of large-amplitude, high-frequency pressure fluctuations enhance mechanically driven crack growth.
N-IV-3	On gas lines, the majority of damage is caused by a few high-amplitude pressure fluctuations.
N-IV-4	Both the frequency and amplitude of pressure fluctuations are important in determining the rate of late-stage crack growth.
N-IV-5	Variable amplitude cyclic loading is more damaging than relatively constant amplitude pressure cycles.
N-IV-6	Unload/reload cycles promote crack growth.
N-IV-7	Underload/reload cycles promote crack growth.
N-IV-8	Overloads inhibit subsequent crack growth.
N-IV-9	Cracking occurs during the loading half of the pressure cycle.
N-IV-10	Cracks in sparse crack patches are more likely to continue to grow than cracks in dense patches.
N-IV-11	The presence of sulphide enhances crack growth.
N-IV-12	Organics can suppress crack growth.

Guideline N-IV-7: Underload/reload cycles promote crack growth.

Underloading without complete unloading is also damaging. Thus, a pipe does not have to experience a complete unload in order to experience accelerated cracking due to the mode of operation. Lines which operate at a constant maximum stress but which experience periodic underloads would be expected to exhibit a higher probability of SCC than a line that operates at near-constant load.

Guideline N-IV-8: Overloads inhibit subsequent crack growth.

Overloads, as experienced during hydrotesting, reduce the rate of subsequent crack growth. Any pipelines that experience overloads as a part of normal service would be expected to exhibit slower crack growth than lines that operate at near-constant load.

Guideline N-IV-9: Cracking occurs during the loading half of the pressure cycle.

This guideline is important if the loading/unloading cycle is asymmetrical. Since the crack growth rate increases with increasing frequency faster loading would be expected to result in more crack growth per cycle than slower loading. Examination of the time-dependent pressure fluctuations will indicate the relative rates of loading and unloading.

Guideline N-IV-10: Cracks in sparse crack patches are more likely to continue to grow than cracks in dense patches.

Cracks in sparse crack patches (defined as a circumferential crack spacing greater than 20% of the wall thickness) are less likely to experience stress shielding by neighbouring cracks and will continue to grow. Observations from prior direct examinations will indicate the crack spacing and should be taken into account in planning re-inspections.

Guideline N-IV-11: The presence of sulphide enhances crack growth.

Sulphide ions promote the absorption of hydrogen by the steel. Although it is difficult to identify the environment at the pipe surface, any indications of anaerobic microbial activity should be taken as an indication of possible enhanced crack growth.

Guideline N-IV-12: Organics can suppress crack growth.

As noted for the early-stage crack growth phase, organics generally inhibit crack growth. Although the presence of organics can be used as one input into the site selection process, this should not be used as a primary indicator of the absence of deep cracks.

4. IMPLEMENTATION OF THE GUIDELINES

Section 4 describes various ways in which pipeline companies can implement these guidelines. The ways in which the guidelines can be used to identify the location of SCC sites and to estimate re-inspection intervals are described in Sections 4.1.1 and 4.1.2, respectively. In Section 4.2, the current SCC Guidelines are compared with existing approaches in various industry standards and recommended practices. Finally, the ways in which an operator can incorporate these guidelines into their in-house procedures and the types of information that they will require to do so are described in Section 4.3.

4.1 USE OF THE GUIDELINES

4.1.1 Identification of SCC Sites

In order to help implement the SCC Guidelines described in the previous Section, the Guidelines are grouped here according to the process or factor to which they refer or based on the type of analysis that is required for their implementation. No single process or factor alone indicates locations of highest probability of finding SCC, but together they can be used to develop an overall “picture” of susceptibility. It is clear, however, that some factors are more important than others in determining the probability of SCC. Therefore, implementation will require that some form of ranking or weighting factor be applied. No attempt is made here to develop such a weighting system since it is likely that such weighting will be pipeline specific. In some cases the analysis will result in a quantitative assessment, in others only a qualitative measure of susceptibility. These different approaches must also be taken into account in the overall ranking method developed for a specific pipeline.

Because of their underlying technical basis, many of the guidelines require specific input data that may not always be readily available. Pipeline operators should make use of information available from other disciplines, such as information on groundwater chemistry from the environmental science literature or data on CO_2 generation from climate change or agricultural studies. State and other local sources of environmental and agricultural data may represent relatively low-cost sources of useful input data.

4.1.1.1 High-pH SCC

Table 11 summarizes the various processes and factors that can be used to identify locations of increased probability of high-pH SCC. For each process or factor, the table lists the associated SCC Guidelines, describes the nature of the analyses that need to be performed and the input data required, and provides a commentary on the application of the derived information.

Table 11: Identification of High-pH SCC Sites.

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Temperature	H-0-2 H-I-1 H-I-2 H-IV-2	Predict temperature as a function of distance downstream of the compressor station. Requires time-dependent gas-discharge T and suitable algorithm for predicting decay in T with distance.	Susceptibility to high-pH SCC increases with increasing T. Allows regional-scale prioritization based on discharge T and local site selection based on predicted distance-dependent T.
Cathodic protection: generation of environment	H-I-3	Qualitative comparison of CP current demand and coating quality. Need coatings database.	Based on concept that generation of permissive environment is a balance between rate of generation (by CP) and rate of loss through degraded coating.
Cathodic protection: potential for cracking	H-I-4 H-I-7 H-I-8 H-I-10 H-IV-3	Comparison of pipe potential based on test-lead or CIS data and potential ranges for SCC. Need to account for possible IR drop in coating. If CP is lost, need to know native potential.	Combined with effect of temperature, useful for identifying specific locations with increased probability of cracking conditions.
Cathodic protection: -100 mV criterion	H-I-9	Assess against specific risk factors in SCC Guideline H-I-9.	Useful for assessing susceptibility if -100 mV polarization criterion is being used.
Coatings	H-I-11 H-I-15 H-II-5	Knowledge of coating type and whether it was mill- or field-applied. For more-detailed assessments, require knowledge of coating porosity, impedance, or breakdown factor.	Can be used as a high-level screening tool or, where detailed knowledge of coating quality is available, as part of a quantitative analysis of the pipe-surface environment.

Continued ….

Table 11: Identification of High-pH SCC Sites (continued).

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Cracking environment: soluble cations	H-I-6 H-IV-4	Knowledge of groundwater composition, particularly of cations (Na^+, K^+, Ca^{2+}, Mg^{2+}), either from field excavations or from local agricultural or other sources.	Development of high-pH environment requires predominance of Na^+ and K^+. Can be used to predict regional susceptibility based on soil type.
Cracking environment: CO_2 generation	H-0-3 H-I-5	Rate of CO_2 generation depends primarily of soil T and moisture content. Temperature data should be readily available. Soil moisture content may be available from local agricultural resources or possible to use surrogates, such as drainage.	Reasonable to expect that probability of cracking increases with rate of CO_2 generation. Could be used for local and/or regional site selection.
Cracking environment: transient conditions	H-I-2	Identify locations or regions where the environmental conditions change, both in time and along the length or circumference of the pipe (e.g., waterways, soil transitions, large seasonal variations).	Increase (or decrease) in T could indicate an increased (or decreased) probability of SCC. Transitional sites could correspond with inadequate CP.
Operating pressure and cyclic loading	H-I-16 H-I-17 H-II-1 H-II-2 H-II-5 H-III-2 H-III-4	Analysis of SCADA pressure fluctuations to determine number, frequency, and magnitude of pressure cycles. Analysis to determine hoop strain rate, especially for loading half of cycle. Identify unload/reload events.	In general, cracking severity increases with increasing frequency and severity of cyclic loading. Absence of aggressive loading could indicate low SCC probability. However, loading conditions are apparently not as significant as for near-neutral pH SCC.
Stress raisers	H-I-18	Identify location of stress raisers, such as dents, gouges, other forms of mechanical damage.	Unlike near-neutral pH SCC, no significant link between stress raisers and high-pH cracking, although could indicate coating damage.

Continued …..

Table 11: Identification of High-pH SCC Sites (concluded).

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Steel properties	H-I-13 H-I-14 H-I-15 H-IV-5	Mill reports of steel composition and mechanical properties (if available). Industry-wide steel properties database (not currently available).	Susceptibility to high-pH SCC has been associated with the cyclic stress-strain properties of the steel. An industry database of these and other steel properties (categorized by grade, manufacturer, mill, age, etc.), obtained on an opportunistic basis, would be useful.
Liquid pipelines	H-I-19	Is product heated or is the pipeline located in a hot climate?	Because of the apparently dominant effect of temperature, there have been few cases of high-pH SCC of liquid lines. However, transmission of hot product or hotter climates are likely to increase susceptibility.

Temperature

Of all of the factors or processes listed in Table 11, probably the most useful parameter for indicating the relative susceptibility to high-pH SCC is the gas temperature. Increasing temperature leads to increased coating degradation, evaporative concentration of the electrolyte, a wider potential window for cracking that is closer to potentials on protected pipelines, and increased rates of crack growth. The effect of temperature on these various aspects of the high-pH SCC mechanism is the primary reason for the observation of decreasing probability of failure with increasing distance from the compressor station discharge.

Time-dependent gas discharge temperatures should be available for each compressor station. Historical data may also be required, especially if after-coolers have been installed at some stage and prior gas temperatures were significantly higher. The dependence of the gas temperature on distance downstream of the compressor station (T_X) can be estimated from simple expressions such as

$$T_X = T_G + (T_X - T_G) \cdot e^{-\alpha x} \quad (1)$$

where T_G is the ground temperature, x is the distance downstream of the compressor station, and the temperature decay constant α has a typical value of 0.045 mile^{-1} (0.028 km^{-1}) (Figure 4).

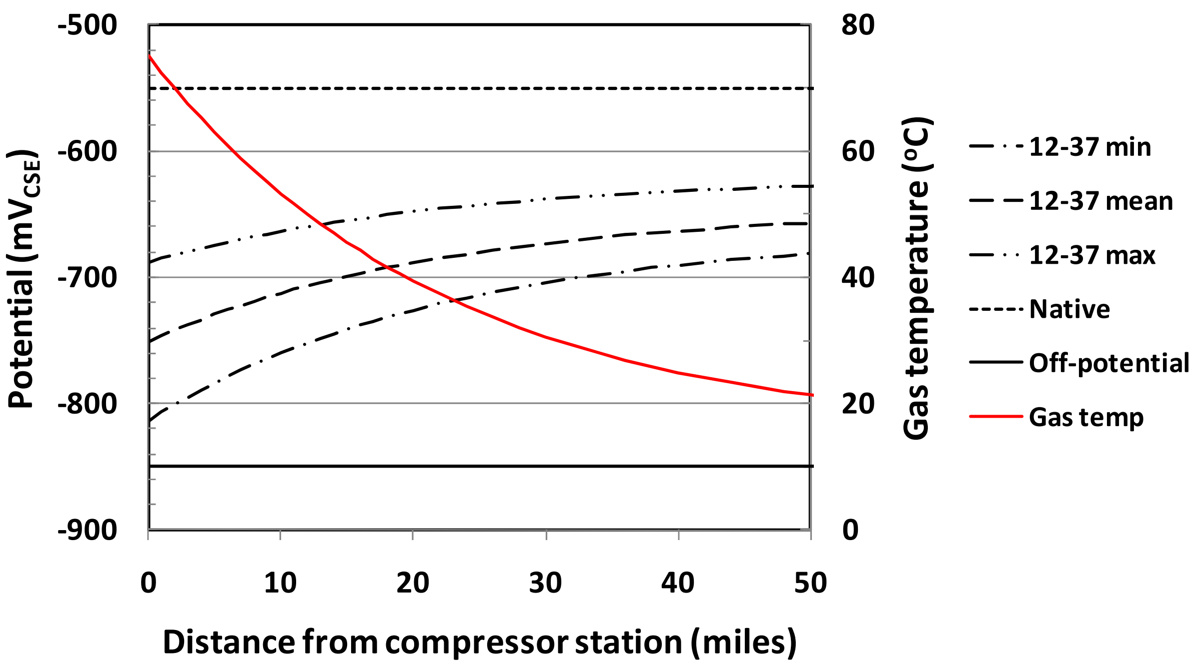

Figure 4: Illustration of the Decrease in Temperature with Distance from the Compressor Station and the Associated Potential Window for Cracking. Also shown are assumed off- and native potentials of -850 mV$_{CSE}$ and -550 mV$_{CSE}$, respectively. See text for details.

A simple comparison of gas discharge temperatures will allow a high-level prioritization of the relative susceptibility of different lines, or different valve sections on a given line, to high-pH SCC. As described in more detail below, knowledge of the distance dependence of the temperature can also be used to judge whether the pipe is within the temperature-dependent potential range for cracking.

Cathodic protection: generation of environment

Determining whether the CP conditions are suitable for generation of the high-pH SCC environment is theoretically possible, but will likely be difficult for operators to do in the absence of detailed knowledge of the condition of the coating. Generation of the high-pH SCC environment is a balance between the rate of alkali generation and the rate at which it is removed from the surface. The former is a function of the current demand, which is generally known, but the latter depends on the permeability of the coating, which is generally not.

It may be possible for operators to develop “rules-of-thumb” for the critical current density on a line-by-line basis. Alternatively, an industry-wide database could be developed relating coating properties, such as impedance, resistance, porosity, etc., to age, manufacturer, and service conditions. Such a database could be developed on an opportunistic basis as and when coating samples become available from excavations or cut-outs.

Cathodic protection: potential for cracking

High-pH SCC occurs within a specific range (or “window”) of potentials. Figure 4 shows the maximum, minimum, and mean potentials for a simulated high-pH SCC electrolyte referred to as 12-37 (Beavers et al. 1998). The values of these potentials are a function of temperature and vary with distance from the compressor station as the temperature decreases. The values are also a function of the composition of the electrolyte, with the corresponding potentials also known for the laboratory standard solution referred to as 1N-1N.

Also shown in the figure are (assumed) values of the off-potential and native potential. It is apparent that cracking only occurs at values between these two potentials. Theoretically, therefore, cracking should not occur on unprotected pipe (provided the native potential is more-positive than the cracking range, as assumed here) or on adequately protected pipe. However, it is difficult to be certain that there will be no IR drop along the disbondment (or through the pores of a permeable coating). If there is additional IR drop associated with the coating, cracking is possible on apparently protected pipe. One condition that has been identified as leading to IR drop in the coating is the formation of hydrogen bubbles on over-protected pipe. For this reason, it has been suggested that IR-free potentials more-negative than -1.2 V_{CSE} should be avoided as hydrogen gas can be evolved at more-negative values (Parkins 1994).

In order to assess whether the pipe potential is within the cracking window, operators need to know the distance-dependent temperature (as discussed above), the off-potentials, and the nature of the trapped electrolyte. In the absence of any knowledge of the latter, the most-conservative approach based on currently available information is to assume that the trapped water is similar to the 12-37 electrolyte shown in Figure 4 which exhibits the more-negative potential window of the two solutions for which such data are available. Given uncertainty in the exact position of the cracking window for the actual electrolyte (if any is present) and because of the uncertain IR drop in the coating, operators should take a conservative approach to deciding whether the pipe potential is within the cracking range.

Cathodic protection: -100 mV criterion

Beavers and Durr (2000) have considered the specific case of the susceptibility to high-pH SCC of pipelines protected using the -100 mV polarization criterion. The list of criteria given in SCC Guideline H-I-9, as well as the flow chart in the original study, should be consulted to determine whether this CP criterion adequately protects the pipe from high-pH SCC.

Coatings

A knowledge of the type of pipe coating can provide a high-level indication of susceptibility to high-pH SCC. It is generally considered that all coatings other than FBE should be considered to be “susceptible coatings” although, theoretically, there is no reason why a permissive high-pH SCC environment could not be established under disbonded FBE coating. The apparent absence of reported cases of high-pH cracking on FBE-coated lines may owe more to the careful pipe surface preparation than any inherent immunity offered by the coating itself. In this regard, it is apparent that pipes with mill-applied coatings are less susceptible to cracking than those with “over-the-ditch” field-applied coatings.

A more-detailed analysis of the effects of coating on the development of a permissive cracking electrolyte can be performed if operators have detailed knowledge of coating properties (King et al. 2004). Such knowledge, including the coating porosity, permeability, and/or impedance, is not generally available but could, if it were to be measured, permit the prediction of the pipe surface environment.

Cracking environment: soluble cations

Because of the limited solubility of calcium and magnesium carbonates, the trapped electrolyte must contain a significant concentration of sodium and potassium ions in order to develop the concentrated carbonate/bicarbonate environment (Beavers and Worthingham 2002). Sodium- and potassium-rich electrolytes can develop either because the groundwater itself is rich in these species or because calcium and magnesium ions precipitate as carbonates in regions of high-pH near the pipe surface. Thus, the composition of the groundwater is a useful, although not foolproof, indicator of the potential for the development of the high-pH SCC environment.

Such detailed groundwater information is not typically available to pipeline operators. However, State, Federal, or Provincial agriculture or environment agencies may have useful data. Alternatively, it may be possible to glean such information from maps of soil types along the pipeline right-of-way. Groundwater (and trapped water, if any) samples should be taken during excavations and analyzed for their cation composition.

Knowledge of regional differences in groundwater compositions will allow prioritization of pipeline segments, but such differences are unlikely to permit selection of specific sites for excavation.

Cracking environment: CO_2 generation

The development of the concentrated carbonate/bicarbonate high-pH SCC electrolyte requires the presence of CO_2. There are indications from the R&D literature that a finite amount of CO_2 is required to maintain the pH in the cracking range. Furthermore, there is evidence that the severity of cracking increases with increasing carbonate/bicarbonate concentration. Therefore, it is reasonable to assume that locations with higher rates of CO_2 generation will exhibit a higher probability of high-pH SCC.

The rate of CO_2 generation is primarily determined by the temperature and moisture content of the soil. Algorithms are available to predict the rate of CO_2 generation but, because of the lack of a direct link between the CO_2 concentration and the probability of cracking, it may be sufficient to simply note that wetter and hotter sites are likely to have higher rates of gas generation and, as a consequence, a higher probability of high-pH SCC. Operators requiring a quantitative estimate of the rate of CO_2 generation can consult the original literature.

Site selection based, in part, on the rate of CO_2 generation could be used to both prioritize lines on a regional scale or select specific sites on a local scale. The requirement for more-precise input data increases as the scale of interest is refined. As discussed above, reasonable estimates of local temperatures should be possible based on gas discharge temperatures and a suitable temperature decay algorithm. Soil moisture content data may be more difficult to obtain, but surrogate measures, such as drainage, may be available or operators can consult local State or Provincial agriculture agencies.

Cracking environment: transient conditions

Locations subject to time-dependent or spatially variable conditions often exhibit an increased probability of integrity issues, including high-pH SCC. Cyclic aerobic-anaerobic conditions have been associated with high-pH SCC on asphalt-coated pipelines, possibly due to alternating aerobic and anaerobic microbial activity and the effect on CO_2 generation. Spatially variable conditions, such as the edge of a water course or a transition between different soil types, may also represent an increased threat, possibly due to inadequate CP. Similarly, changes in operational conditions, for example, an increase (or decrease) in gas temperature of pressure, could indicate an increased (or decreased) probability of cracking.

Pipeline operators are best positioned to identify such locations on their system.

Operating pressure and cyclic loading

Various aspects of the cracking process are affected by the gas pressure and pressure fluctuations. Pressure fluctuations cause a decrease in the threshold stress for cracking and increasing pressure results in a larger number of more-densely spaced cracks. Pressure cycling also promotes crack growth due to the "cyclic softening" of the steel. Failures due to high-pH SCC have been reported for pipes with MOP greater than 46% SMYS.

Operators should understand the nature of the pressure fluctuations on their pipeline systems. Both gas discharge and suction pressures can be characterized by any of a number of cycle counting techniques, rainflow counting being the most commonly used. The traditional rainflow counting technique of characterizing the number and magnitude of the cycles should be extended to also include time-dependent effects in order to predict the strain rate, particularly of the loading part of each cycle. Unload-reload events can be particularly damaging and should be specifically tracked. High-pH SCC is unlikely to occur on statically loaded pipelines and some guidance is available on what degree of cyclic loading constitutes "static loading" (see SCC Guideline H-I-17).

Armed with a knowledge of the characteristics of the pressure fluctuations, operators can then assess the consequences for high-pH SCC. This can be done either qualitatively, with larger cycles of higher loading rate generally being more damaging, or quantitatively, for example, by relating the maximum stress and stress ratio to the threshold stress for cracking reported in the literature. If pressure fluctuation data are only available at the compressor stations, then this information is only useful for prioritizing different valve sections. However, if the pressure data can be interpolated between discharge and suction locations, more local site selection based on loading effects may be possible.

Although the loading conditions play a role in high-pH SCC, the effects of fluctuating pressure (stress) are not as significant as for near-neutral pH cracking.

Stress raisers

Unlike near-neutral pH SCC, there is no indication that high-pH cracking is more likely at locations with increased stress. Therefore, locations of higher tensile residual stress or stress raisers such as the long seam weld, dents, or gouges, are not associated with a higher incidence of cracking.

Nevertheless, operators may wish to take into account local stress raisers due to mechanical damage or corrosion as they can indicate locations of coating damage.

Steel properties

The properties of the steel clearly influence the cracking behaviour, but are of limited use in identifying SCC sites because the necessary information is generally not available. Crack initiation and early-stage growth is clearly influenced by the cyclic stress-strain behaviour of the steel, but such information is not available on mill reports. Nevertheless, mill reports, where available, should be reviewed in order to collect other pertinent information, such as the chemical composition and actual (as opposed to specified minimum) yield strength, the latter representing the threshold stress for cracking under static load.

Because it would be useful to understand the steel composition and mechanical properties, there would be considerable benefit in developing an industry-wide database of typical steel properties. Such a database could be developed by testing material on an opportunistic basis, for example on material removed from hydrotest failure sites or for other reasons (e.g, hot tapping). Over time, based on sharing information from different companies, a database of typical properties categorized by pipe manufacturer, pipe mill, vintage, etc. could be established. As a minimum, a sufficiently large database would allow a probabilistic assessment of these important properties.

Unless a given pipeline is constructed of steel from a number of different sources, which does happen in some cases, any site selection based on steel properties would be on a regional or line-by-line scale.

Liquid pipelines

Because of the apparently dominant effect of temperature on high-pH SCC, there have been few cases of high-pH SCC of liquid lines. However, if the liquid product is heated either to assist flow or for some other reason or if the climate is hotter, some consideration should be given to the possibility of high-pH SCC. It is difficult to define a threshold temperature for high–pH SCC since failures have occurred many miles downstream of the compressor station where temperatures would be expected to be close to ambient.

4.1.1.2 Near-neutral pH SCC

Table 12 summarizes the various processes and factors that can be used to identify locations of increased probability of near-neutral pH SCC. For each process or factor, the table lists the associated SCC Guidelines, describes the nature of the analyses that need to be performed and the input data required, and provides a commentary on the application of the derived information.

Pressure fluctuations: general considerations

Of all of the various factors that contribute to near-neutral pH SCC, the effect of pressure fluctuations is probably the most important. Crack growth, especially of deeper cracks or on lines with large magnitude and/or frequent fluctuations (e.g., liquid lines), is primarily determined by the effects of mechanical loading.

Operating companies should be aware of the nature of the mechanical loading on their systems. Time-dependent SCADA pressure data should be analyzed to determine the number, magnitude, and frequency of pressure fluctuations. This analysis can be carried out using any of a number of fatigue-based cycle-counting algorithms, of which rainflow counting is the most commonly used. These fatigue-oriented methods do not specifically predict strain rates, although the algorithms can be used to derive such information, which may also be important for some aspects of crack growth.

Once the pressure fluctuations have been characterized, this information can be used to assess the probability of crack initiation and the rate of crack growth, the latter using one of a number of fatigue-based crack growth rate expressions that have been developed (Appendix A). Alternatively, knowledge of the frequency and severity of the pressure fluctuations can be used to estimate the relative susceptibility to near-neutral pH SCC based on an in-house ranking system.

Pressure fluctuation data can be used to predict the occurrence and severity of near-neutral pH SCC on both a regional and local basis. Regional information comes from comparison of pressure fluctuations at compressor or pump station discharge locations. Local information can be obtained if measured data are available at locations between compressor stations or if data can be interpolated between discharge and suction (Figure 5).

Pressure fluctuations: specific types of loading

Within the overall spectrum of pressure fluctuations, certain types of loading are more damaging than others. Particularly damaging types of fluctuation include:

- unload/reload cycles
- high-frequency fluctuations

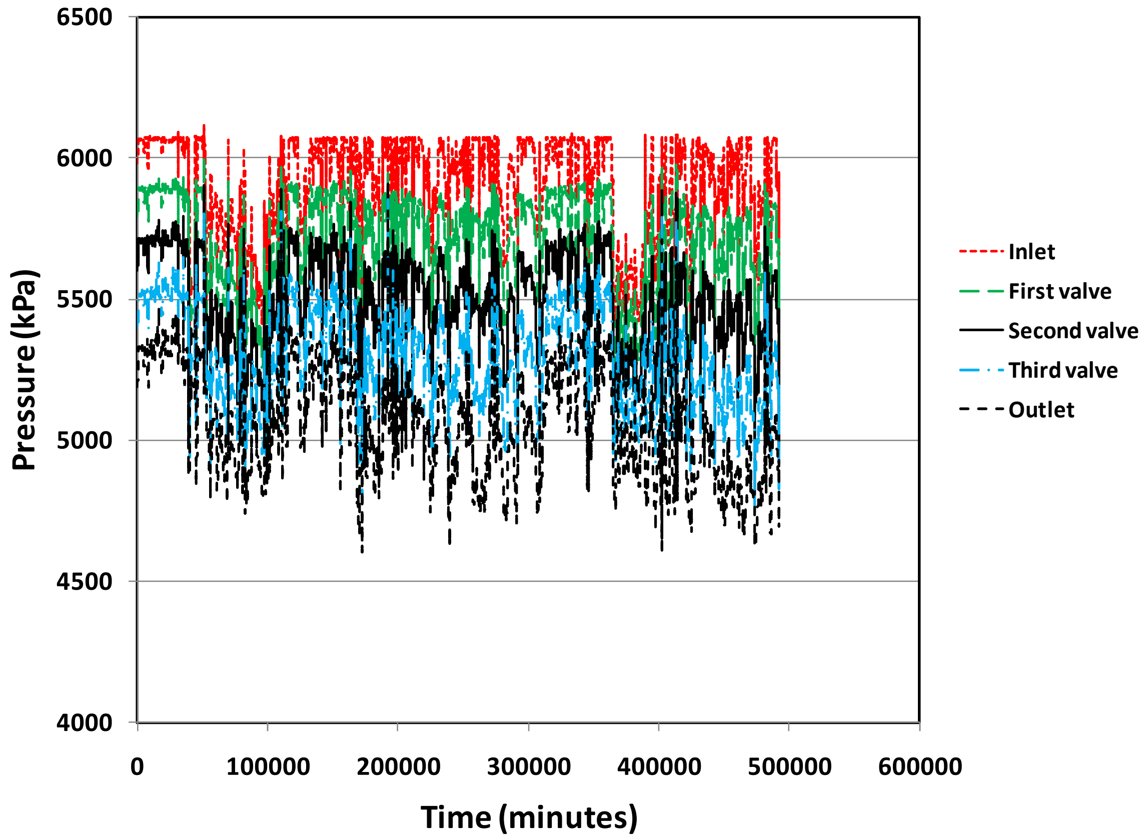

Figure 5: Measured Inlet and Outlet Pressure Fluctuations for a Gas Transmission Pipeline and the Predicted Fluctuations at the End of the First, Second, and Third Valve Sections.

- variable load and frequency
- underload/reload cycles

In contrast, overload cycles inhibit subsequent crack growth.

Operators should keep track of the number and location of damaging cycles as this may identify locations of accelerated crack growth or of the re-activation of dormant cracks. The effects of these cycles on crack growth can be accounted for by using fatigue-based crack growth models. The effects of these cycles on, for instance, the re-activation of dormant cracks is more difficult to quantify and, based on currently available knowledge, can only be done qualitatively.

Table 12: Identification of Near-neutral pH SCC Sites.

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Pressure fluctuations: general considerations	N-0-3 N-0-10 N-I-14 N-II-2 N-III-4 N-IV-2 N-IV-4 N-IV-9	Analysis of SCADA pressure fluctuations to determine number, frequency, and magnitude of pressure cycles. Analysis to determine hoop strain rate, especially for loading half of cycle. Analysis of measured or interpolated SCADA pressure data at locations <u>between</u> successive compressor or pump stations.	The number and size of pressure fluctuations is probably the single most important factor determining the severity of near-neutral pH SCC, particularly for deeper cracks and/or severe loading conditions. Such characterization can be used to locate areas of higher probability both on a regional and local scale.
Pressure fluctuations: specific types of loading	N-I-13 N-III-2 N-III-3 N-III-5 N-IV-5 N-IV-6 N-IV-7 N-IV-8	Identification and characterization of specific loading patterns, including: • Unload/reload cycles • High frequency cycles • Variable load and frequency cycles • Underload/reload cycles • Overload cycles	Pressure cycles in general are important for near-neutral pH SCC, but certain types of cycle are particularly important. Of the various types of cycle listed here, most are damaging, resulting in either accelerated crack growth or the prevention of dormancy. Only overloads, as during hydrotesting, are beneficial. Identifying where and how often such cycles occur can help identify locations with increased probability of cracking.
Stress raisers and residual stress	N-I-9 N-I-12 N-I-14 N-I-15 N-II-1 N-IV-1	Identify location of stress raisers, such as dents, wrinkles, areas of corrosion. Characterize stress concentration factor due to shape of long-seam weld cap. Characterize magnitude and distribution of residual stress.	There is a clear link between stress raisers and the incidence of near-neutral pH SCC. Knowledge of the total stress distribution, a combination of hoop stress, stress concentration, and residual stress, will help locate cracking on both regional and local scales.

Continued ….

Table 12: Identification of Near-neutral pH SCC Sites (continued).

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Steel properties: observable properties	N-I-15 N-I-16 N-I-17 N-I-18 N-I-19 N-II-5	Identify linepipe with susceptible microstructures or metallurgical features: • Cold work (e.g., areas of mechanical damage) • Vintage ferrite-pearlite microstructure vs. modern bainite TMCP alloys • Presence of millscale • ERW pipe	Certain microstructural and metallurgical features are known or can be inferred from the age and manufacturing process. To the extent that these features (listed here) influence susceptibility, they can be used to identify regional and local areas of increased probability.
Steel properties: non- observable properties	N-I-20 N-II-6 N-II-7	Identify linepipe with susceptible microstructures or metallurgical features: • Excessive room temperature creep • High MnS inclusion content • Martensitic microstructure Industry database required.	Other microstructural and metallurgical features are also useful for locating pipe of increased susceptibility, but there is generally no information with which to identify where such features occur.
Coatings	N-I-8 N-I-18 N-II-8	Identify the type of pipeline coating and whether the coating was applied in the mill or over-the-ditch.	Based on field evidence, near-neutral pH SCC has been reported for all coating types with the exception of FBE. In general, pipe with mill-applied coatings will be less susceptible to cracking, to a significant degree because of the pipe surface preparation.
Environment: hydrogen	N-0-1 N-0-9 N-I-1 N-III-1	Identify locations where: • Native potential is between -670 and -790 mV_{CSE} for at least part of the year • Permanently or periodically wet sites • Potentially active SRB • High total stress	Hydrogen plays an important role in many aspects of near-neutral pH SCC. Identifying where hydrogen can be produced and where conditions exist that lead to enhanced H concentrations in the steel can be used to identify locations of increased probability on both local and regional scales.

Continued ….

Table 12: Identification of Near-neutral pH SCC Sites (continued).

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Environment: miscellaneous factors	N-0-4 N-0-5 N-I-2 N-I-3 N-I-4 N-I-7 N-IV-11 N-IV-12	Various environmental parameters contribute to an increased probability of cracking: • time-dependent transitions • soil transitions • presence of sulphide Other factors inhibit or prevent cracking: • presence of organics • soil resistivity >14,000 ohm·cm	No single environmental parameter has been linked with the occurrence of near-neutral pH SCC. Instead, SCC sites are characterized by a range of environmental conditions, all of which should be considered when selecting sites. In general, however, selection of sites based only on environmental conditions is challenging.
CP	N-I06	Identify locations where CP is shielded or ineffective. Various factors could contribute to shielded or inadequate CP, including: • highly resistive coating (e.g., PE tape) • conversion of a permeable coating to a shielding coating • loss of CP for an extended period of time	The environment associated with near-neutral pH SCC is not consistent with CP reaching the pipe surface. In some cases it is easy to identify where conditions could support cracking, e.g., PE tape coating. In other cases, however, it is more difficult, such as where a traditionally permeable coating, such as asphalt, becomes shielding.
Temperature	N-0-2	Identify locations of elevated temperature.	Unlike high-pH SCC, there is no apparent correlation between near-neutral pH SCC and temperature. Elevated temperatures could, however, increase the probability of coating degradation.

Continued ….

Table 12: Identification of Near-neutral pH SCC Sites (concluded).

Process or Factor	Associated SCC Guideline(s)	Analysis and Data Requirements	Comments
Management of cracks: liquid pipelines	N-0-6 N-0-10 N-1-10 N-III-4 N-IV-2	Analysis of SCADA pressure fluctuations to determine number, frequency, and magnitude of pressure cycles. Analysis of measured or interpolated SCADA pressure data at locations between pump stations.	For liquid pipelines, near-neutral pH crack growth is determined more by the effect of P fluctuations than any other single factor. Corrosion fatigue models can be used to predict the location and rate of cracking with some confidence.
Management of cracks: gas pipelines	N-III-6 N-III-7 N-III-10 N-III-11 N-IV-3	Analysis of SCADA pressure fluctuations to determine number, frequency, and magnitude of pressure cycles. Analysis to determine hoop strain rate, especially for loading half of cycle. Analysis of measured or interpolated SCADA pressure data at locations between compressor stations.	For gas pipelines, the effect of pressure fluctuations on crack growth is less important than for liquid pipelines, except for the later stages of crack growth.
Management of cracks: crack dormancy	N-III-8 N-III-9 N-III-12 N-III-14	Identify pipelines, or periods of time, for which loading and environmental conditions may lead to dormancy, including: • lower-amplitude, lower-frequency pressure fluctuations • regions of compressive or reduced tensile residual stress • near-static loading • absence of unload/reload events	Near-neutral pH SCC is only an integrity threat if cracks continue to grow and either fail to become dormant or are reactivated following a period of dormancy. Identifying conditions that do, or do not, lead to dormancy can help locate regions of SCC.

Stress raisers and residual stress

Many near-neutral pH SCC failures have been associated with some type of stress raiser (NEB 1996). Crack colonies have been found to be closely associated with areas of high tensile residual stress (Beavers et al. 2000). It is the total stress to which the pipe is subjected that determines the susceptibility to SCC, not just the applied stress. The total stress includes contributions from stress raisers (or stress concentrators), such as dents or areas of corrosion, which multiply the effect of the operating stress, and residual stress, which adds to it.

Many sources of information are available for identifying possible stress raisers. Metal-loss ILI tools can indicate the depth and shape of areas of corrosion (and of gouges) and, of course, also indicate areas of coating damage which is a pre-requisite for SCC as well as for corrosion. Calliper tools indicate areas of mechanical damage and the severity of the dent or wrinkle. Operators should also consider characterizing the shape of long seam weld crowns as these also lead to stress concentration. Although more difficult to obtain, knowledge of the distribution and magnitude of residual stress is also helpful.

This type of information can be used to both identify specific locations for direct examination as well as to prioritize the inspection of different lines. Specific dig sites should clearly be targeted at locations of severe deformation. It is more difficult to use corrosion data to identify possible SCC sites because although an area of deep corrosion may indicate a region of higher stress (because of the loss of wall thickness), it may also indicate a region in which the rate of corrosion exceeds the rate of cracking. Regardless of the depth of corrosion, metal-loss features with steep walls will tend to act as stress raisers. On a regional scale, pipe with high tensile residual stress or with long seam weld beads that lead to high stress concentration because of their shape or (mis-)alignment should be inspected on a priority basis.

Steel properties: observable properties

A number of properties increase the susceptibility of the steel, but not all of these properties are known or are easily obtained. Of those properties that are observable or easily obtained, the following have been associated with increased susceptibility to near-neutral pH SCC:

- cold work (e.g., areas of mechanical damage)
- ferrite-pearlite steels (as opposed to modern TMCP steels)
- ERW pipe
- millscale-covered pipe (typically that with field-applied coating)

Steel properties: non-observable properties

Other steel properties that influence the SCC susceptibility are not as easily identifiable on existing pipelines. For example, each of the following properties increase susceptibility:

- excessive room temperature creep
- high MnS inclusion content
- martensitic microstructure

but few pipeline operators would have such information. There may be some benefit to the development of an industry database of steel properties, categorized by manufacturer, individual pipe mill, and vintage. If a sufficiently large database of shared information can be developed, it may be possible to establish that pipe from Pipe Mill A operated by Manufacturer X in the early 1960's produced pipe with a higher than average inclusion content which is, as a consequence, more susceptible to crack initiation than other pipe. Such a database could be extended to include other steel properties of relevance for both high-pH and near-neutral pH cracking.

Coatings

Near-neutral pH SCC has been reported for all coating types with the exception of FBE and, possibly, the modern urethane, epoxy, and multi-layer coatings. In the latter cases, the apparent absence of SCC may be either because these coatings have not been in service as long as other coating types or, as is the case for FBE, that the necessary surface preparation inhibits cracking. All older field-applied coatings should be considered to be supportive of near-neutral pH cracking.

The nature of the pipeline coating is, therefore, rather a broad discriminator of SCC susceptibility, with possibly the most useful criterion being whether the coatings were applied in the field or in a coatings mill.

Environment: hydrogen

In general, identification of SCC sites based on environmental considerations is more challenging for near-neutral pH SCC than for the high-pH form of cracking. Near-neutral pH SCC has been observed in many different types of environment. Because of the close association of the cracking mechanism with the effects of absorbed hydrogen, one condition that must be met is that the pipe potential must be sufficiently negative that hydrogen is produced. Furthermore, since the field evidence is that near-neutral pH SCC occurs in the absence of CP, the native potential must be sufficiently negative for hydrogen formation. In most soil types this means that the native potential must be equal to or more-negative than -670 to -790 mV_{CSE} for some fraction of the time. It is important to note that the potential does not have to be below this threshold at all times.

As well as the requirement to generate hydrogen, other factors that promote the absorption or concentration of this hydrogen can also be expected to correlate with sites with increased probability of near-neutral pH SCC, such as the presence of sulphide, most likely due to the activity of sulphate reducing bacteria (SRB), or high stresses.

In the absence of depolarization data, it may be possible to use surrogate parameters to identify locations with low native potentials. For example, permanently or periodically wet sites would be expected to be anaerobic and, hence, support hydrogen generation. On the other hand, permanently dry, aerobic sites would not be expected to be supportive, although it is always dangerous to be too definitive when it comes to excluding sites based on environmental conditions.

Environment: miscellaneous factors

A number of other environmental factors have been associated with either the presence or absence of near-neutral pH SCC. Sites at which the environmental conditions change with time, especially for asphalt-coated pipe, or at which there is a transition in soil type of other soil property (e.g., moisture content) are often associated with near-neutral pH SCC. As noted above, the presence of sulphides also leads to increased susceptibility. On the other hand, high soil resistivity and the presence of organics have been found to either inhibit SCC or correlate with an absence of cracking.

In using these environmental parameters to locate sites of increased probability of cracking, it must be remembered that no single parameter has been found to uniquely identify the presence of SCC. Instead, supportive environments tend to be indicated by a combination of numerous environmental and mechanical factors.

Cathodic protection

The nature of the environments in which near-neutral pH SCC has been observed in the field and reproduced in the laboratory are not consistent with CP reaching the pipe surface. A pre-requisite for cracking, therefore, is that the CP should either be shielded or ineffective. A number of factors could contribute to the loss or ineffectiveness of the CP system and which, therefore, could be used as site-selection criteria, including:

- highly resistive or dielectric coatings (e.g., PE tape)
- transformation of a permeable to a shielding coating (e.g., due to the blockage of pores in the coating by precipitated salts)
- loss of CP for operational reasons for an extended period

The difficulty of identifying near-neutral pH SCC sites based on this CP criterion is highlighted, however, by the common observation of this form of cracking under asphalt coating, a coating system that has been traditionally considered to be CP-permeable. The mechanism(s) by which a permeable coating such as asphalt becomes shielding is (are) not currently understood.

Temperature

Unlike high-pH SCC, there is no reason to believe that increased temperature correlates with an increased probability of finding near-neutral pH cracking. The only reason for selecting sites based on temperature would be if there is some reason to believe that the resultant increase in coating damage correlates with the incidence of cracking.

Management of cracks: liquid pipelines

Cracks with a depth of less than 10% of the wall thickness present little if any integrity threat. Cracks that are deeper than 50% of the wall thickness require some form of mitigation in the immediate or near future. Cracks with depths in between these two limits may be managed, either by carefully monitoring their growth until such time that mitigation is required or by adjusting operational parameters to slow or halt their growth.

In the case of liquid pipelines which exhibit relatively large and rapid pressure fluctuations, the primary method for managing cracks is through knowledge or control of these fluctuations. Crack growth is dominated by the effects of the mechanical loading conditions, with environmental factors playing a secondary role.

Management of cracks on liquid lines, therefore, requires a knowledge of the frequency and magnitude of pressure fluctuations and the rate of change of pressure for a given cycle.

Management of cracks: gas pipelines

Whilst understanding of the nature of the pressure fluctuations is also useful for the management of near-neutral pH SCC on gas pipelines, there are additional factors that play a role in the growth of cracks in the 10-50% wall thickness depth range. Characterization of pressure fluctuations on gas pipelines has shown that the magnitude and number of cycles is not sufficient to grow cracks by predominantly mechanical means. There are additional factors that determine the growth of such cracks which are not currently understood.

Management of cracks: dormancy

It is well known that the vast majority of near-neutral pH SCC cracks are less than 10% deep and pose no integrity threat. These cracks are thought to be dormant. Understanding the factors that cause cracks to become dormant, or alternatively to be re-activated, can be used to identify locations at which deep cracks may be present.

Factors that prevent dormancy include:

- high amplitude, high-frequency pressure fluctuations

- high tensile residual stress
- unload/reload events

Operators should prioritize pipelines displaying these characteristics.

4.1.2 Estimation of Re-inspection Intervals

In addition to identifying where high-pH or near-neutral pH SCC can be expected to occur, a number of the SCC Guidelines in Section 3 can also be used to estimate re-inspection intervals. The mechanistically based flowchart illustrated in Figure 3 identifies four distinct stages, each of which may require periodic reassessment. For example, pipelines may become increasingly susceptible as coatings age or as CP systems become less effective. For pipelines known to contain cracks, it is important to estimate how often the line should be inspected or hydrotested.

The SCC Guidelines offer both qualitative and quantitative guidance on the length of re-inspection intervals for each of the four mechanistic phases. The qualitative guidance is largely based on the question "has there been any significant change in the condition of the pipeline or in the operating or environmental conditions?" The quantitative guidance is based on crack growth models and is primarily limited to the early-stage and late-stage crack growth phases. The R&D literature offers little quantitative guidance as to when re-inspection should be performed to determine susceptibility or the possibility of crack initiation.

4.1.2.1 High-pH SCC

Table 13 summarizes the factors and processes (and the associated SCC Guidelines) for estimating re-inspection intervals for the various mechanistic stages of high-pH SCC.

Susceptibility

A pipeline is most likely to become more susceptible to high-pH SCC because of changes in environmental conditions. A re-assessment of the susceptibility to high-pH SCC could be triggered by one or more of the following factors:

- an increase in temperature (associated SCC Guidelines H-0-2, H-I-1, H-I-2),
- an increased rate of CO_2 generation due, for example, to increased temperature or soil moisture content (H-0-3, H-I-5),
- a change in the CP conditions that would shift the off-potential into or closer to the cracking range (H-I-3, H-I-4, H-I-7, H-I-8, H-I-10)

Table 13: Qualitative and Quantitative Bases for estimating Re-inspection Intervals for High-pH SCC.

Mechanistic stage	Qualitative estimation	Quantitative estimation
Susceptibility	Have operational or environmental conditions changed since the last inspection, including: • CO_2 generation (H-0-3, H-I-5) • Temperature (H-0-2, H-I-1, H-I-2) • CP (H-I-3, H-I-4, H-I-7, H-I-8, H-I-10) • Coating permeability (H-I-11) • Cyclic loading conditions (H-I-16, H-I-17)?	Prediction of the undercoating environment
Crack initiation	Compare stress ratio (R value) and maximum stress of pressure fluctuations to threshold stress for crack initiation (H-II-1, H-II-2, H-II-3).	
Early-stage crack growth	Has any operational or environmental condition changed (as for the susceptibility stage)? Analyze hoop strain rate, since crack growth rate increases with increasing crack-tip strain rate (H-III-2) Have there been any unload/reload events since the last inspection which could prevent crack dormancy (H-III-4)?	Various possible approaches to predicting crack growth rates: • empirical crack growth rate from previous experience on same line • micro-mechanics based crack growth models (H-0-8) • slip-dissolution based crack growth models (H-0-8) Regardless of method used, account should be taken of crack coalescence (H-0-4) and the stochastic nature of high-pH SCC (H-0-7).
Late-stage crack growth	Has any operational or environmental condition changed (as for the susceptibility stage), with special attention to the effects of: • temperature (H-IV-2) • CP (H-IV-3) • electrolyte composition (H-IV-4)?	As for early-stage crack growth stage. In addition, estimate K_I to determine if exceed K_{ISCC} (H-IV-1).

- a change in coating permeability, possibly indicated by a change in current demand (H-I-11)
- more aggressive or higher frequency cyclic loading (H-I-16, H-I-17)

In addition to a qualitative indication of possible increased susceptibility based on the parameters above, a quantitative prediction of the pipe-surface environment can be performed using information about the CP and soil conditions (King et al. 2004).

Crack initiation

The mechanical loading conditions for crack initiation in high-pH electrolytes have been established in laboratory testing. The threshold stress for crack initiation is a function of the cyclic loading stress ratio and the maximum stress (H-II-1, H-II-2, H-II-3). Therefore, reassessment of the possibility of crack initiation should be performed if the magnitude of the pressure fluctuations and/or the maximum pressure have increased since the previous assessment.

Early-stage crack growth

On susceptible pipelines known to contain high-pH SCC cracks, crack management should be focussed on the early-stage crack growth process, defined by Parkins (1994) as corresponding to surface crack lengths of less than 6 mm. There are both qualitative and quantitative indicators of the need to re-inspect cracks in this stage.

Qualitatively, any change in the operational or environmental conditions discussed above for the Susceptibility stage could also indicate a change in early-stage crack growth rates. Crack growth rates also increase with increasing strain rate (H-III-2), which can be estimated based on the rate of loading. The re-inspection interval should be decreased if the strain rate has increased since the previous inspection or if there have been a number of unload/reload events, the latter preventing the dormancy of existing cracks (H-III-4).

A number of methods are available for estimating the crack growth rate quantitatively. Empirically determined crack growth rates can be used to define a suitable re-inspection intervals. Alternatively, micro-mechanics based models are available (H-0-8), but require some knowledge about the dependence of the crack growth rate and rate of initiation as a function of cyclic loading. In the absence of specific data for the particular pipeline steel of interest, typical values can be found in the literature. Crack growth models based on the kinetics of the slip-dissolution mechanism have also been developed (H-0-8) and can be similarly used to predict a suitable re-inspection interval.

A key uncertainty in the prediction of crack growth during both the early- and late-stage phases for both high-pH and near-neutral pH SCC is the existing crack size. Calculation of crack-tip strain rates or stress intensity factors requires a knowledge of the crack length and depth. If a previous hydrotest has been performed, a maximum defect size at the time of the hydrotest can be estimated. Alternatively, a prior ILI run will indicate either the actual size of detected cracks or a maximum size of any undetected feature based on the accuracy of the tool. However, in the absence of such information a pre-existing crack size will need to be assumed.

Late-stage crack growth

Parkins (1994) has cautioned that the crack growth rate during the latter stages of the crack growth process can be rapid and is only limited by the rate of dissolution. The rate of dissolution is strongly influenced by temperature (H-IV-2), potential (H-IV-3), and the composition of the electrolyte (H-IV-4).

Either empirical data or slip-dissolution models (H-0-8) can be used to estimate the rate of crack growth. These estimates should account for the effects of crack coalescence (H-0-4) and the inherent variability in high-pH SCC cracking (H-0-7).

4.1.2.2 Near-neutral pH SCC

Table 14 summarizes the factors and processes (and the associated SCC Guidelines in parentheses) for estimating re-inspection intervals for the various mechanistic stages of near-neutral pH SCC.

Susceptibility

Re-assessment of the susceptibility to near-neutral pH SCC could be triggered by changes to the following parameters:

- more-negative native potential or a native potential that is below the threshold for hydrogen evolution for a longer period of time (N-0-1, N-0-9, N-I-1)
- more aggressive cyclic loading (N-0-3, N-I-10)
- increase in CO_2 generation rate (e.g., due to increased temperature or soil moisture content) if there was previously little or no CO_2 generation (N-0-4)
- decrease in soil resistivity, if the resistivity was previously >14,000 ohm·cm (N-I-4)
- stress raiser, due to recent mechanical damage or corrosion (N-I-9, N-I-12)
- coating degradation, as indicated by recent corrosion activity
- unload/reload cycles (N-I-13)

Because no single parameter has been found to uniquely indicate susceptibility to near-neutral pH SCC, increased susceptibility would only be indicated if several of the above parameters were found to have changed since the previous assessment.

Table 14: Qualitative and Quantitative Bases for estimating Re-inspection Intervals for Near-neutral pH SCC.

Mechanistic stage	Qualitative estimation	Quantitative estimation
Susceptibility	Has there been any change to the following parameters since the last inspection: • native potential (N-0-1, N-0-9, N-1-1) • cyclic loading conditions (N-0-3, N-I-10) • CO_2 generation (N-0-4) • soil resistivity (N-1-4) • stress raisers (N-1-9, N-1-12) • coating condition • unload/reload cycles (N-1-13)?	
Crack initiation	Has there been any change to the following parameters since the last inspection: • stress raisers (N-II-1) • cyclic loading (N-II-2)?	
Early-stage crack growth	Has there been any change to the following parameters since the last inspection: • unload/reload cycles (N-III-2, N-III-9) • magnitude and frequency of cycles (N-III-8) • strain rate (N-III-3)?	For liquid lines, crack growth rate can be reasonably predicted using one of a number of corrosion fatigue models (N-III-4) Quantitative prediction of re-inspection intervals for gas lines is less certain than for liquid lines. Corrosion fatigue models may under-estimate the crack growth rate, and analyses based on strain rate may be more useful (N-III-5).

continued …..

Table 14: Qualitative and Quantitative Bases for estimating Re-inspection Intervals for Near-neutral pH SCC (concluded).

Mechanistic stage	Qualitative estimation	Quantitative estimation
Late-stage crack growth	Has there been any change to the following parameters since the last inspection: • stress raisers (N-IV-1) • unload/reload cycles (N-IV-5) • variable load cycles (N-IV-6) • underloading (N-IV-7) • absence of overloads (N-IV-8)	For late-stage cracks, corrosion fatigue models can be used to predict crack growth rates for both liquid and gas lines (N-IV-2, N-IV-3, N-IV-4, N-IV-5, N-IV-6, N-IV-7). For gas lines, majority of damage may be caused by a relatively few low R cycles. Unload/reload cycles, variable load cycles, and underload cycles are important.

Crack initiation

An increased possibility of crack initiation, requiring re-assessment or re-inspection, would result from changes in:

- stress raisers, due to recent mechanical damage or excessive corrosion (N-II-1)
- more aggressive cyclic loading conditions (N-II-2)

Early-stage crack growth

Corrosion fatigue models allow quantitative prediction of the re-inspection interval for liquid lines and, with caution, for gas pipelines (N-III-4). These models were developed based on laboratory crack growth experiments performed under relatively aggressive loading conditions. Such conditions are commonly encountered on liquid lines, especially those that operate in batch mode, but less frequently on gas lines. It is possible that these corrosion fatigue models under-estimate the rate of early-stage crack growth on gas pipelines because they over-emphasize the effect of mechanical loading and under-emphasize as-yet unidentified environmental effects. Descriptions of the different models that have been developed can be found in Appendices A and B.

As discussed above, this type of crack growth model requires some prior knowledge of the existing crack size. Crack size information can be derived from prior hydrotest or ILI data or can be estimated based on expert judgement.

Qualitatively, increased early-stage crack growth requiring more frequent re-inspection is promoted by:

- unload/reload cycles (N-III-2, N-III-9)
- increased magnitude (smaller stress ratio) and higher frequency cyclic loading (N-III-8)
- increased strain rate (N-III-3)

If any or all of these factors apply then a decreased re-inspection interval is warranted. Conversely, the absence of unload/reload cycles and small magnitude (high R), low-frequency cycles tend to promote crack dormancy, in which case re-inspection intervals could be reasonably extended.

Late-stage crack growth

Various factors promote late-stage crack growth and the occurrence of one or more of these factors could warrant more-frequent re-inspection. These factors include:

- the presence of stress raisers (N-IV-1)
- unload/reload cycles (N-IV-5)
- variable loading (N-IV-6)

- underloads (N-IV-7)
- the absence of overloads (N-IV-8)

Late-stage crack growth is primarily supported by mechanical loading factors, rather than specific environmental parameters (provided, of course, that the environment remains supportive of near-neutral pH SCC). Therefore, corrosion fatigue models can be used to predict crack growth rates for both liquid and gas lines, from which a suitable re-inspection interval can be determined.

4.2 IMPLEMENTATION THROUGH CONSENSUS STANDARDS

A number of standard and recommended procedures exist to assist pipeline operators to manage external SCC. The SCC Guidelines developed here may be useful in supplementing one or more of these existing standards. Here, those standards are briefly described and compared with the information contained in this report.

4.2.1 NACE SP0204

The NACE International Standard Practice for SCC DA (NACE 2008) is the primary industry standard for identifying SCC sites using the four-step Direct Assessment methodology. The SP describes the overall SCCDA process, from threat assessment, through collection of data, identification of candidate dig sites, prioritization and selection of dig sites, indirect assessment, direct examination, post assessment, and reporting.

The current document can be used to supplement and extend various parts of the NACE SCCDA methodology. For example, the SP lists a large number of factors to consider when prioritizing susceptible segments for indirect and direct examination. Many of these factors are based on operational experience alone, rather than on any mechanistic input from the R&D literature. In contrast, the SCC Guidelines described here are based purely on R&D studies. It would be interesting to compare the current guidelines in NACE SP0204 with those described here and to highlight those that have both an operational and laboratory basis as well as supplementing the current guidelines with additional guidelines based on the R&D literature.

The current version of NACE SP0204 offers no guidance as to how frequently pipeline segments should be "re-inspected" using either the DA process or other techniques, such as ILI or hydrotesting. In contrast, various crack growth expressions have been reviewed as part of the current study and, without necessarily recommending one model or procedure over another, there would seem to be an opportunity to extend the current NACE SP by including discussion of the various methods available for estimating re-inspection intervals.

4.2.2 ASME B31.8S

The American Society of Mechanical Engineers (ASME) standard B31.8S (ASME 2004) deals with the integrity management of gas pipelines. One of the threats considered is SCC. Paragraph A3 of B31.8S describes an integrity management plan to assess and mitigate the threat from high-pH SCC and, by extension, of near-neutral pH SCC.

A list of criteria is provided for assessing the threat from high-pH SCC that includes:

- operating stress >60%
- operating temperature >100^{o}F (38^{o}C)
- distance from compressor station ≤20 miles (≤32 km)
- age ≥10 years
- all coatings other than FBE

These criteria are based on operating experience, but are broadly consistent with the findings, or implications, of the R&D studies reviewed here. A similar set of criteria is proposed for near-neutral pH SCC, with exception of the effect of temperature.

There are clearly opportunities to supplement and extend the treatment of external SCC in B31.8S, including:

- additional criteria for assessing the threat from high-pH SCC
- additional criteria for assessing the threat from near-neutral pH SCC
- inclusion of crack growth rate methodologies for estimating re-inspection intervals for high-pH and near-neutral pH SCC

4.2.3 CEPA SCC Recommended Practices 2nd Edition

The Canadian Energy Pipelines Association (CEPA) has recently published the 2nd edition of its Recommended Practices (CEPA 2007). The CEPA RP deals exclusively with near-neutral pH SCC and covers all aspects from detection, through assessment, mitigation, and prevention. Section 5 of the RP deals with SCC investigation programs and includes a detailed listing of the various factors that have been found to correlate with near-neutral pH SCC. These factors are categorized as coating type and coating conditions, pipeline attributes, operating conditions, environmental conditions, and pipeline maintenance data. As for the NACE SP and ASME B31.8S, these factors are largely based on field experience, but many are broadly consistent with the SCC Guidelines developed here from the R&D literature. On re-inspection intervals, Section 4.3.3 of the RP provides no specific guidance, other than that the maximum reassessment interval should be 10 years. Section 5.6 provides a more-detailed discussion that is largely based on monitoring changes in environmental and operating conditions, similar to the qualitative approach outlined in Tables 13 and 14.

The findings from the current study based on the R&D literature could be used to supplement the information available in the CEPA RP, including:

- providing a mechanistic basis for the empirically derived factors for assessing susceptibility to near-neutral pH SCC
- extending the list of factors for identifying and prioritizing SCC sites
- developing a quantitative basis for estimating re-inspection intervals based on corrosion fatigue and other crack growth models proposed in the R&D literature

4.2.4 API RP579

The American Petroleum Institute Recommended Practice 579 (API 2000) is a fitness-for-service standard that presents various assessment techniques for pressurized equipment in the refinery and chemical industries. It, therefore, covers a wide range of equipment and is not specifically directed towards hydrocarbon-containing pipelines.

The RP describes assessment procedures for various defect types and processes, including: general metal loss, local metal loss, pitting corrosion, blisters and laminations, weld misalignment and shell distortion, crack-like flaws, and creep. Estimation of the crack growth rate is required for any component that is used in a service environment that supports SCC (or other types of cracking).

Because the RP is not specifically directed towards pipeline operation, the example SCC crack growth rate expressions that are presented are not appropriate for predicting the rate of external cracking of underground pipelines. Appendix F of RF579 lists various fatigue and SCC crack growth expressions, but none of these are suitable for predicting the rates of high-pH or near-neutral pH SCC. Instead, when using the assessment procedures defined in API RP579, the rates of high-pH SCC should be estimated based one of the following methods:

- empirical crack growth rates
- micro-mechanics based models
- slip-dissolution based models
- laboratory-based correlation of crack growth rate and strain rate

For near-neutral pH SCC, crack growth rates should be estimated based on:

- empirical crack growth rate data
- corrosion-fatigue models, for deeper cracks and/or more-severe loading conditions
- strain-rate based expressions

4.3 IMPLEMENTATION BY PIPELINE OPERATORS

These guidelines represent one aspect of a company SCC IMP (Figure 6). The aim of the guidelines is to assist in the identification of SCC sites and the estimation of re-inspection intervals. The output of these analyses can then be used in the company risk assessment procedures to enable decisions about suitable mitigation, if any.

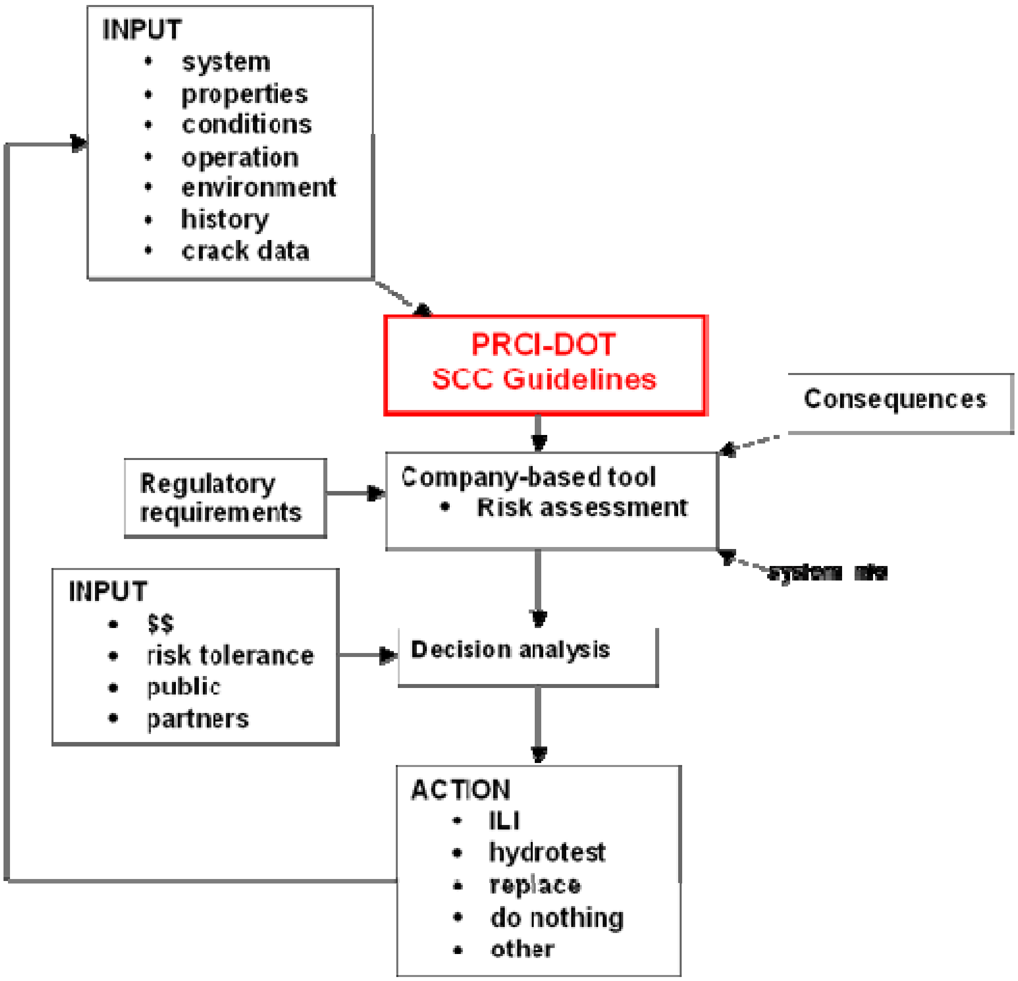

Figure 6: Relationship Between the SCC Guidelines and an Overall SCC Integrity Management Plan.

By their very nature and the fact that they have been derived from the R&D literature, many of the SCC Guidelines are mechanistically based and may not, on first inspection, appear to contain guidance of a practical nature. However, there are a number of practical actions that pipeline operators can take to implement these guidelines and to improve the identification of SCC sites and to optimize re-inspection intervals. These practical actions, categorized by material-, environment-, and stress-related factors, are summarized in Tables 15 and 16 for high-pH and near-neutral pH SCC, respectively. These practical actions are designed to provide data for implementing some of the various SCC Guidelines presented above.

Table 15: Summary of Practical Actions to Improve the Identification of SCC Sites and the Estimation of Re-inspection Intervals for High-pH SCC.

	Action
Material-related	Determine cyclic stress-strain properties on material from cut-outs or hot taps
Environment-related	Monitor gas temperature and estimate decrease in temperature with distance downstream of the compressor station Determine Na/K content of groundwater by sampling or for local agricultural or environmental sources Compare CP level with the temperature-dependent potential range for high-pH SCC crack growth Sample coating during excavations and determine coating porosity and/or impedance Estimate soil CO_2 generation rates based on temperature and soil moisture content
Stress-related	Characterize SCADA pressure data to determine number and magnitude (maximum stress and stress ratio) of pressure cycles Estimate hoop strain rate for loading part of pressure cycles Identify and track unload/reload cycles

Table 16: Summary of Practical Actions to Improve the Identification of SCC Sites and the Estimation of Re-inspection Intervals for Near-neutral pH SCC.

	Action
Material-related	Check S content of steel from mill reports or material from cut outs
Environment-related	Identify locations where native potential is more-negative than -670 and -790 mV_{CSE} for at least part of the year Sample coating during excavations and determine whether it is CP permeable of shielding Identify sites with high soil resistivity Identify sites where conditions change seasonally or due to transitions in soil properties
Stress-related	Identify location of stress raisers Characterize stress concentration at long seam weld based on shape of weld crown Determine residual stress distribution on cut outs Characterize SCADA pressure data to determine number and magnitude (maximum stress and stress ratio) of pressure cycles Estimate hoop strain rate for loading part of pressure cycles Identify and track unload/reload cycles, underloads

5. FURTHER DEVELOPMENT OF THE GUIDELINES

These guidelines can be developed further, both by further development and testing of the guidelines themselves and also by further underlying laboratory studies to fill gaps in our current mechanistic understanding.

5.1 DEVELOPMENT OF THE GUIDELINES

Further testing and development of the guidelines

Although there has been some partial validation of the SCC Guidelines against field data, much of the data collected as part of this study has been related to in-service or hydrotest SCC failures. Pipeline failure is a consequence of all four mechanistic stages and it has proven difficult to validate guidelines for specific stages using this overall measure of SCC susceptibility. Detailed information from SCC digs may be more useful for validating individual guidelines.

Further testing and validation of the various crack growth expressions proposed for estimating re-inspections intervals would also be useful. For example, there are two broad approaches for predicting the rate of high-pH SCC crack growth, mechanics-based models and slip-dissolution models, but no direct comparison of these models has been conducted. Similarly, a comparison of the various superposition and corrosion fatigue based models for near-neutral pH for mechanically short and long cracks and for pressure fluctuations typical of both gas and liquid lines would be of interest.

Incorporation of the R&D guidelines with practical guidelines from field experience

The guidelines provided in the existing consensus standards are based primarily on practical experience. A detailed comparison of these guidelines with those derived here from the R&D literature would provide a more-robust set of guidelines for identifying SCC sites.

Development of industry databases

A number of the SCC Guidelines require input data that are not generally available, most commonly associated with the properties of the pipe or coating. For instance, for predicting high-pH SCC susceptibility, it would be helpful to know the cyclic stress-strain properties of the steel or the porosity of the degraded coating. For near-neutral pH cracking, knowledge of the magnitude and distribution of residual stress is an important parameter. Some data currently exist and should be reviewed and summarized. Additional data could be collected opportunistically from material removed during digs or cut outs. Once a sufficiently large database is available, distributions of these parameters could be developed for use in probabilistic modelling.

Incorporation of SCC Guidelines into consensus standards

It has been suggested that the results of this study could be incorporated into one or more consensus standards. A strategy is required for working with the various standards organizations to achieve this goal.

Statistical basis for number of digs for SCC DA

Unlike ILI or hydrotesting, SCC DA only directly inspects (examines) a small fraction of the pipe. There is continuing debate about how many digs are necessary in a given pipeline segment to ensure a valid DA process. For instance, if three consecutive 12-m-long digs along a 25-km-long valve section show no indications of SCC, is it valid to conclude that the entire section is free of cracking? An associated question relates to the severity of SCC. If one of these same three digs revealed cracking with a maximum depth of 10% of the wall thickness, what is the probability of there being a crack colony with a maximum crack depth of 30-50% of the wall thickness somewhere within the segment?

Other industries face these same issues when doing analogous inspections or when assuring quality in manufacturing processes. For example, the nuclear industry has developed statistical methods for selecting the number and location of fuel channels required to be representative of the condition of the hundreds of channels in the entire reactor. These and other methods should be transferable to the pipeline industry.

5.2 UNDERLYING LABORATORY STUDIES

Growth behaviour of mechanically short (shallow) near-neutral pH SCC cracks

The existing near-neutral pH SCC crack growth models have been developed based on laboratory measurements on cracks and under loading conditions representative of liquid lines or of long (deep) cracks on gas pipelines. It is known from studies in other areas that the mechanism of the growth of mechanically short (shallow) cracks can differ from that of longer (deeper) cracks. Specifically, the crack growth rate can be up to a factor of ten times higher than would be predicted based on the mechanical loading conditions, implying that there may be some environmentally-enhanced mechanism that is not accounted for in typical laboratory tests. This potential under-estimation of the early-stage crack growth rate may explain why the existing corrosion-fatigue models predict lifetimes for gas pipelines significantly greater than the lifetimes indicated by in-service and hydrotest failures. This is an important issue because it affects the growth rate of cracks in precisely that range of depths that are being managed by pipeline operators. The absence of such information is the reason for the current inability to confidently predict re-inspection intervals for gas pipelines based on mechanistic crack growth rate expressions.

Development of a high-pH SCC susceptibility model

There is a high degree of mechanistic understanding of the environmental conditions that lead to high-pH SCC and how they develop in the field. It is possible to predict susceptibility based on operational (CP, temperature) and environmental (groundwater composition, soil moisture content) data that are generally available. Model predictions should be validated by comparison with field measurements.

Characteristics of electrolytes that maintain sharp near-neutral pH SCC cracks

It has been found that certain electrolytes result in sharp crack tips that then resist the tendency for near-neutral pH cracks to become dormant. Counter-intuitively, these environments tend to be quite corrosive, implying that hydrogen generation during corrosion may be responsible for maintaining a sharp crack. Furthermore, the presence of millscale has also been shown to maintain sharp crack tips. An understanding of the factors that maintain sharp cracks would permit better site selection based on environmental conditions or the surface properties of the pipe.

Validated crack-tip strain rate expressions

A number of expressions have been developed for estimating crack-tip strain rates based on a knowledge of the magnitude and frequency of cyclic loading. These expressions are useful for predicting the crack growth rates for both high-pH and near-neutral pH SCC. However, there is significant variation between the different models and a systematic comparison and validation of the different expressions is required.

When do near-neutral pH SCC cracks coalesce?

There are different opinions in the literature regarding when near-neutral pH SCC cracks coalesce. This is an important question since if cracks coalesce early in their life then it is important to predict the time-dependent crack aspect ratio in order to estimate crack growth rates. However, if cracks coalesce just prior to failure then the range of aspect ratios during the majority of the crack growth phase will be limited. This question also affects whether failure results in a rupture or a leak.

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APPENDIX A: SUMMARIES OF THE PUBLISHED R&D LITERATURE

Appendix A contains a collection of the "1-page summaries" for each of the R&D reports, articles, and papers that were critically reviewed as part of this project. (In some cases the summary covers more than a single page).

Each summary includes:

- a unique reference number
- bibliographic information, including title, authors, source, and publication date
- an indication to which of the stages of SCC the article refers and for which form of cracking
- a list of sub-phases or keywords, if any
- a list of the R&D Guidelines listed in Appendix B that were derived from the given study
- a summary of the critical review, including a brief synopsis of the work, a list of ket observations/conclusions, and any summary comments from the current author.

The papers are not listed in any particular order or sequence.

A complete list of references is added at the end of Appendix A.

Ref. no.: 001	
Title: Characteristics of near-neutral-pH stress corrosion cracks in an X-65 pipeline	
Authors: W. Chen, F. King, E. Vokes	
Source: Corrosion 58(3), 267-275	*Year:* 2002
Relevant phase(s) in SCC Guidelines: Crack Initiation, Crack Growth and Dormancy	
Sub-phase/keywords: Crack coalescence, crack initiation, crack morphology	
Results support R&D Guideline no.: None	

Comments:

Paper describes measurements and characterization of near-neutral pH SCC SCC cracks from two relatively small patches (~1"x1") removed from X-65 steel in service for 15-20 years. Experimentally, each patch was mounted and then sequentially polished in the length direction, with measurements of crack depth made at grinding intervals of ~100 μm.

Patches were described as containing dense or sparse cracks, based on spatial separation. In addition, cracks were either "linked" or "independent", with "linked" referring to cracks that had clearly coalesced, based on the multiple peaks on the crack "face." These cracks were generally shallow (<0.5 mm in depth), and the depth did not increase as the crack length increased beyond 2 mm. On the other hand, the "independent" cracks exhibited a smooth crack profile, suggesting the absence of crack coalescence. Characteristics of the crack width (i.e., the distance between the crack walls) were also noted.

Various implications of the cracking mechanism were made based on the measured results, e.g, the possibility of a hydrogen-related mechanism. However, caution should be exercised in using these results as the measurements may have been subject to various experimental artifacts. For example, the width of the cracks would have been influenced by the deformation that occurred during the in-service rupture elsewhere on the pipe from which these samples were taken.

Check if additional Comments made ☐

Ref. no.: 002	
Title: Change of physiochemical parameters of soils near stress-corrosion defects on gas pipelines	
Authors: S.K. Zhigletsova, V.B. Rodin, V.V. Rudavin, G.E. Rasulova, N.A. Alexandrova, G.M. Polomina, V.P. Kholodenko	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 323-333	*Year:* 2008
Relevant phase(s) in SCC Guidelines: Susceptibility	
Sub-phase/keywords: Soil type, large-diameter, gas transmission, tape coating, SCC failures, groundwater, pH, redox potential, near-neutral pH SCC, correlation, land use, Russian	
Results support R&D Guideline no.:	

Comments:

This paper describes Russian experience with developing a “soils model” based on field observations at SCC failure sites. The paper is of interest for the following reasons:

1. it describes foreign (Russian) data and experience with SCC for comparison with North American experience,
2. it deals with severe SCC that led to failures
3. it describes a form of soil transformation known as gleying which is typically associated with near-neutral pH SCC in Canada and the U.S.,
4. it describes the attempted development of a correlative-type predictive model, and
5. the critical review reveals a number of pitfalls and shortcomings that are useful learnings for the development of the guidelines for this study.

A total of 40 excavations were carried out at SCC failure sites at various locations in Russia. All failures occurred on tape-coated NPS48-56 gas transmission pipelines. The different regions where excavations were performed represented different soils types and land uses. Different levels of relative aggressiveness were ascribed to the different regions based on the historical incidence of SCC failures. However, no indication was given that the number of failures had been normalized to the length of pipeline in each region, or had been corrected for different periods of service (although all lines were reported to have been in service for a minimum of 20 years.

Various analyses were made on the groundwater, soil extracts, and directly on the soil itself. After some preliminary technique development, the authors chose the following analyses for their study:

1. field measurements of the pH of the groundwater (if any) and the redox potential (Eh) of the soil in the side of the excavation,
2. laboratory measurements of the soil moisture content and of the concentration of sulphide,
3. laboratory measurements on water extracts of the soil for pH, electrical conductivity, carbonate/bicarbonate, sulfate, nitrate, and chloride ions, and
4. laboratory measurements on acid extracts of the soil for reduced and total iron ions.

Check if additional Comments made ☒

Comments (continued):

Soil samples were taken from immediately adjacent to the pipe (but outside of the coating) and at a distance of 1.5-2.5 m from the pipe. The latter samples were used as “control” samples. Although there is reference in the paper to some measurements of corrosion products, the authors do not seem to have taken many samples at the pipe surface underneath the disbonded coating.

In some cases, sulfate-reducing bacteria were characterized and, although the authors refer to the “activity” of the microbes, it is apparent that only their population was enumerated. There are also references in the paper to the characterization of other microbes, but no data are presented.

The authors presented data from ten sites, nine corresponding to SCC failures and one site with no SCC. Because the sites corresponded to SCC failures, any correlation that might be obtained from this study could relate to any one of the four modules in the current study, i.e., susceptibility, crack initiation, crack growth and dormancy, and crack growth to failure.

The authors reported mean and maximum and minimum values for each of the parameters at each of the ten sites, and for the pipe “surface” and “control” samples. There was little statistically significant correlation between any of the measured parameters and the observation of SCC. Visually, all sites exhibited gleying of the soil (as also reported in North America) and the greatest circumferential extent of gleyed soil was observed in that geographical region deemed to be the most aggressive. This gleying also seemed to be correlated with the ratio of Fe(II) to total Fe in the soil. The authors refer to this Fe(II) as “mobile” iron, but it is not clear from the study how this was determined or what the significance of this observation might be.

There was marginal correlation between redox potential and sulphide concentrations with SCC, with susceptible sites apparently more reducing than less-susceptible sites.

There was no correlation between SCC and the other parameters, including: water content, Cl^-, NO_3^-, electrical conductivity, absolute amount of Fe(II) (as opposed to the Fe(II):Fe_{TOT} ratio).

On the basis of this study, the authors concluded that the presence of mobile iron and of gleyed soil correlated with SCC of gas transmission pipelines and that this might be a useful indicator of susceptibility.

Although this paper presents some interesting data, there are a number of limitations of the work, including:

1. All sites were at locations of SCC failures. The relevance of environmental parameters to the development of deep cracks is uncertain, and the study may have been biased by not focusing on environmental conditions at sites with <u>any</u> cracking, not just the most severe form.
2. The relative aggressiveness of the different areas was not quantified by normalizing the number of failures to the length of installed pipeline or corrected for the different lengths of service. It is possible that the most-aggressive region simply reflected the region with the longest length of pipe in service.
3. A mixture of field and laboratory analyses were used. It is known that samples taken from the field oxidize upon exposure to air, resulting in time-dependent changes in the concentrations of various species. Samples should be taken and maintained in an anaerobic condition.
4. The type of SCC was not identified. Furthermore, the authors erroneously attempted to classify the form of cracking based on the pH pf the soil extract, not of the trapped water.
5. There was a poor use of control samples. The main controls were soil samples taken from SCC sites only further from the pipe. There was only one non-SCC site included in the study.
6. The sample size (10 sites, 20-100 samples per site) was too small for a meaningful correlative model.

Ref. no.: 003	
Title: A correlation between electrochemical parameters and stress corrosion cracking	
Authors: R.D. Armstrong, A.C. Coates	
Source: Corrosion Science 16, 423-433	*Year:* 1976
Relevant phase(s) in SCC Guidelines: Initiation, crack growth and dormancy, crack growth to failure	
Sub-phase/keywords: Crack chemistry, trapped water chemistry, high-pH SCC, electrochemistry, film formation	
Results support R&D Guideline no.:	

Comments:

This paper describes a detailed study of the electrochemical characteristics of C-steel in concentrated carbonate/bicarbonate solutions at 70°C, the environment associated with high-pH SCC. In the laboratory, cracking is associated with a certain range of potentials, which lie on the passive side of the active-passive transition. In this range of potentials, there is a balance between active dissolution of the steel (as might occur at the crack tip to drive crack growth) and passivation (which would occur on the crack walls to maintain passivity).

The study finds a close correlation between the cracking during constant strain SCC measurements and a parameter τ related to the rate of passivation of the electrode in the passive region of the active-passive transition.

This work was some of the earliest published on the electrochemical characteristics of C-steel in the high-pH environment, and was supported by later work by Parkins and co-workers.

The study provides an explanation for the potential-dependence of SCC observed in the laboratory, which should also relate to a similar potential dependence in the field. The potential-dependence of high-pH SCC should be verifiable from field data.

Although the potential-dependence of high pH SCC has been amply demonstrated in the lab, this (as other studies) is based on a number of implicit assumptions:

1. the concentrated high-pH carbonate/bicarbonate environment found under disbonded costing is also present in the crack
2. the potential at the crack tip (which in general is difficult to measure) is the same as, or at least can be related to , the potential on the bold surface (which can be measured)

Check if additional Comments made ☐

Ref. no.: 004	
Title: The effect of pipe surface oxide upon crevice polarization and stress corrosion cracking under fusion bonded low density polyethylene coatings	
Authors: A.A. Fletcher, L. Fletcher, R.J. Morrison	
Source: Fifth Int. Conf. Internal and External Protection of Pipes, Innsbruck, 25-27 October 1983, BHRA Fluid Engineering	*Year:* 1983
Relevant phase(s) in SCC Guidelines: Susceptibility, initiation	
Sub-phase/keywords: Polyethylene coating, millscale, grit blasting, surface finish, polarization, high-pH SCC	
Results support R&D Guideline no.:	

Comments:

This paper describes a study to determine the effect of a pre-existing oxide film on the polarization behaviour of the pipe. High-pH SCC is known to occur within a given potential range, which can theoretically be avoided through proper cathodic protection, However, if the pipe surface is covered by an oxide which affects the polarization behaviour of the surface, the pipe surface potential may stay within the cracking range for longer than expected.

Different effects of surface condition (millscale, grit blasted, heavy or light rust scales) were observed at levels of cathodic polarization.

This work has implications for the susceptibility of different surface finishes to the development of potentials for cracking.

With adequate construction and operations records, the results from this study may be useful for ranking susceptibility of lines to high-pH SCC based on the nature of the surface pretreatment applied to the pipe before coating. However, the results may be limited to fusion-bonded polyethylene coatings, which are not widely used in North America.

Check if additional Comments made ☐

Ref. no.: 005
Title: Hydrogen-facilitated anodic dissolution-type stress corrosion cracking of pipeline steels in near-neutral pH solution
Authors: B. Gu, J. Luo, X. Mao
Source: Corrosion 55, 96-106 — *Year:* 1999
Relevant phase(s) in SCC Guidelines: Crack initiation, crack growth, near-neutral pH SCC
Sub-phase/keywords: CO_2, pH, potential, HIC, threshold
Results support R&D Guideline no.: N001, N002, N003, N004, N005, N006, N007, N008

Comments:

Paper describes the results of an experimental program in which the effects of H on (i) the dissolution rate, (ii) SSRT behaviour, (iii) the appearance of the fracture surface were determined. The work provided evidence in support of a H-facilitated anodic dissolution mechanism for NNpH SCC.

Experimental: X-52 and X-80 pipeline steels in as-received condition (from service?), NS-4 solution, pH 3-8 (pH adjustment using CO_2/N_2 or H_2SO_4), SSRT at strain rates of 2×10^{-7} to 8×10^{-6} s^{-1}, limited CT crack growth tests (no details given), CV's at scan rate of 1 mV/s, SIMS analysis for H distribution in loaded CT specimens, SEM on SSRT fracture surfaces, aggressive H pre-charging in acidified As_2O_5 solution at 3 mA/cm^2 for 24 hrs.

Key findings:

1. Dissolution current in passive and active regions increases for H pre-charged specimens in $NaHCO_3$ and NS-4 solutions.
2. Reduced ductility and maximum stress for H pre-charged specimen during SSRT in NS-4 solution, but little or no effect of H pre-charging for specimens tested in air.
3. Susceptibility to SCC (as measured by %RA of SSRT specimens) increases with decreasing pH and potential.
4. At the same pH, samples tested in solution in which pH was adjusted by CO_2/N_2 were more susceptible than in solutions in which the pH was adjusted using H_2SO_4, suggesting a role for CO_2 other than simply pH adjustment.
5. %RA of H pre-charged specimens lower at intermediate potentials, but little effect under cathodic polarization at -1.0 V_{SCE} or at -0.3 $V_{SCE.}$
6. Distribution of H exhibits two peaks, one at crack tip (location of highest stress) and one ~1 mm ahead of crack tip (location of highest hydrostatic stress).
7. Peak H concentration increases with decreasing pH.
8. Increased quasi-cleavage on fracture surfaces with conditions leading to increasing H.
9. Proposed H-assisted anodic dissolution mechanism to account for observed increased initiation and propagation of NNpH SCC with increasing H content.

Check if additional Comments made ☒

Comments (continued):

1. Proposed thermodynamic model to account for enhanced dissolution in presence of H. However, model ignores any kinetic effect of H on the exchange current density for the Fe dissolution reaction.
2. Propose that NNpH SCC occurs at E/pH below the H_2/H_2O equilibrium line but above a threshold E/pH for HIC
3. Propose pH-dependent potential threshold for HIC of E = -0.567 – 0.0514pH V_{SCE} at 25^{o}C.

Evidence for effect of H on dissolution is at potentials far removed from E_{CORR} and for aggressive H-charging conditions. Thermodynamic model for H effects ignores kinetic effects.

Ref. no.: 006	
Title: Stress intensification and crack growth in the presence of dents on pipelines	
Authors: J. Been, B. Carroll, A. Dinovitzer, R. Sutherby	
Source: Proc. IPC 2006, ASME (New York, NY), paper IPC2006-10415	*Year:* 2006
Relevant phase(s) in SCC Guidelines: Susceptibility, crack growth	
Sub-phase/keywords: Dents, mechanical damage, stress raisers	
Results support R&D Guideline no.: N009, N010, N011	

Comments:

Presents an analysis of the effects of dents on NN pH SCC SCC through a combination of an existing corrosion fatigue model and an existing Dent Assessment Model (DAM).

Dent is assumed to affect only K_{max} and ΔK, which are the crack driving forces in the corrosion fatigue model. The effect of the dent on K_{max} and ΔK is estimated by abstracting Stress Intensification (SI) factors from detailed FEA of the stresses around the dent. Stresses were calculated for 80% SMYS and for zero operating stress; for both constrained and unconstrained dents; for indent diameters of 50, 100, and 200 mm; and for NPS36 and NPS42 Grade 448 (X-65) pipe with a wall thickness of 9.53 mm (0.375"). The SCC model was run using a pressure spectrum for an oil pipeline.

The results of the DAM indicated that:

- the SI varied from 1 to 2 at different locations around the dent
- the SI was higher for unconstrained dents (up to a value of 2) than for restrained dents (SI $\leq$ 1.4)
- SI was not affected by the pipe diameter
- SI did not vary monotonically with indenter diameter
- for an unconstrained dent, the stressed area was larger for the 200 mm indenter due to the joining of areas of high stress
- lower ductility resulted in higher local stresses at an unrestrained dent

When these results were combined with the SCC model, the conclusions were"

- crack growth rate was higher for unconstrained dents
- crack growth is promoted by larger high-stressed areas as cracks slow when encountering lower stresses
- lower ductility, higher strength material resulted in higher crack growth rates

It was suggested that the effects of dents may be less for gas lines (for which the mechanical driving forces are smaller) and for short (shallow) cracks.

It should be noted that the SI were derived for surface stresses only which were assumed (a) to be the same throughout the wall thickness and (b) to be unaffected by crack growth. The conclusion that more damage occurs for unconstrained dents is not supported by field evidence suggesting more damage on the lower part of the pipe (which are assumed to be due to rocks).

Check if additional Comments made ☐

Ref. no.: 007	
Title: Thermodynamic analysis on the role of hydrogen in anodic stress corrosion cracking	
Authors: L. Qiao, X. Mao	
Source: Acta metal. mater. 43(11), 4001-4006	*Year:* 1995
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, growth	
Sub-phase/keywords: -	
Results support R&D Guideline no.: None	

Comments:

This paper is the basis for subsequent studies in which a H-assisted anodic dissolution mechanism is proposed for the initiation and propagation of NNpH SCC. The evidence presented is for systems other than C-steel in dilute groundwater solutions, such as austenitic stainless steels in boiling LiCl solution.

A general theoretical derivation of the effect of H on the rate of dissolution is provided. The separate and synergistic effects of stress and hydrogen on the rate of dissolution are considered, leading to three enhancement factors k_H, k_σ, and $k_{H\sigma}$ for the dissolution rate (current density) i_A

$$i(\sigma,H) = k_H \cdot k_\sigma \cdot k_{H\sigma} \cdot i_A$$

k_H is related to change in free energy of the lattice due to the absorption of H in the absence of a volume change, k_σ is related to the strain energy density in the absence of hydrogen induced by stress, and $k_{H\sigma}$ is related to the volume change of the lattice due to absorption of H.

Expressions are given for the temperature-dependent factors k_H, k_σ, and $k_{H\sigma}$. Using typical values for the various parameters involved, an enhancement factor of ~3 was estimated for austenitic stainless steels in boiling chloride solutions.

The major concerns with this model and its derivation are:

- The evidence for H-enhanced dissolution is generally obtained from samples which have undergone severe charging in acidic environments containing H-recombination poisons and which, therefore, contain very high concentrations of absorbed H. The relevance of any enhanced dissolution observed to less-severe charging conditions is unclear.
- It is explicitly assumed that the effects of H and stress on the dissolution behaviour are due only to the thermodynamic driving force for dissolution, not the kinetics of the reaction. No justification is provided for this arbitrary decision. An alternative derivation could be easily developed based on the assumption that H and stress only affect the kinetics of dissolution (e.g., through effects on the exchange current density).

Check if additional Comments made ☐

Ref. no.: 008	
Title: Hydrogen evolution and enrichment around stress corrosion crack tips of pipeline steels in dilute bicarbonate solution	
Authors: L.J. Qiao, J.L. Luo, X. Mao	
Source: Corrosion 54(2), 115-120	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N012	
Comments: Provides experimental evidence for the distribution of H around the crack tip and the parameters that affect the amount and distribution of H. H profiles detected by SIMS. Effects of pH, potential, and stress intensity considered. Enrichment of H at tip of notch (NB. notch not crack) enhanced by decreasing pH, more-negative potential, and increasing stress intensity. Stress intensity, in particular, seems to have a significant effect, with enhancement factors at the notch tip of 2, 5, and 9.5 over that for unloaded samples for stress intensities of 21 $MPa{\cdot}m^{1/2}$, 70 $MPa{\cdot}m^{1/2}$, and 87 $MPa{\cdot}m^{1/2}$, respectively. Little difference in enhancement between X-52 and X-80 steels. However, extreme charging conditions were used, with a current density of 10 mA/cm^2 in the presence of thiourea (H recombination poison).	

Check if additional Comments made ☐

Ref. no.: 009	
Title: Effect of hydrogen on the mechanical properties of X-70 pipeline steel in diluted $NaHCO_3$ solutions at different heat treatments	
Authors: A. Torres-Islas, V.M. Salinas-Bravo, J.L. Albarran, J.C. Gonzalez-Rodriguez	
Source: Int. J. Hydrogen Energy 30, 1317-1322	*Year:* 2005
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Determined effects of heat treatment (as-received, water sprayed, water quenched, quenched and tempered) on susceptibility of X-70 pipeline steel to NNpH SCC in bicarbonate-containing (0.005, 0.01, 0.05, 0.1 mol/L) solution as estimated from %RA from SSRT. Specimens were precharged with H in an acidic As_2O_3-containing solution. Results expressed as a factor I_{SCC} given by $(RA_{AIR} – RA_{SOLN})/RA_{AIR}$. The authors suggest that I_{SCC} values close to unity indicate no effect of the environment. But if there was no effect of the environment, then $RA_{SOLN} = RA_{AIR}$ and $I_{SCC} = 0$. In fact, an absence of any environmental effect is indicated by an I_{SCC} value of 0. The value of the conclusions from this paper, which are based mostly on the values of I_{SCC}, is, therefore, uncertain. H permeation tests also performed. The permeation current increased with increasing bicarbonate concentration, although no details of the solution pH or purge gas were given. It is noteworthy that the severity of SCC, as measured by the value of I_{SCC}, decreased with increasing bicarbonate concentration. This is contrary to the expected behaviour given the increase in H permeation current and supports the suggestion above that I_{SCC} is, in fact, directly related to the SCC severity.	

Check if additional Comments made ☐

Ref. no.: 010	
Title: The influence of hydrogen on crack growth in pipelines	
Authors: R.N. Parkins	
Source: Proc. Materials for Resource Recovery and Transport, L. Collins (ed.), (Metallurgical Society of Canadian Institute of Mining, Metallurgy and Petroleum (CIM), Montreal, QC), p. 35-49.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N013	
Comments: Review of various forms of environment-sensitive cracking of pipeline steels, with emphasis on NNpH SCC. Discusses various mechanisms of hydrogen-assisted failures of ferritic steels, in particular decohesion and localized plasticity (otherwise referred to as hydrogen-enhanced localized plasticity or HELP). Dissolution is also likely involved to some extent (although the observation of areas of quasi-cleavage on fracture surfaces rules out extensive dissolution), but does not discuss H-enhanced dissolution. Concludes that, at the time of publication, the mechanism of NNpH SCC was uncertain, but the involvement of H was possible. This hinders the development of predictive models, and imposes more reliance on the measurement of crack growth rates for lifetime predictions.	

Check if additional Comments made ☐

Ref. no.: 011	
Title: Factors influencing stress corrosion cracking of carbon steel in diluted bicarbonate environments	
Authors: M. Yunovich, Z. Xia, Z. Szklarska-Smialowska	
Source: Corrosion 54(2), 155-161	*Year:* 1998
Relevant phase(s) in SCC Guidelines: High-pH SCC crack growth	
Sub-phase/keywords: Cathodic polarization, CP, cold work, hydrogen, X-52	
Results support R&D Guideline no.: H001, H002, H003	

Comments:

SSRT with specially designed test specimens to allow study of the effect of cold work. Tests performed in 0.01 mol/L $NaHCO_3$ at 50°C (pH 8-11) at potentials between E_{CORR} and -1.0 V_{SCE}. The effect of aeration was also studied for non-cold worked specimens. The amount of cold work introduced into the specimen during manufacture was expressed as an equivalent degree of "engineering bending" (ε). Specimens with 35% ε gave similar results to specimens made from plate with 35% cold rolling, suggesting that ε is a reasonable measure of the amount of cold work.

The results obtained suggested that:

- Cold work increases the susceptibility to SCC, with a maximum sensitivity at ~20%
- Aeration increased the susceptibility to SCC at E_{CORR} at pH 8 and 10
- Increasing pH lead to a decrease in susceptibility at E_{CORR}
- CP increased the susceptibility to SCC, particularly at pH 10 and pH 11

Because the time-to-failure of the tensile specimens was the major measure of SCC susceptibility, and because no fractographic evidence is presented, it is difficult to be certain that the failure mechanism was the same for all conditions considered. The introduction of cold work could have increased the susceptibility to HIC, especially under cathodic polarization. Aeration at E_{CORR} may have shifted the potential into the cracking range.

Study at the dilute and low pH end of the ranges associated with high-pH SCC.

However, in general terms, the results suggest an adverse effect of cold work and cathodic polarization.

Check if additional Comments made ☐

Ref. no.: 012	
Title: Transgranular stress corrosion cracking of high-pressure pipelines in contact with solutions of near neutral pH	
Authors: R.N. Parkins, W.K. Blanchard Jr., B.S. Delanty	
Source: Corrosion 50(5), 394-408	*Year:* 1994
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Mechanism, hydrogen, dissolution, SSRT	
Results support R&D Guideline no.: N014, N015, N016, N017, N018, N019	

Comments:

One of the first detailed studies of NNpH SCC published in the open literature.

SSRT (strain rate 2 x 10^{-6} s^{-1}), X-65, four test solutions designated NS1-NS4, with and without CO_2 purging, E_{CORR} and controlled potential, 5-45°C.
Cyclic load tests, room temperature, NS4, CO_2/N_2 purge (pH 6.5), tests at E_{CORR} (-0.68 to -0.72 V_{SCE}) and at a controlled potential of -0.7 V_{SCE}, longitudinal tensile specimens with one millscale-covered and one polished surface, cyclic load tests at range of maximum stress (345, 414, 483, and 552 MPa (50, 60, 70, 80 ksi)) and R values, frequencies of 0.074 Hz and 0.00032 Hz, test times 1 week to 3 months

Summary of key observations:

- SSRT
  - No significant effect of sample orientation (longitudinal or transverse)
  - In absence of CO_2 (pH 8.2), two distinct zones of susceptibility at -0.7 V_{SCE} and one at -0.9 V_{SCE} and lower, the latter thought to be due to H
  - In presence of 100% CO_2 (pH 5.8), %RA significantly lower than in CO_2-free solutions and more cracks initiated and %RA decreased with increasing cathodic polarization
  - In presence of 5% CO_2/N_2, again two zones of susceptibility
  - No systematic effect of temperature
  - Fracture surfaces exhibited evidence of quasi cleavage, characteristic of HIC
  - TGSCC
- Cyclic load tests
  - Cracks rarely initiated on polished side of specimens
  - Cracks initiated in groups
  - Coalescence occurred if vertical crack separation $y < 0.156 \cdot (2a)$, similar to observations on large cracks from the field
  - Crack velocity increased with increasing stress
  - No corrosion at crack tip, but crack walls away from crack corrode

Check if additional Comments made ☒

Comments (continued):

Solutions did not exhibit active-passive behaviour and maximum dissolution rate was orders of magnitude lower than the observed crack growth rate from SSRT. Therefore, discount the possibility of a dissolution mechanism, although large amounts of corrosion products indicate that some dissolution does occur.

Suggested that propensity for cracks to form from original surface is due to localization of aggressive chemistry (acidification and concentration of Cl^- and sulphate) in "pits", rather than stress concentration. Lower pH in pit promotes H evolution which plays some undefined role in initiation. Proposed a significant role for pits in crack initiation, the stochastic nature of pitting explaining to some degree the scatter in crack growth rates.

Suggested a role of H, since significant loss of ductility was observed even in specimens with no or few initiated cracks. Role of CO_2 is to lower pH to facilitate H formation.

No evidence for continued crack nucleation in cyclic load tests, as there is for high-pH SCC.

Tendency for cracks to initiate in close proximity to each other is important for crack coalescence and, hence, crack growth. High-pH SCC cracks tend to initiate at random locations. For NNpH SCC propensity for cracks to initiate close by may suggest a role of H, which will tend to accumulate at crack tips as locations of high stress.

Evidence that crack coalescence is less important in the latter stages of the growth of NNpH SCC cracks than for high-pH SCC. For NNpH SCC, crack coalescence occurs in the early stages of crack growth.

Ref. no.: 013	
Title: Effect of cathodic protection on corrosion of pipeline steel under disbonded coating	
Authors: X. Chen, X.G. Li, C.W. Du, Y.F. Cheng	
Source: Corrosion Science 51, 2242-2245	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: Coating, shielding, CP, corrosion, pH	
Results support R&D Guideline no.: N020	

Comments:

Experiments based on a simulated disbonded shielding coating with measurement of potential, pH, and [O_2] profiles down the 25-cm-long disbondment. Various potentials, ranging from OCP (approx. -0.70 V_{SCE}) to -1.2 V_{SCE}, applied at mouth of disbondment. Bulk solution aerated 0.01 mol/L Na_2SO_4. Height of disbondment controlled by a 0.9-mm-thick plastic shim. Although it states that the height of the disbondment could be adjusted, no height (other than the 0.9 mm height of the shim) is given; therefore, it is assumed that the disbondment height for the tests reported was 0.9 mm.

Key observations:

- O_2 is largely consumed within a distance of 5 cm of the mouth of the disbondment
- after 72 h, CP is able to penetrate to the bottom of the disbondment resulting in an increase in pH
  - the measured potentials at a depth of 25 cm for different levels of CP were
    - -0.70 V_{SCE} for a CP level of -0.775 V_{SCE}
    - -0.80 V_{SCE} for a CP level of -1.0 V_{SCE}
    - -0.875 V_{SCE} for a CP level of -1.2 V_{SCE}
  - thus, although there was iR drop down the disbondment, there was significant penetration to the maximum depth measured of 25 cm

The reported results suggest that significant cathodic protection can be achieved to depths of up to 25 cm under shielding disbondments. This conclusion seems contrary to observations from the field.

Check if additional Comments made ☐

Ref. no.: 014	
Title: Characterization of corrosion of X70 pipeline steel in thin electrolyte layer under disbonded coating by scanning Kelvin probe	
Authors: A.Q. Fu, X. Tang, Y.F. Cheng	
Source: Corrosion Science <u>51</u>, 186-190	*Year:* 2009
Relevant phase(s) in SCC Guidelines: High-pH SCC, NNpH SCC, suscpetibility	
Sub-phase/keywords: Passivation, thin layer, humidity, moisture content	
Results support R&D Guideline no.: N021	

Comments:

Used SKP to characterize electrochemical characteristics of X-70 pipeline steel in thin films. NS4 solution purged with 5% CO_2/N_2 to represent NNpH SCC conditions and 0.05 mol/L Na_2CO_3 + 0.1 mol/L $NaHCO_3$ + 0.1 mol/L NaCl to represent high-pH SCC conditions (no indication if any purge gas was used for the high-pH solution, but discussion refers to O_2 reduction so suspect solution was aerated). Tests performed at 22^{o}C. Thin solution layer covered by a 100-μm-thick (4 mil) FBE layer. Polarization scans performed at 0.5 mV/s.

Key observations:

- Apparent passive current observed in NS4 solution for solution layer thickness of 60 μm, but less apparent in thicker solution layers and not apparent at all in bulk solution.
- In concentrated carbonate/bicarbonate solution, passive region observed regardless of solution film thickness.
- In NS4 solution, anodic and cathodic currents increased with time (results reported for 1 h and 1 day), even in the apparent passive region in the 60-μm-thick layer.
- In concentrated carbonate/bicarbonate solution, evidence for cathodic limiting current in thin solution layers, but not in bulk solution.

Key conclusions:

- Passivation of C-steel in dilute electrolyte represent of NNpH SCC environments is possible, contrary to conclusions from studies in bulk solution.
- Passivation thought to be due to precipitation of $FeCO_3$ from super-saturated solution.
- In thin films, evidence for transport-limited O_2 reduction, but not in bulk high-pH solution. Conclude that reduction of H_2CO_3 and HCO_3^- are main cathodic reactions in bulk high-pH solution.
- Increase in dissolution rate with time in NS4 solution is ascribed to a self-catalytic role of adsorbed Fe(I) and Fe(II) species.
- The presence of a passive film under NNpH SCC conditions will inhibit H entry. Hence, H may play less role in NNpH SCC mechanism than otherwise believed.

Comments:

- Possibility of passivation in thin-film NNpH solutions is an interesting one, as is the possibility of blocking H pickup.
- However, the observed increase in current with time is troubling and the proposed mechanism involving adsorbed species is unlikely and, of course, cannot explain the observed increase in the rate of the cathodic reaction
- The inference that the reduction of H_2CO_3 and HCO_3^-, and not of O_2, are the main reactions in bulk solution is unlikely to be correct as the concentration of H_2CO_3 is vanishingly small at those pH values and the kinetics of HCO_3^- reduction are slow. The observation for a limiting cathodic current in the thin-film studies may be due to O_2 transport control through the FBE layer.

Check if additional Comments made ☐

Ref. no.: 015	
Title: Local additional potential model for effect of strain rate on SCC of pipeline steel in an acidic soli solution	
Authors: Z.Y. Liu, X.G. Li, C.W. Du, Y.F. Cheng	
Source: Corrosion Science doi:10.1016/j.corsci.2009.08.019	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility	
Sub-phase/keywords: Mechanism, hydrogen	
Results support R&D Guideline no.: None	
Comments: Propose a local additional potential model (LAPM) to account for the effect of strain rate on SCC. According to this model, strain results in an increase in the number of emergent slip planes, which in turn result in local additional polarization of the surface (either cathodically in the presence of CP or anodically in the presence of anodic polarization). Attribute maximum SCC susceptibility at a strain rate of 10^{-6} s^{-1} during SSRT to enhanced H evolution due to cathodic local polarization.	

Check if additional Comments made ☐

Ref. no.: 016

Title:
Corrosion fatigue and near-neutral pH stress corrosion cracking of pipeline steel and the effect of hydrogen sulfide

Authors:
R.L. Eadie, K.E. Szklarz, R.L. Sutherby

Source: Corrosion 61(2), 167-173	*Year:* 2005

Relevant phase(s) in SCC Guidelines:
Near-neutral pH SCC crack growth

Sub-phase/keywords:
Mechanism, corrosion fatigue, hydrogen, H_2S

Results support R&D Guideline no.:
N022, N023, N024

Comments:

Corrosion fatigue study of X-70 in dilute electrolyte purged with 10% CO_2 at 30°C, using distribution of R values typical of gas transmission line operation, but at higher frequency (0.04-4 Hz, as opposed to 10^{-5} Hz typically on gas lines). Also performed tests with 1% H_2S + 10% CO_2 purge. K_{MAX} values were in the range 50-76 $MPa \cdot m^{1/2}$ and ΔK in the range 7.5-27.5 $MPa \cdot m^{1/2}$. Fatigue tests in air also performed.

Key observations:
- crack advance observed in both CO_2-purged and H_2S/CO_2-purged solutions
- presence of H_2S resulted in a factor of 5-10 greater crack advance
- apparent threshold ΔK of ~10 $MPa \cdot m^{1/2}$

Key conclusions:
- crack advance can be explained by a corrosion fatigue model
- if conclusions also true at lower frequency, then NNpH SCC may be explained by a CF mechanism
- sulphide had a significant impact
- magnitude of the threshold ΔK suggests that stress intensification would be required for the growth of short (shallow cracks)

Comments:
- one of the first papers to suggest a CF mechanism for NNpH SCC
- aggressive loading conditions and, as noted by authors, would require stress intensification to account for growth of shorter cracks and/or for most gas lines
    - for example, a 6-mm deep crack on a 12-mm wall, NPS 42, operating at 6000 kPa is equivalent to a K_{MAX} of 68 $MPa \cdot m^{1/2}$ with ΔK values for typical gas lines fluctuations of <12 $MPa \cdot m^{1/2}$
- although H_2S clearly has an effect, 1% in the gas phase is likely to be much more than is present in an external soil environment
- effect of sulphide is consistent with both anodic dissolution and H corrosion contributions

Check if additional Comments made ☐

Ref. no.: 017	
Title: Fundamentals of hydrogen evolution reaction and its implications on near-neutral pH stress corrosion cracking of pipelines	
Authors: Y.F. Cheng	
Source: Electrochim. Acta 52, 2661-2667	*Year:* 2007
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: H-assisted anodic dissolution, thermodynamic model	
Results support R&D Guideline no.: N001	

Comments:

Electrochemical study of HER on, and H permeation through, X-70 pipeline steel in NS4 and four soil extracts (purged with 5% CO_2/N_2). SSRT tests also performed with susceptibility determined from %RA.

Key observations:

- X-70 pipeline steel corrodes under active conditions with no film formation
- cathodic Tafel slope is very large (more negative than -450 mV/dec) and becomes larger (more negative) as the potential is scanned more anodically during the potential scan
- %RA decreases linearly with increasing sub-surface H concentration

Key conclusions:

- NNpH SCC does not obey a slip-dissolution mechanism
- form of H-assisted anodic dissolution model proposed

Comments:

- as with the original formulation of the H-assisted anodic dissolution model by Qiao and Mao (1998), the H-assisted dissolution model developed here is based on assumption that the presence of H and stress affects the thermodynamics only
- an additional enhancement factor for the dissolution rate is defined compared with the original Qiao and Mao (1998) model due to the effect on the anodic dissolution reaction of the difference in H concentration between the stressed and unstressed metal

Check if additional Comments made ☐

Ref. no.: 018	
Title: Micro-electrochemical characterization of the effect of applied stress on local anodic dissolution behavior of pipeline steel under near-neutral ph condition	
Authors: X. Tang, Y.F. Cheng	
Source: Electrochim. Acta 54, 1499-1505	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Stress-assisted dissolution	
Results support R&D Guideline no.: N025	

Comments:

Localized electrochemical impedance spectroscopy (LEIS) and scanning vibrating microelectrode (SVME) study of the effect of stress on the anodic dissolution of ferrite-pearlite X-70 in NS4 solution purged with 5% CO_2/N_2 at 22°C. Smooth tensile and pre-cracked CT specimens.

Key observations:

- anodic dissolution rate of steel is enhanced by applied tensile stress, especially at stress levels greater than 80% YS
- a similar effect is observed at a crack tip under tensile load
- dissolution rate increases with time due to increasing stress intensification at the tip of the growing crack

Comments:

- the conclusions from this paper would seem to support a form of dissolution model, contrary to the conclusions of other papers from the same group

Check if additional Comments made ☐

Ref. no.: 019	
Title: Effect of inclusion on initiation of stress corrosion cracks in X70 pipeline steel in an acidic soil environment	
Authors: Z.Y. Liu, X.G. Li, C.W. Du, L. Lu. Y.R. Zhang, Y.F. Cheng	
Source: Corrosion Science 51, 895-900	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: Alumina, Si	
Results support R&D Guideline no.: N026, N027	

Comments:

Ferrite-marten-austenitic X-70 exposed to acidic (pH 4.0-4.5) Chinese soil solution, pH adjustment with acetic acid, N_2 purge. Tensile specimens loaded monotonically at a strain rate of 5×10^{-7} s^{-1} under potential control (-0.65, -0.85, -1.20 V_{SCE}). Specimens polished to 800 grit. Specimens pre-exposed to test solution for 24 h before testing.

Key observations:

- Specimens slightly anodically polarized at potential of -0.65 V_{SCE} and cathodically polarized at -0.85 and -1.20 V_{SCE}
- Cracks initiated at Al-containing inclusions particularly under cathodic polarization, but not Si-containing inclusions
- Cracks did not initiate under anodic polarization

Key conclusions:

- initiation promoted by H
- Trapping of H at "interstices" (apparently voids between the inclusion and steel matrix, possibly resulting from the pre-exposure to the acidic soil solution) promotes the development of cracks (presumably by developing a H_2 pressure?)

Comments:

- the relevance of these observations, as with all initiation studies involving polished samples, for vintage steels covered by a millscale is questionable

Check if additional Comments made ☐

Ref. no.: 020	
Title: Characterization of corrosion of X65 pipeline steel under disbonded coating by scanning Kelvin probe	
Authors: A.Q. Fu, Y.F. Cheng	
Source: Corrosion Science 51, 914-920	*Year:* 2009
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation	
Sub-phase/keywords: Wet-dry cycle, oxygen, FBE	
Results support R&D Guideline no.: None	

Comments:

SKP measurements on FBE-coated X-65 pipeline steel, 0.05 mol/L Na_2CO_3 + 0.1 mol/L $NaHCO_3$ + 0.1 mol/L NaCl (pH 9.6) at 22^{o}C.

Key observations:

- Kelvin potential of coated area shifts negatively with time indicative of water uptake
- Kelvin potential on disbonded area shifts negatively with time (more so than on intact coating), attributed to corrosion reaction
- Upon wet-dry cycling solution layer thickness decreases and solute concentration increases. Resulting negative shift in Kelvin potential attributed to decrease in O_2 solubility and decrease in corrosion rate.

Comments:

- Negative shift in Kelvin potential is variously attributed to an increase in corrosion rate for disbonded coating and a decrease in corrosion rate during wet-dry cycling

Check if additional Comments made ☐

Ref. no.: 021	
Title: Effect of solution composition and electrochemical potential on stress corrosion cracking of X-52 pipeline steel	
Authors: R.B. Rebak, Z. Xia, R. Safruddin, Z. Szklarska-Smialowska	
Source: Corrosion 52(5), 396-405	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Sulphate, transgranular, intergranular, mixed-mode cracking	
Results support R&D Guideline no.: N028, N029, N030, N031, N032	

Comments:

Experimental study in a range of sulphate- and bicarbonate-based solutions (0.1 mol/L Na_2SO_4 at pH 6 and 8; 0.01 mol/L Na_2SO_4 pH 6; 0.1 mol/L $NaHCO_3$ pH 8.3; 0.01 mol/L $NaHCO_3$ pH 8.3; NS-4 at pH 8.3), performed at 50°C. SSRT (2.3 x 10^{-7} s^{-1} and 3.2 x 10^{-6} s^{-1}) and constant load (55 $MPa \cdot m^{1/2}$, OCP, NS4 solution) tests, X-52, NPS30 pipe from two different sources, ferrite-pearlite with abundant MnS inclusions. SSRT samples included cold work deformation.

Key observations:

- cracking observed in all solutions studied at E_{CORR} and more-negative potentials
- minimum susceptibility at E_{CORR} and increased with increasing cathodic polarization
- anodic polarization reduced extent of SCC
- CGR of the order of 10^{-6} mm/s, approximately 100x faster than observed in field
- threshold potential of -0.725 V_{SCE} above which susceptibility to SCC diminished
- cold work and localized strain enhanced cracking
- in a given solution, crack path changes with potential, with IG predominant at anodic potentials and TG at cathodic potentials

Key conclusions:

- because of enhanced SCC at cathodic potentials, hydrogen embrittlement is most likely mechanism

Comments:

- non-traditional solutions used
- interesting that crack path changes with pH
- could mechanism be different under cathodic polarization (HIC) than at E_{CORR}?

Check if additional Comments made ☐

Ref. no.: 022

Title:
Distribution of steady-state cathodic currents underneath a disbonded coating

Authors:
R. Brousseau, S. Qian

Source:	*Year:*
Corrosion 50 (12), 907-911	1994

Relevant phase(s) in SCC Guidelines:
NNpH SCC susceptibility

Sub-phase/keywords:
Disbondment, shielding coating, CP penetration

Results support R&D Guideline no.:
N033

Comments:

Simulated shielding disbondment tests to determine penetration of CP along disbondment. Acrylic simulated coating, polished steel specimens, E and pH microelectrodes, very dilute mM solution, tests performed up to 388 h. Tapered disbondment height (8 mm at mouth, 0 mm at ~400 mm from mouth)

Key observations:

- CP penetrates a distance of a 10-12.5 cm from mouth of disbondment
- higher CP levels promote greater penetration
- some CP penetration even to depths of 30+ cm
- CP penetration accompanied by increase in pH, although increased pH far into disbondment may be due to diffusion of OH^- from closer to mouth
- less penetration of CP in higher-resistivity solutions

Key conclusions:

- application of higher CP potentials could promote protection inside disbondment

Comments:

- increase in pH in disbondment inconsistent with field observations that CP does not penetrate into disbondment, unless CO_2 diffusing through coating maintains a lower pH in the disbondment

Check if additional Comments made ☐

Ref. no.: 023	
Title: Transgranular stress corrosion cracking of low-alloy steels in diluted solutions	
Authors: G. Gabetta	
Source: Corrosion 53(7), 516-524	*Year:* 1997
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Review	
Results support R&D Guideline no.: None	
Comments: Review of TGSCC of low alloy steels, primarily nuclear reactor pressure vessel steels, and implications for NNpH SCC of underground pipelines. Key conclusions: • generally considered that HIC is involved	

Check if additional Comments made ☐

Ref. no.: 024	
Title: Role of stress in transgranular stress corrosion cracking of transmission pipelines in near-neutral pH environments	
Authors: S.L. Asher, P.M. Singh	
Source: Corrosion 65(2), 79-87	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: Hydrogen, inclusions	
Results support R&D Guideline no.: N034, N035, N036	

Comments:

SSRT on polished samples, smooth and notched samples, 0.006 or 0.012 mol/L $NaHCO_3$ solution purged with 5% CO_2, E_{CORR} at room temperature. Samples either monotonically loaded at a strain rate of 2 x 10^{-6} in/s or interrupted loading with a hold of 24 h at 100 MPa intervals, with longer hold times (up to 30 d) for notched samples at 85% YS.

Key observations:

- exposure of samples to NNpH SCC conditions under stress-free conditions did not lead to degradation of mechanical properties
- smooth samples loaded to 85% YS exposed to NNpH SCC environment did not experience any loss in mechanical properties
- notched samples loaded to 85% YS exposed to NNpH SCC exhibited evidence for quasi-cleavage and a degree of embrittlement that increased with exposure time
- stressed samples exhibited localized corrosion near MnS inclusions, with development of pits at ~30% YS
- inclusions fail by brittle fracture at ~65% YS
- at stresses just below 100% YS, cracks initiated at pits formed by dissolution of inclusions as a result of stress concentration by pits

Key conclusions:

- stress concentration required for adequate H to accumulate in order to promote cracking
- local dissolution at or near inclusions result in localized corrosion which, in turn, acts as a stress raiser
- NNpH SCC cracks develop from pits at stresses ~YS
- crack-like features due to inclusion removal observed at 30% YS

Comments:

- as with all studies related to initiation which employ polished samples, the relevance to millscale-covered surfaces is unclear
- distinction between cracks initiating from sites of inclusions at 30% YS and cracks initiating at pits (which develop from inclusions) at 100% YS confusing, but might indicate chemical as well as mechanical effect of inclusions

Check if additional Comments made ☐

Ref. no.: 025	
Title: A statistical model for the prediction of SCC formation along a pipeline	
Authors: O.O. Youzwishen, A. Van Aelst, P.F. Ehlers, A. Nettel	
Source: Proc. IPC 2004 (ASME, New York, NY), paper IPC04-0267	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility	
Sub-phase/keywords: Model, correlation, bend	
Results support R&D Guideline no.: None	

Comments:

Statistical correlation of SCC found, or not found, during excavations to environmental (soil conditions, drainage, local geography) and operational data (pipe geometry, metal loss features, CIS, operating pressure). Multi-variable regression statistical tools used. Tool "trained" against complete data set. Eleven sites selected for verification, including 10 high-probability and one low-probability site.

Key observations:

- of the ten "high-probability" verification sites, seven exhibited SCC
- SCC was not found at the one "low-probability" site
- overall success rate 73% (8 of 11)
- predictors showing best correlation with SCC, and which were included in the final version of the model, were:
    - CP on-potential
    - iR drop
    - presence of ground depression
    - bend angle of pipe
    - direction of bend (side or over/under bend)
    - proximity to metal loss and whether metal loss was near girth weld
    - metal loss severity

Comments:

- model does not seem to discriminate severity of cracking, as the seven positive verification sites exhibited depths of 5-50%
- not, in itself, useful for identifying mechanistic guidelines, but useful for validation purposes

Check if additional Comments made ☐

Ref. no.: 026	
Title: History of pressure fluctuations related to severity of near-neutral pH SCC	
Authors: J. Been, R.R. Fessler, S. Keane, W. Kresic	
Source: Proc. IPC 2006 (ASME, New York, NY), paper IPC2006-10412	*Year:* 2006
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth	
Sub-phase/keywords: Pressure fluctuations, strain rate	
Results support R&D Guideline no.: N037, N038	

Comments:

Statistical correlation between pressure ratio R, frequency f, and ratio of operating stress to SMYS using exponents (m_1, m_2, m_3) whose value is determined by the nature of the assumed crack growth process. Mechanisms considered included three strain-rate based models (with different expressions for the dependence on crack-tip strain rate, as well as the inter-dependence on maximum pressure) and three fatigue-type models ("traditional" (based on ΔK only), model based on K_{MAX} and ΔK, and one including frequency effect). Strain rate and fatigue data obtained from pipeline SCADA data. Correlated with ILI SCC indications characterized into seven groups.

Key observations:

- strong correlations with fatigue-based models for liquid line
- no correlation for strain-rate based models for liquid line
- no clear correlations for gas line

Key conclusions:

- authors cautious because of limited duration of SCADA data, especially for gas line

Comments:

- interesting to note that strain rate models showed poor correlation
- inclusion of frequency effects in fatigue model produces no better or worse correlation, contrary to what might be expected based on UofA CF model
- good correlation with fatigue models may be specific to liquid line operation, and may be even specific to Enbridge

Check if additional Comments made ☐

Ref. no.: 027	
Title: Transgranular stress corrosion cracking of X-80 and X-52 pipeline steels in dilute aqueous solution with near-neutral pH	
Authors: B. Gu, W.Z. Yu, J.L. Luo, X. Mao	
Source: Corrosion 55(3), 312-318	*Year:* 1999
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N039, N040, N041	

Comments:

SSRT studies on X-80 and X-52, polished smooth samples, monotonic loading at strain rates of 1.8×10^{-7} to 7.8×10^{-6} s^{-1}, with %RA used to assess SCC severity. Some specimens cathodically pre-charged in acidic, As_2O_3-containing solution at 3 mA/cm^2 for 24 h. NS4 solution and a "Nova" solution with higher carbonate and Mg/Ca concentrations, bubbled with CO_2/N_2 to give pH 5.4-8.0.

Key observations:

- addition of CO_2 increases SCC susceptibility in NS4 solution, but no difference between 5% CO_2 (pH 6.8) and 100% CO_2 (pH 5.4)
- at -1.0 V_{SCE}, no effect of added CO_2
- H pre-charging increases susceptibility in intermediate potential range where there is insufficient H produced by corrosion (at E_{CORR}) or because of anodic polarization
- significant increase in susceptibility with decreasing strain rate

Key conclusions:

- mechanism of SCC near E_{CORR} dominated by anodic dissolution
- HIC at cathodic potentials

Comments:

- the presence of CO_2 seems to be important, but not necessarily the concentration (or the pH that it creates)
- likely that different mechanism at -1.0 V_{SCE}, e.g., some form of HIC
- but the big question is whether %RA from SSRT is a measure of SCC susceptibility or simply of the effect of H on ductility?
- evidence for role of dissolution seems to be decrease in ductility at potentials around E_{CORR} – at these potentials, observe cracking rather than general dissolution, but insufficient H to support a H mechanism

Check if additional Comments made ☐

Ref. no.: 028
Title: Environmental acceleration of fatigue crack growth in reactor pressure vessel materials and environments
Authors: W.A. Van Der Sluys, R.H. Emanuelson
Source: Environmentally Assisted Cracking: Science and Engineering, ASTM STP 1049, W.B. Lisagor, T.W. Crooker, and B.N. Leis (eds.), American Society for Testing and Materials (Philadelphia, PA), pp. 117-135 — *Year:* 1990
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility
Sub-phase/keywords:
Results support R&D Guideline no.: N042

Comments:
 	
Study of environmentally assisted fatigue crack growth in reactor pressure vessel steels in water at 288°C. Despite the apparent dissimilarity between this environment and that for NNpH SCC, there are some similarities between the two forms of damage.
 	
Key conclusions:
• most important factor controlling cracking was S content of steel as well as inclusion morphology
    o material not susceptible for S < 0.01 wt.%
    o material may be susceptible for 0.01 < S < 0.02, provided particles are off the order of 5-10 µm in size
    o material is susceptible for S > 0.02 wt.%
• apparent need to have S present at crack tip
 	
Comments:
• is there a similar threshold for the initiation of NNpH SCC in pipeline steels

Check if additional Comments made ☐

Ref. no.: 029	
Title: Critical cathodic potential and fatigue lifetime evaluation for hydrogen stress cracking on gas transmission pipelines	
Authors: Y. Yamaguchi, H. Nonaka, Y. Nishikawa	
Source: Proc. 1998 Int. Gas Research Conf., San Diego, CA, pp. 394-404.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: Hydrogen stress cracking	
Results support R&D Guideline no.: N043	

Comments:

Primarily a study of HSC in X-65 pipeline steels. SSRT to determine susceptibility, as measured by %RA tests performed as a function of H content (H charging in acetic acid solution).

Key observations:

- observed loss of ductility at H contents greater than 10 ppb, which corresponds to a potential of about -1.0 V_{SCE}

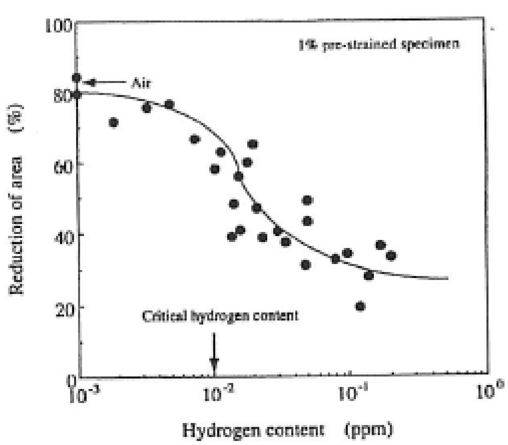


Figure 5. Relationship between reduction of area and hydrogen content on 1% pre-strained specimen of X-65.

Comments:

- study relates to how distinguish NNpH SCC from HSC (or HIC), in both the field and the lab
- likely that some lab studies involving SSRT with H-charged samples (either pre-charged, cathodically charged, or naturally charged at E_{CORR}) are due to HSC (or HIC) rather than NNpH SCC
- in the field, there should be a threshold potential that distinguishes HSC/HIC from NNpH SCC. This potential will depend on the severity of the charging environment (cf. Gu et al. 1999)

Check if additional Comments made ☐

Ref. no.: 030	
Title: Cyclic crack growth rates of X-60 pipeline steel in a neutral dilute solution	
Authors: T.M. Ahmed, S.B. Lambert, R. Sutherby, A. Plumtree	
Source: Corrosion 53, 581-590.	*Year:* 1997
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N045, N046, N047	

Comments:

Cyclic load tests with pre-cracked cantilever bend specimens, crack growth measured by DCPD. NS4 solution, 5% CO_2/N_2, pH 7. SRB added to some early long-term tests. X-60 pipeline steel from service, ferrite-pearlite microstructure, 0.018 wt.% S, 10-20 µm grain size. Test duration 40 days to 1 yr. Loading conditions chosen to simulate those for gas pipeline, R values of 0.82-0.98, frequencies of 1-400 cycles/day in long-term tests and R of 0.5-0.9, frequencies of 40-5000 cycles/day in short-term tests. Ranges of R and K_{MAX} values used:

- R = 0.98, K_{MAX} 20-28 $MPa\cdot m^{1/2}$, 1 cycle/day (1.16 x 10^{-5} Hz) in early long-term tests
- R = 0.82, K_{MAX} 30-36 $MPa\cdot m^{1/2}$, 40-400 cycles/day (4.6 x 10^{-4} to 4.6 x 10^{-3} Hz) in later long-term tests
- R = 0.5, 0.82, 0.9, K_{MAX} 30-40 $MPa\cdot m^{1/2}$, 40 or 5000 cycles/day (4.6 x 10^{-4} to 5.8 x 10^{-2} Hz) in short-term tests

Key observations:

- average CGR (da/dn) of 4.5 x 10^{-8} to 1.25 x 10^{-4} mm/cycle (da/dt = 1.4 x 10^{-9} to 7 x 10^{-7} mm/s), depending upon applied load range
- quasi-cleavage fracture under less-severe loading conditions
- observed cracks adjacent to MnS inclusions

Key conclusions:

- corrosion fatigue mechanism proposed for more-severe loading conditions
- TG SCC mechanism proposed for less-severe loading conditions
- proposed H-related mechanism, exacerbated by MnS inclusions that act both as a source of H and act as a trap

Comments:

- One of the original studies considering the effect of cyclic loading on NNpH SCC
- Strong fractographic and fracture mechanics input
- Compared with later studies, fairly moderate testing conditions

Check if additional Comments made ☐

Ref. no.: 031

Title:
Transgranular stress corrosion cracking of X-60 pipeline steel in simulated ground water

Authors:
X.-Y. Zhang, S.B. Lambert, R. Sutherby, A. Plumtree

Source: Corrosion 55(3), 297-305	*Year:* 1999

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:
Superposition model

Results support R&D Guideline no.:
N048, N049, N050

Comments:
Static and cyclic load tests on cantilever bend specimens. X-60 pipe from service. Loading conditions similar to those for gas transmission lines, namely: K_{MAX} 34-38 MPa·$m^{1/2}$. Static load tests lasted 111 days, cyclic load tests for up to 378 days with R of 0.5-0.9, at 40-5000 cycles/day.

Key observations:

- TGSCC observed as in the field
- maximum CGR of 6.1×10^{-10} to 2.6×10^{-7} mm/s, depending upon loading conditions
- observed quasi-cleavage and microvoid coalescence

Key conclusions:

- CF at low R (0.5, 0.82) and/or high frequency(5000 cycles/day)
- TGSCC under static load or high R/low freq
- superposition model proposed
- $\left.\frac{da}{dn}\right|_{total} = \left.\frac{da}{dn}\right|_{fatigue} + \left.\frac{da}{dt}\right|_{SCC} \cdot \frac{1}{f}$
- boundary between CF and TGSCC proposed

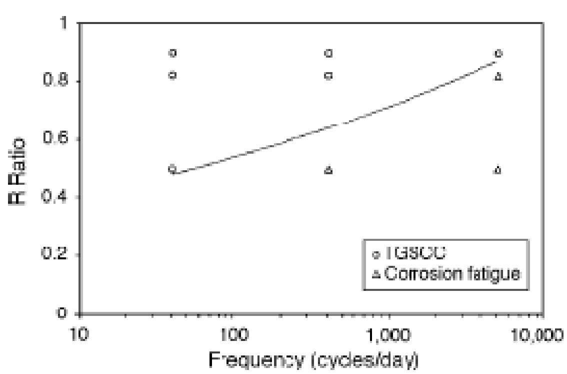


FIGURE 9. *Fracture map summarizing cyclic loading conditions for TGSCC and corrosion fatigue.*

Comments:

- continuation of studies of Ahmed et al. (1997)
- distinction between SCC and CF depends on K, i.e., crack depth
- crack growth under static load

Check if additional Comments made ☐

Ref. no.: 032	
Title: Modeling of environmental crack growth in pipeline steel	
Authors: S.B. Lambert, A. Plumtree, R. Sutherby	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00364	*Year:* 2000a
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Superposition model	
Results support R&D Guideline no.: N051	

Comments:

Extended superposition model for single cracks (Zhang et al. 1999) to growth in colonies.

Key considerations:

- accounted for shading of cracks (from stress) by adjacent cracks
- applied a modified Parkins and Singh coalescence rule

Key conclusions:

- reasonable predictions of growth behaviour of colony claimed

Check if additional Comments made ☐

Ref. no.: 033	
Title: Mechanical factors affecting stress corrosion crack growth rates in buried pipelines	
Authors: S.B. Lambert, J.A. Beavers, B. Delanty, R. Sutherby, A. Plumtree	
Source: Proc. IPC 2000 (ASME, New York, NY), Vol. 2, pp. 961-965	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Superposition model	
Results support R&D Guideline no.: N048	

Comments:

Application of superposition model to both Waterloo and CC Technologies cyclic load data. Waterloo data are for surface cracks (cantilever bend), CCT data are through-wall cracks determined using CT specimens

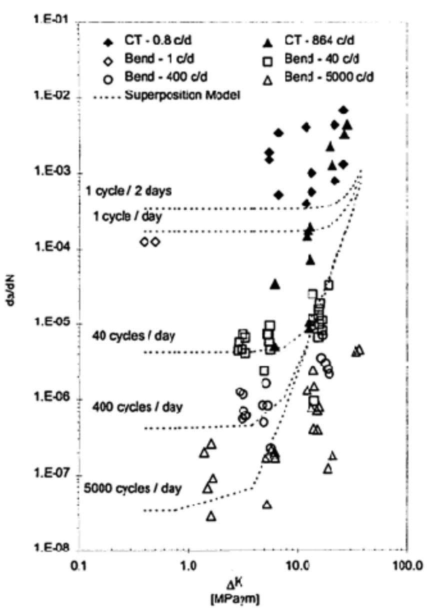


Figure 3: Crack growth rates for edge notch bending and compact tension (CT) specimens.

Key conclusions:

- superposition model successful
- implied SCC CGR of da/dt = 3 x 10^{-9} mm/s for surface cracks, ~10x higher for CT cracks
- implies different CGR for surface and through-wall cracks, but for some reason suggest surface CGR faster!

Comments:

- higher CGR for CT specimens may be due to not including any effect of K_{MAX} which is likely higher for CT specimens

Check if additional Comments made ☐

Ref. no.: 034	
Title: Environmental crack growth under variable amplitude loading of pipeline steel	
Authors: B.W. Williams, S.B. Lambert, A. Plumtree, R. Sutherby	
Source: Corrosion 60(1), 95-103	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Early-stage and late-stage cracking	
Results support R&D Guideline no.: N052, N053	

Comments:

Continuation of cantilever beam tests with surface cracks (thumbnails in surface but do not extend to edges of specimen), K_{MAX} 20.6-31.4 MPa·$m^{1/2}$, R of 0 or 0.5, 1 or 40 cycles/day for 40 days using either constant amplitude or variable amplitude loading (either 1 in 40 or 1 in 160 R=0 cycles, with remainder at R=0.5). NS4 with 5% CO_2/N_2, pH ~7.

Key observations:

- under constant amplitude loading, superposition model fitted for surface cracks gave SCC rate of da/dt = 2.5 x 10^{-9} mm/s
- proposed frequency-dependent CF model based of Paris law format based on constant amplitude data
  $\left(\frac{da}{dn}\right)_{total} = bf^d \Delta K_{eff}^{(ef+g)}$ where f is frequency, K_{eff} is the effective SIF, and b, d, e, g are constant, where da/dn is in units of mm/cycle, b = 4.8 x 10^{-18}, d = -2.25, e = 5.320, g = 1.94
- acceleration of growth (compared with that predicted from constant amplitude data) following an underload, particularly for evenly distributed underloads in loading pattern

Key conclusions:

- underload may result in compressive forces which flatten crack-face asperities and reduce crack-closure effects in subsequent cycles – here could also be due to corrosion products in crack (ie, either compaction or expelling of corrosion products during underload)

Comments:

- underloads could also promote refreshment of crack solution
- no K_{MAX} term in frequency-dependent CF model
- could this model account for growth of short (shallow) cracks?

Check if additional Comments made ☐

Ref. no.: 035	
Title: Fatigue crack initiation on low-carbon steel pipes in a near-neutral-pH environment under potential control conditions	
Authors: M. Puiggali, S. Rousserie, M. Touzet	
Source: Corrosion 58(11), 961-970	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: CP, overprotection, underprotection, hydrogen	
Results support R&D Guideline no.: N054, N055	

Comments:

Study of effect of CP conditions on initiation of NNpH SCC during cyclic loading. X-52 pipeline steel , 0.036 wt.% S, ferrite-pearlite microstructure with pearlitic colonies and elongated MnS inclusions along longitudinal direction of pipe. NS4 test solution, purged with 5% CO_2/N_2, pH 6.8, ambient temperature. Cyclic loading comprised a triangular waveform, max load 90% YS, R = 0.6, loading rate 32 MPa/min, 25 cycles/day (2.9×10^{-4} Hz), hold time of 48 min at max. load.

Key observations:

- No macroscopic plastic deformation during cyclic loading (elastic strain reversibility), although possibility of local microplasticity in the softer ferrite phase or at the matrix/inclusion interface cannot be excluded
- surface was active, observed ferrite dissolution at OCP
- alternating between underprotection (OCP), protection (-0.95 V_{SCE}) and/or overprotection (-1.15 V_{SCE}) during cyclic loading seems to promote most crack initiation by promoting H ingress
- surface damage leading to crack initiation can result from dissolution (insufficient CP) or surface blistering at MnS inclusions (overprotection)

Key conclusion:

- NNpH SCC crack initiation is not solely due to dissolution due to poor CP – protection or overprotection can also lead to initiation due to H ingress

Comments:

- again, to what extent would conclusions change for a millscale-covered surface

Check if additional Comments made ☐

Ref. no.: 036	
Title: SCC growth in pipeline steel	
Authors: A Plumtree, B.W. Williams, S.B. Lambert, R. Sutherby	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 199-210	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Superposition model	
Results support R&D Guideline no.: N048, N051, N053	
Comments: Paper based on work previously published as Lambert et al. (2000) and Williams et al. (2004).	

Check if additional Comments made ☐

Ref. no.: 037	
Title: Environmental effects on near-neutral pH stress corrosion cracking in pipelines	
Authors: W. Chen, R.L. Eadie, R.L. Sutherby	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 211-220.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Dormancy	
Results support R&D Guideline no.: N056	

Comments:

Experimental study involving corrosion rate and crack growth rate measurements in various synthetic electrolytes containing differing amounts of $CaCO_3$ (C1-C4) solutions which, when purged with 5% CO_2/N_2 gave pH values of 5.89-7.19 with increasing $CaCO_3$ content. Also used NS4 and the Ca/Mg-rich carbonate-based NOVA trapped water solution. X-65 pipeline steel from service. Corrosion rates determined from weight loss. CT specimens used for crack growth tests, cyclically loaded using a triangular waveform, frequency 0.005 Hz, R = 0.6, K_{MAX} ~35 $MPa \cdot m^{1/2}$ and ΔK of 10-20 $MPa \cdot m^{1/2}$.

Key observations:

- weight loss increased with decreasing pH of the solution, with tendency for the rate to decrease with time especially for solutions of higher pH
- crack growth rates higher in C2 solution than NOVA trapped water, despite higher corrosion rate in former (and, hence, possibly a greater tendency to dissolution and dormancy). In fact, crack tip appeared sharper in the supposedly more-corrosive C2 solution

Key conclusions:

- greater H production in C2 solution may have lead to crack growth by H as sharp crack tip would allow high stress intensities and, hence, high local concentrations of H
- argue that crack-tip creep was more likely in NOVA trapped water solution which then blunted crack

Check if additional Comments made ☐

Ref. no.: 038	
Title: Environmentally assisted cracking of pipeline steels in near-neutral pH environments	
Authors: J. Been, F. King, R. Sutherby	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 221-230.	*Year:* 2008a
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Dormancy, crack closure, modelling	
Results support R&D Guideline no.: N057, N058	

Comments:

Review of factors relating to NNpH SCC crack growth.

Key considerations:

- Superposition models based on separate environmental and mechanical effects underestimate crack growth on gas transmission lines suggesting some form of synergistic effect
- evidence suggests K_{MAX} important for large cycles but not for small cycles, so for gas lines ΔK is most important parameter
- however, there is still a threshold K value which increases with increasing R value
    - K_{th} ~30 MPa·m$^{1/2}$ at R = 0.82, 20 MPa·m$^{1/2}$ at R = 0.5
- threshold ΔK values
    - 3-5.5 MPa·m$^{1/2}$
    - ~10 MPa·m$^{1/2}$ (Beavers and Jaske)
    - ~2 MPa·m$^{1/2}$ for early stage growth (Parkins), due to fewer surface constraints and closure effects
- ΔK generates dislocations, K_{MAX} "breaks bonds"
- Mechanical factors promoting crack dormancy (by reducing K_{MAX} and/or ΔK_{eff}):
    - Overload
    - Crack deflection
    - Crack closure
    - Work hardening
    - Shielding by neighbouring cracks
- Mechanical factors promoting crack growth (by increasing K_{MAX} and/or ΔK_{eff}):
    - residual stress
    - stress intensifiers
- Crack closure effects:
    - On the assumption that crack growth only occurs when crack faces are separated, any mechanism that leads to the crack faces contacting at a load greater than the minimum load effectively reduces the load range for crack growth

Check if additional Comments made ☒

Comments (continued):

- o Crack closure effects more evident at higher ΔK
- o Crack closure may also be important at lower frequencies typical of
- o Can explain effects of corrosive environments, microstructure, retardation due to overloads or underloads, accelerated growth of short cracks
- o for NNpH SCC, crack closure effects due to oxide and roughness of fracture surfaces are thought to be most important
- o high peak load (overload), eg, hydrotest, may reduce crack growth through blunting of crack tip, introduction of compressive zone ahead of crack tip, or crack deflection

- stress concentrators and residual stress
    - NEB hearing 94% NNpH SCC failures associated with stress raiser
    - Corrosion leads to pits, extensive corrosion
    - Longseam weld stress raiser 1.7-2x at surface
    - Residual stress up to 25% of operating stress(Parkins?)
- Environmental factors that affect crack growth:
    - shielding coating or inadequate CP
    - chemical species
        - organics have been found to increase and decrease crack growth
        - amount of CO_2 affects amount of H absorbed and consequent ductility in SSRT
        - in crack growth tests, presence of CO_2 increases rate, but amount is not important apparently
        - no effect of Cl^-
        - effect of O_2 small
        - presence of sulphide (from SRB) increases crack growth rate and appears to result in plateau at high ΔK values
            - HELP at crack tip may sustain crack growth under constant load in presence of sulphide
- Crack growth modelling
    - superposition – no synergistic effect between environment and mechanical loading
        - by adjusting fitting parameters, can get failure in between 12 yrs and 80 yrs
    - corrosion fatigue
        - evidence that cgr increases with decreasing f indicates that either have to develop a separate $da/dn = f(\Delta K)$ expression for each frequency or that a non-traditional frequency-dependent CF model is required

Ref. no.: 039	
Title: Crack initiation of line pipe steels in near-neutral pH environments	
Authors: J.A. Colwell, B.N. Leis, P.M. Singh	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 233-242.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N059	

Comments:

Study of the initiation of NNpH SCC and the role of CO_2. The proposed mechanism simply involves the cathodic reduction of H^+ in a buffered H_2CO_3/HCO_3^- system, followed by the precipitation of $FeCO_3$. Proposed mechanism appears to simply involve the well-established electrochemical and chemical processes involved in the corrosion of Fe in buffered CO_2-containing environments.
Limited series of SSRT in water or $NaHCO_3$ solutions purged with CO_2 with visual observation of secondary cracking.

Key observations:

- Mechanism apparently centres around role of HCO_3^- as source of H^+, but this dissociation only occurs at higher pH. The proposed mechanism would make more sense if it was suggested that HCO_3^- was the species being reduced, although in that case the kinetics of this reaction are known to be slow
- Propose that HCO_3^- may act as a H-recombination poison, but seems unlikely based on the work of Flis
- State that cracking would not occur at low pH where H_2CO_3 is the predominant species – but in the proposed mechanism H_2CO_3 dissociation is supposedly the source of H^+ being reduced
- Propose that NNpH SCC could transform into high-pH SCC in poorly buffered systems
- Propose that O_2 promotes formation of adsorbed H as the OH^- produced by O_2 reduction forms HCO_3^- which then promotes H^+ reduction – but as noted above, the dissociation of HCO_3^- occurs at higher pH, HCO_3^- is kinetically not a good oxidant, and ignores the effect that the reduction of O_2 will have on the potential on the reduction of H^+.
- No secondary cracking in SSRT in pure water purged with CO_2, only in $NaHCO_3$ solutions

Comments:

- Proposed mechanism is confusing
- Interesting suggestion that in poorly buffered solutions, could get transition from NNpH to high-pH SCC

Check if additional Comments made ☐

Ref. no.: 040	
Title: A mechanistic study on near-neutral pH stress corrosion cracking of pipeline steel	
Authors: B.T. Lu, J.L. Luo	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 243-253.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth, initiation	
Sub-phase/keywords: H permeation, SSRT	
Results support R&D Guideline no.: N060	

Comments:

Experimental study with cyclically loaded planar specimen contained in modified Devanathan cell, one side of specimen was cathodically polarized to generate H and the other side was maintained at E_{CORR} (potential not sufficiently positive to oxidize H arriving at surface). Test environment: NS4 with 5% CO_2/N_2, ~pH 6.7 on both sides of cell. X-60 samples (1.2 mm thick) were cyclically loaded at 0.1 Hz, R = 0.5, maximum load 434 MPa (105% SMYS). Also performed voltammetry and conventional H permeation measurements.

Key observations:
- cracks initiated at similar times on cathodically polarized side and side of coupon at E_{CORR}
- initiation time (for both sides) decreased with increasing cathodic polarization of charging side
- the crack growth rate was similar on the two sides of the cyclically loaded sample and increased with increasing cathodic polarization
- crack growth rate varied from 5 x 10^{-8} mm/s at -0.6 V_{SCE} (100-150 mV anodic of E_{CORR}) to ~1.4 x 10^{-7} mm/s at -1.2 V_{SCE}
- monotonic trends of initiation time and cgr perturbed at E_{CORR}, with shorter initiation and faster crack growth at E_{CORR} than at potentials immediately above or below E_{CORR}
- model developed to explain synergistic effects of hydrogen and anodic dissolution-induced plasticity

Key conclusions:
- both dissolution and H play role in initiation, but crack growth process dominated by HIC rather than dissolution

Comments:
- observation of "local" increased susceptibility at ~E_{CORR} is interesting and suggests that dealing with continuum of mechanisms
    - NNpH SCC at E_{CORR} and perhaps ±50-100 mV of E_{CORR}
    - HIC/HSC at -0.9 V_{SCE} and more cathodic, ie, >150 mV cathodic polarization

Check if additional Comments made ☐

Ref. no.: 041	
Title: The role of hydrogen in EAC of pipeline steels in near-neutral pH environments	
Authors: J. Been, H. Lu, F. King, T. Jack, R. Sutherby	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 255-266.	*Year:* 2008b
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, crack growth	
Sub-phase/keywords: H permeation, SSRT	
Results support R&D Guideline no.: N061, N062, N063, N064	

Comments:

Review of role of H, plus summary of electrochemical polarization and corrosion tests, SSRT, H permeation studies, and cyclic loading tests.

Key observations:

- o corrosion rate is higher in H_2O than in D_2O, and in both solutions increases with increasing rate of mass transport
- o the rate of H_2O reduction at E_{CORR} is approx. one order of magnitude higher on millscale-covered surfaces than polished surfaces
- o the rate of reduction of H_2O on polished surfaces is higher than the rate of reduction of D_2O
- o the apparent diffusivity of H is lower on millscale-covered surfaces
- o the ductility is smaller and the time to failure shorter in H_2O than D_2O solutions
- o the crack growth rate is higher in H_2O than in D_2O solutions
- o galvanic coupling to millscale increases the cgr and maintained a sharper crack tip

Key conclusions:

- o synergistic role of corrosion and H

Comments:

- o consistent observation of faster kinetics and greater damage in H_2O as compared with D_2O solutions suggests an important role for H

Check if additional Comments made ☐

Ref. no.: 042	
Title: The roles of crack-tip plasticity, anodic dissolution and hydrogen of mild and C-Mn steels	
Authors: D. Delafosse, B. Bayle, C. Bosch	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 267-278.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: N065	

Comments:

Comparison on vintage high-S X-52 (actual YS 380 MPa, 0.025 wt% S) (banded microstructure, large elongated MnS inclusions (200x20x1 μm) axially aligned along pipe) and modern low-S X-52 pipeline steel (actual YS 490 MPa, <0.005 wt.% S, no large MnS inclusions). Samples: smooth or pre-notched, SSRT at 10^{-7} s^{-1}, susceptibility based on time to failure. Environment: NS4, 7% CO_2/N_2, pH 6.7, at OCP (-0.75 V_{SCE}), -1.0, -1.2, -1.7 V_{SCE}.

Key observations:

- for both steels, elongation/time to failure decreased with increasing cathodic polarization
- Vintage X-52
  - at E_{CORR} cracks initiate from pits formed by localized dissolution around MnS inclusions
  - at -1.0 and -1.2 V_{SCE}, crack initiated on or around MnS inclusions (but not necessarily requiring their dissolution)
- Modern X-52
  - no crack initiation, although loss of ductility with cathodic polarization

Key conclusions:

- primary role of MnS inclusions in crack initiation

Check if additional Comments made ☐

Ref. no.: 043	
Title: Influence of strain rate on the stress corrosion cracking of X70 pipeline steel in dilute near-neutral pH solutions	
Authors: B. Fang, J.Q. Wang, E. Han, Z. Zhu, W. Ke	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 303-311.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: SSRT study of X-70 (0.001 wt.% S) exposed to NS4 and Chinese soil extract purged with 5% CO_2/N_2. Susceptibility estimated from %RA and time to failure. Samples from longitudinal and transverse directions, with weld and from HAZ	

Check if additional Comments made ☐

Ref. no.: 044	
Title: Assessment of stress corrosion cracking and hydrogen embrittlement susceptibility of buried pipeline steels	
Authors: A.H.S. Bueno, B.B. Castri, J.A.C. Ponciano	
Source: Proc. Environmentally Assisted Cracking of Materials. Volume 2: Prediction, Industrial Developments and Evaluation. S.A. Shipilov, R.H. Jones, J.-M. Olive, and R.B. Rebak (eds.), (Elsevier, Amsterdam, 2008), pp. 313-322.	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC suspcetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	

Comments:

SSRT at 9 x 10^{-7} s^{-1} in NS4 and aggressive soil extract at E_{CORR} and 300 mV cathodic of E_{CORR}. X-46 (0.009 wt.% S) and X-60 (0.009 wt.% S)

Key observations:

- o greatest loss of ductility under cathodic polarization and at slower strain rate
- o soil extract more severe than NS4 solution
- o TGSCC under cathodic polarization due to H mechanism
- o $FeCO_3$ on surface in NS4 solution under cathodic polarization, but not in soil solution

Comments:

- o Focus seems to be on results under cathodic polarization, but these are probably due to HIC rather than NNpH SCC

Check if additional Comments made ☐

Ref. no.: 045	
Title: Effect of passivity of the oxide film on low-pH stress corrosion cracking of API 5L X-65 pipeline steel in bicarbonate solution	
Authors: J.-J. Park, S.-I. Pyun, K.-H. Na, S.-M. Lee, Y.-T. Kho	
Source: Corrosion 58(4), 329-336	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	

Comments:

Electrochemical study of X-65 (0.03 wt.% S) in NS4-based solutions, supported by additional SSRT tests. Three different solutions; NS4 with 100% CO_2 (pH 5.97), deaerated(?) NS4 (pH 8.01), NS4 + 1 mol/L $NaHCO_3$ (pH 9.55). CV's from -1.0 to +1.5 V_{SCE} at 0.5 mV/s; potentiostatic (-0.5 to +0.5 V_{SCE}) current transients on abraded electrodes; EIS measurements to measure film resistance; SSRT at 5 x 10^{-6} s^{-1}.

Key observations:

- passive behaviour in 1 mol/L $NaHCO_3$ at pH 9.55, with obvious E_{pit}
- no apparent passivity at pH 8.01, none at pH 5.97
- suggest pitting occurred in all three solutions!
- absence of passivity in pH 8.01 and 5.97 solutions consistent with i-t transients

Comments:

- no evidence for pitting in lower-pH solutions used

Check if additional Comments made ☐

Ref. no.: 046
Title: Effect of microstructure on the stress corrosion cracking of X-80 pipeline steel in diluted sodium bicarbonate solutions
Authors: J.G. Gonzalez-Rodriguez, M. Casales, V.M. Salinas-Bravo, J.L. Albarran, L. Martinez
Source: Corrosion 58(7), 584-590 — *Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility
Sub-phase/keywords: Heat treatment
Results support R&D Guideline no.: N066

Comments:

Effect of heat treatment of modern X-80 (Nb and high Mn for strength, 0.009 wt.% S) in 0.01 mol/L and 0.05 mol/L $NaHCO_3$. SSRT at 1.36 x 10^{-6} s^{-1}. Four heat treatments considered: water-quenched, water-quenched + tempered, water-sprayed (simulates improper weld procedure), AR. Most tests at E_{CORR}, some under potential control. Supporting CV's in 0.005, 0.01, 0.05, 0.1 mol/L $NaHCO_3$ (pH values not given).

Key observations:
- microstructures:
  - AR: ferrite-pearlite banded, finely dispersed precipitates
  - Q&T: acicular ferrite, isolated pearlite grains, finely dispersed precipitates
  - WS: incompletely transformed pearlite in ferrite matrix, fewer precipitates
  - Q: martensite, segregation at lath boundaries, finely dispersed precipitates
- passivity in 0.05 and 0.1 mol/L, active diss in 0.005 mol/L, authors suggest passivity in 0.01 mol/L but marginal
- in 0.05 mol/L, most passive was AR, WS highest i_{pass}
- pitting observed (presumably due to massive anodic polarization)
- assessed tendency for slip dissolution by comparison of i_{pass} at slow and fast scan rates!
- order of susceptibility: Q (most) > Q&T > WS > AR (least) based on elongation
- samples were more ductile with increasing cathodic polarization

Key conclusions:
- propose slip dissolution mechanism in 0.01 mol/L $NaHCO_3$

Comments:
- used i_{pass} to assess possibility of slip dissolution, instead of current on passive side of active-passive transition
- solutions used, and presumably pH values, span from NNpH to high-pH conditions
- claim that Q&T was highly susceptible does not seem to be consistent with data
- observation of greater ductility with more-negative potentials is unusual

Check if additional Comments made ☐

Ref. no.: 047	
Title: Effects of metallurgical factors and test conditions on near neutral pH SCC of pipeline steels	
Authors: T. Kushida, K. Nose, H. Asahi, M. Kimura, Y. Yamane, S. Endo, H. Kawano	
Source: Proc. CORROSION/2001 (NACE International, Houston, TX), paper no. 01213	*Year:* 2001
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N067	

Comments:
Study of effects metallurgical factors on susceptibility in NS4 with 10% CO_2/N_2, with samples polarized to -0.83, -0.93, -1.0 V_{SCE}, 25°C. Steels produced by quenching and tempering (QT), thermomechanical-controlled processing (TMCP) or controlled rolling (CR). Steels: X-80 (TMCP), X-65 (TMCP, QT, CR), 5L B (as rolled). Susceptibility assessed by cyclic loading of notched samples: one polished side, one millscale side with V notches of 0.1, 0.2, and 0.3 mm depth on both sides, triangular waveform, max stress of 85% or 100% actual YS, R ratio of 0.7 or 0.5, duration 4 weeks, loading rate 980 N/min. Increasing susceptibility was indicated by shallower notch in which cracking occurred. Also conducted H permeation tests.
 	
Key observations:
o microstructures:
    o TMCP and QT: bainitic ferrite or bainite
    o CR and 5L B: pearlite-ferrite
o millscale surfaces were <u>less</u> susceptible than polished surfaces
o increasing susceptibility with increasing cathodic polarization
o no apparent effect of strength for the three X-65 materials
o no cracking at max stress of 85% YS
 	
Key conclusions:
o Susceptibility: X-65 Q&T (least) < X-65 TMCP and X-80 TNCP < X-65 CR < 5L B
o Uniform microstructures such as bainitic-ferrite or bainite were resistant to SCC, whereas non-uniform microstructures, such as ferrite-pearlite, were susceptible
o concluded H mechanism
 	
Comments:
o observation of less susceptibility of millscale-covered surfaces is interesting, and contrary to most other observations
o to what extent are these results due to HSC/HIC, rather than NNpH SCC?	

Check if additional Comments made ☐

Ref. no.: 048	
Title: Stress corrosion cracking of X-52 carbon steel in dilute aqueous solutions	
Authors: Z. Szklarska-Smialowska, Z. Xia, R.B. Rebak	
Source: Corrosion 50(5), 334-338	*Year:* 1994
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Sulphate solutions, TGSCC	
Results support R&D Guideline no.: H004, H005, H006, N068, N069, N070	

Comments:

SSRT study of susceptibility of X-52 steel in dilute sulphate solutions. X-52: banded ferrite-pearlite, 0.05 wt.% S, 358 MPa actual YS. SSRT: LT specimens with banding parallel to loading axis, cold-pressed hump to concentrate strain, 2.3 x 10^{-7} s^{-1}. Solutions: 0.05 mol/L Na_2SO_4 (pH 8.0), either aerated, purged with 5% O_2, or deaerated; some tests done at pH 6.2. Temperatures: 25, 50, 80°C. Tests at E_{CORR} and with 40-200 mV cathodic polarization or 150 mV anodic polarization.

Key observations:

- cracking observed in all cases
- crack path was a function of conditions:
    - pH 6.2: TG
    - pH 8 at E_{CORR}: TG
    - pH 8 anodic or cathodic polarization: IG

Key conclusions:

- do not need CO_2 or HCO_3^-/CO_3^{2-} to observe TG and IGSCC of C-steel
- IGSCC observed at cathodic potentials at which dissolution could not be occurring and TGSCC at anodic potentials at which H could not be involved

Check if additional Comments made ☐

Ref. no.: 049	
Title: Effect of cathodic potential on hydrogen content in a pipeline steel exposed to NS4 near-neutral pH soil solution	
Authors: D.X. He, W. Chen, J.L. Luo	
Source: Corrosion 60(8), 778-786	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords: H permeation, cathodic potential	
Results support R&D Guideline no.: None	
Comments: Study of H permeation in X-65 in NS4 solution. X-65 steel from in-service NNpH SCC rupture. NS4 solution purged with 5% CO_2/N_2 (pH 7.0). Polished samples, H charging at potentials ranging from E_{CORR} to -1.5 V_{SCE}. Following permeation tests, total absorbed H was measured by thermal desorption. Key observations: o $CaCO_3$ observed to form of surface under cathodic polarization and resulted in lower H fluxes Comment: o majority of studies performed under cathodic polarization and relevance to NNpH SCC is, therefore, limited.	

Check if additional Comments made ☐

Ref. no.: 050	
Title: Effect of microstructure on near-neutral-pH SCC	
Authors: J. Bulger and J. Luo	
Source: Proc. IPC 2000 (ASME, New York, NY), Vol. 2, pp. 947-952	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N071	

Comments:

SSRT study of effect of microstructure, supported by corrosion rate measurements, CV's, and EIS. X-70 (0.003 wt.% S); heat treatments: quenched, Q+T, annealed, normalized. Environment: NS4 solution, purged with 5% CO_2/N_2 (pH 6.7). Electrochemical tests: EIS, CV's, LPR. Mechanical testing: SSRT 3.33 x 10^{-7} s^{-1}, susceptibility based on %RA and fractography

Key observations:

- Microstructures:
  - annealed and normalized: ferrite-pearlite
  - quenched: acicular and polygonal ferrite
  - Q+T: coarsening of Q microstructure with some recrystallization
  - as-received: pearlite-free acicular ferrite
- SSRT susceptibility:
  - quenched (most) > normalized > Q+T > annealed (least)
- Corrosion rate:
  - quenched (highest) > normalized ~ Q+T > annealed (lowest)
- evidence for local cathodes in microstructure consisting of Ti nitride

Key conclusions:

- microstructure affects both corrosion and SCC behaviour

Check if additional Comments made ☐

Ref. no.: 051	
Title: The role of hydrogen in the process of stress corrosion cracking of pipeline steels in dilute carbonate-bicarbonate solution	
Authors: L.J. Qiao, J.L. Luo, X. Mao	
Source: J. Mater. Sci. Lett. 16, 516-520	*Year:* 1997
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: N012	
Comments:	

Experimental study to determine concentration effect of H at crack inNNpH SCC environments. Material: X-80 (0.018% S) and X-52 (0.030% S). Specimen: CT specimens with sharp notch, WOL, no fatigue crack, pre-charged in 2 mol/L H_2SO_4 + 250 ppm As_2O_3. Environment: NS4, pH 3 and 5 adjusted using H_2SO_4. Loading conditions: calibrated WOL. H detection by SIMS.

Key observations:

- H accumulates at notch tip under load
- pH of solution and cathodic potential appear to have relatively little effect on H concentration
- H concentration of up to 10 ppm are observed close to notch tip

Comments:

- supports concept of H enrichment at crack tip, although conditions used (pH, cathodic potential, aggressive pre-charging solutions) are not typical of NNpH SCC environments

Check if additional Comments made ☐

Ref. no.: 052	
Title: Hydrogen facilitated anodic dissolution type stress corrosion cracking of pipeline steels in coating disbondment chemistry	
Authors: X.X. Mao, J.L. Luo, B. Gu, W. Yu	
Source: Proc. 2nd International Pipeline Conference (ASME, New York, NY), Vol. I, pp. 485-492.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: H-assisted anodic dissolution	
Results support R&D Guideline no.: N001, N002, N003, N004, N005, N006, N007, N008	

Comments:

Experimental study forming basis for H-assisted anodic dissolution mechanism of NNpH SCC. Material: X-80 (0.005% S) and X-52 (0.003 %S). Specimens: round tensiles for SSRT, CT specimens for H measurements; some samples cathodically pre-charged in acidic solution + As_2O_3. Environment: NS4, pH 3-8 by purging with various CO_2/N_2 mixtures or addition of H_2SO_4; also 0.005 and 0.05 mol/L HCO_3^- solutions.

Comments:

- Contents very similar to paper of Gu et al. (1999)

Check if additional Comments made ☐

Ref. no.: 053	
Title: Mechanistic studies on non-classical stress corrosion cracking initiation and propagation of pipeline steels in near neutral pH bicarbonate solution	
Authors: B. Gu, V. Sizov, L. Yang, X. Mao	
Source: Proc. NACE Northern Region Western Conference (NACE International, Houston, TX)	*Year:* 1999b
Relevant phase(s) in SCC Guidelines: NNpH SCC initation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N072, N073	

Comments:

Experiemntal study of crack initation and growth using SSRT. Material: X-52, as-received, annealed, quenched and tempered. Specimens: straight tensile and conical tensile. Environment: NS4, purged with 5% CO_2, at -0.9 V_{SCE}. Loading: strained at 5 x 10^{-7} s^{-1} to strain of 2-15%, followed by examination for pits and cracks.

Key observations:

- most susceptible potential range for initiation was -0.8 to -0.9 V_{SCE}
- crack density increased with applied stress
- critical stress for SCC initiation is ~actual yield stress (~380 MPa)
- stress-relieved (annealed) material less susceptible than as-received, and both less susceptible than Q+T, due to martensite in latter

Comments:

- relevance of work compromised to some degree by use of cathodic polarization in most of the tests. Are we seeing effects of NNpH SCC or HSC/HIC?

Check if additional Comments made ☐

Ref. no.: 054
Title: Effect of applied potential on cracking of low-alloyed pipeline steel in low pH soil environment
Authors: M. Touzet, N. Lopez, M. Puiggali

Source: Proc. EUROCORR'98, European Federation of Corrosion, paper no. 226	*Year:* 1998

Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation
Sub-phase/keywords: Hydrogen, mechanism
Results support R&D Guideline no.: N074, N075, N076

Comments:

Experimental study of susceptibility to NNpH SCC by SSRT in NS4. Material: X-60, 0.032% S, outer half of pipe wall homogeneous distribution of small ferrite and pearlite grains, inner half of wall banded elongated ferrite-pearlite grains, longitudinally orientated MnS and titanium carbonitrides. Specimens: transverse tensile specimens, so crack orientation as for pipe, outer surface of pipe retained, parallel-sided, initially curved samples samples straightened during initial part of test. Loading: SSRT, 4 x 10^{-7} s^{-1}. Environment: NS4, purged with 5% CO_2/N_2 (pH 6.7), room temp.

Key observations:

- little change in TTF at E_{CORR}, but decreases with increasing cathodic polarization
- density and depth of cracks independent of potential, so reduction in ductility not due to cracks but likely due to H
- lower ductility and more cracks for non-polished surface at E_{CORR} (-0.58 V_{SCE} for non-polished and -0.78 V_{SCE} for polished)
- application of CP after pits and cracks initiated at E_{CORR} results in deeper cracks and lower ductility than if CP applied throughout

Key conclusions:

- greater susceptibility of non-polished surfaces may have been due to localization of H entry
- greater susceptibility with increasing cathodic polarization
- more-severe damage on as-received surface if CP applied in plastic range

Comments:

- greater susceptibility if CP applied only in plastic range suggests dissolution effect on crack initiation
- don't necessarily agree that non-polished surface localizes H entry, as greater susceptibility at E_{CORR} occurred at an OCP for the non-polished surface of -0.58 V_{SCE}, at which there would be relatively little HER

Check if additional Comments made ☐

Ref. no.: 055

Title:
Laboratory tests reproduce transgranular stress corrosion cracking

Authors:
G. Gabetta, S. Di Liberto, A. Bennardo

Source:	*Year:*
Proc. CORROSION/2000 (NACE International, Houston, TX), paper no. 00372	2000

Relevant phase(s) in SCC Guidelines:
NNpH SCC

Sub-phase/keywords:
Geotech, circumferential SCC

Results support R&D Guideline no.:
N077, N078, N079

Comments:

Experimental study of NNpH SCC comparing SSRT and load control methods. Material: X-52, 0.02% S. Specimens: CT specimens with crack orientated to simulate circumferential SCC. Environment: NS4, either aerated (pH~8) or purged with 5% CO_2/N_2 (pH 6.8). Loading: load control or strain control.

Key observations:

- in presence of CO_2, cgr lower for load control than SSRT, but in both cases 2-3 orders of magnitude higher than observed in field (10^{-6}-10^{-5} mm/s)
- in SSRT, cgr with CO_2 2.5x higher than in aerated solution

Key conclusions:

- lab cgr is greater than field cgr because cracks are only growing part of time
- consider crack loading conditions (eg, crack-tip strain rate) to be more important than environmental considerations
- HE mechanism

Comments:

- for the lab rates to be representative of field rates, the field cracks could only be growing for 0.1-1% of the time. This equivalent time might be so in the case of geotech/landslides, but it then implies that circumferential SCC cgr is 100-1000x faster than axial cgr

Check if additional Comments made ☐

Ref. no.: 056

Title:
Strain rate induced stress corrosion cracking in buried pipelines

Authors:
G. Gabetta, S. Di Liberto, A. Bennardo, N. Mancini

Source: Br. Corros. J. 36(1),24-28.	*Year:* 2001

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:
Landslides, geotechnical

Results support R&D Guideline no.:
N077, N078, N079

Comments:

Major focus of this work is the effect of landslides, circumferential SCC.

Same data as in CORROSION/2000 paper (ref. no. 055)

Key conclusions:

- by analogy with cracking of reactor pressure vessel steels, loading conditions are more important for TGSCC of C-steels than environmental conditions

Check if additional Comments made ☐

Ref. no.: 057	
Title: Stress corrosion cracking of pipeline steels in simulated ground water: from mechanisms to a ranking test	
Authors: D. Le Friant, B. Bayle, C. Adam, Th. Magnin	
Source: Proc. EUROCORR 2000, 10-14 September, 2000, London, UK (Institute of Metals, London, UK)	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: Ranking test, hydrogen, overprotection	
Results support R&D Guideline no.: N080, N081, N082, N083, N084, N085, N086, N087, N088, N089, N090	

Comments:

Lab study using SSRT and cyclic loading on two X-52 steels. Material: vintage X-52 (0.025% S), banded microstructure, elongated MnS inclusions parallel to crack orientation; modern X-52 (0.003% S), no MnS inclusions. Samples: smooth; pre-notched. Loading: SSRT at 10^{-7} s^{-1}; cyclic load tests at R=0.5 at 95 or 110% SMYS and 0.008 Hz. Environment: NS4, 7% CO_2/N_2, pH 6.7, some tests at E_{CORR} (-0.75 V_{SCE}), others at -1.0, -1.2, -1.7 V_{SCE}.

Field observations:

- aged over-the-ditch AE coating; porous or disbonded
- typical stress associated with cracking 60% SMYS, R ratio as low as 0.1
- CP reaches surface, ctg not shielding, with potentials sometimes exceeding -1 V, so periods of overprotection
- corrosion of crack walls indicate local underprotection
- many crack in colonies, cracks typically 1 mm transverse spacing
- TG, decohesion around MnS
- presence of MnS taken to be an indication of the involvement of H

Key lab observations:

- elongation to failure in SSRT is a function of potential, with lower %el the more-negative the potential
- modern steel exhibits minimal loss of ductility at E_{CORR}
- for interrupted SSRT with vintage X-52, cracks shown to initiate at MnS inclusions at -1.0 and -1.2 V_{SCE}, and at pits produced by the dissolution of inclusions at E_{CORR}
- evidence for quasi-cleavage on fracture surfaces for cathodically protected vintage X-52 and for over-protected modern alloy
- internal defects connected by TG cracks observed for over-protected (-1.7 V_{SCE}) vintage X-52, a clear indication of H due to trapping at MnS interfaces
- dynamic strain required to induce HSC failure in vintage X-52 at -1.7 V_{SCE}
- SSRT results same for notched and smooth specimens for vintage X-52

Check if additional Comments made ☒

Key observations (continued):

- unlike smooth samples, crack propagation was observed for modern X-52 on cracked SSRT samples, with TG crack growth with some quasi-cleavage
- slight (50 mV) cathodic polarization of notched modern X-52 resulted in lower susceptibility
- vintage X-52 cracks under cyclic load under CP, with H and MnS inclusions playing important roles; crack growth also at E_{CORR}, albeit less
- internal defects due to H accumulation at MnS inclusions observed only ahead of crack tip and not elsewhere in the material, implying the importance of triaxial stress

Key conclusions:

- cracking has been observed in field in locations where both under- and over-protection have occurred
- presence of inclusions is the primary factor affecting initiation at E_{CORR}
- dynamic strain, rather than the stress level, is important for HSC unlike regular HE (for which stress is important)
- MnS inclusions play a predominant role, acting as H traps and locations for H_2 precipitation
- quasi-cleavage appearance of fracture surface is inconsistent with a dissolution mechanism
- at E_{CORR}, anodic dissolution is important as the source of H
- less H produced under slight cathodic polarization as increase in rate of H reduction does not compensate for higher solution pH as a result of less hydrolysis due to suppression anodic dissolution
- it is the local H concentration, not the bulk concentration that is important in promoting defects
- propose a ranking test based on dynamic loading using a notched sample under cyclic polarization between E_{CORR} and -1.2 V_{SCE}
- H is considered to be responsible for crack growth at E_{CORR} and at cathodic potentials

Comments:

- potentially a very important paper as it may indicate subtle differences between "NNpH SCC" or, more correctly, TGSCC on asphalt- and tape-coated lines
    - for asphalt-coated lines, cracking appears to be similar, but is exacerbated by periods of over-protection
    - therefore, it is dangerous to over-protect on asphalt lines, whereas it may be OK for tape-covered lines
    - perhaps best characterized as a case of TGSCC with CP-permeable coating
    - this form of cracking may be mitigated in the field because (i) requires excessive plastic strain and/or continuous dynamic strain, (ii) hardened microstructures are more susceptible, (iii) permanent cathodic polarization will increase pH, leading to passivation and suppression of H pickup

Ref. no.: 058	
Title: Some effects of strain rate on the transgranular stress corrosion cracking of ferritic steels in dilute near-neutral-pH solutions	
Authors: R.N. Parkins, J.A. Beavers	
Source: Corrosion 59(3), 258-273.	*Year:* 2003
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Modelling, lifetime prediction	
Results support R&D Guideline no.: N091, N092, N093, N094, N095, N096, N097, N098, N099	

Comments:

Background: the difficulty of separating effects of H and dissolution for a process that occurs at E_{CORR} means that it may be difficult to develop a mechanistically based model as for high-pH SCC. As a result, lifetime prediction may have to rely on the extrapolation of measured crack growth rates.

Hypothesis: strain rate effects are important, regardless of whether a dissolution (e.g., film rupture) or H (e.g., diffusion of H) mechanism is involved.

Mechanistic evidence: corrosion of crack walls suggests role of dissolution, but the apparent dissolution rates from CV are too small to account for observed field CGR (although rates from scratched or rapidly strained electrodes likely higher). The fact that the cracking severity increases with decreasing potential and the evidence for quasi-cleavage on fracture surfaces support a H mechanism.

Experimental study involving SSRT, H perm, and electrochem on rapidly strained electrodes. Materials: X-52, 383 MPa (0.013S); X-60, 489 MPa (<0.005S); X-65, 531 MPa (<0.002S); annealed C-steel, 240 MPa (0.033S). Solution: NS4, various CO_2/N_2 to vary pH. Tests: H-perm at various E; rapid strain rate tests at controlled E; SSRT at various strain rates.

Key observations:

- interstitial (diffusible) H concentration increases with decreasing pH and potential, but approximately independent of the type of steel
- trap density decreases as follows: X-52 > X-65 > X-60 (lowest), which is in order of C content, although pearlite interfaces are only one type of trap site
- current transients show evidence for film formation at pH 6.5 and 8.3
- peak currents from scratched and rapidly strained electrodes are consistent with a dissolution mechanism and observed field CGR at high strain rates
- ductility decreases with decreasing strain rate and decreasing pH
- cracks initiate at pits, but not all pits initiate cracks
- pits often associated with inclusions

Check if additional Comments made ☒

Key observations (continued):

- CGR decreases with exposure time, which is inconsistent for a stress-based mechanism since K is increasing
    - o decreasing crack velocity could be due to: (i) work hardening of crack-tip region, (ii) changes in the crack chemistry which promotes blunting, and (iii) for smooth samples, an increase in the number of cracks, resulting in a decrease in crack-tip strain rate.
- CGR increases with increasing strain rate for SSRT and with increasing crack-tip strain rate for CT specimens
- CGR increases with frequency of cyclic loading for CT specimens
- pre-exposure to environment followed by testing in air results in ductility similar to air

Key conclusions:

- under NNpH SCC conditions, H entry occurs and is involved in crack growth process, but there is also evidence for dissolution
- extrapolating measured CGR as a function of $\dot{\varepsilon_{CT}}$ to starin rates expected of an operating pipeline give CGR of 0.03-0.3 mm/yr, the upper end of the range being similar to that observed in the field
- scratched or rapid-straining expts give much higher current densities than during cyclic voltammetry and corresponding crack growth rates that exceed those observed in field; however, extrapolation to field strain rates gives rates much lower than observed in field, implying role of H
- loss of ductility needs exposure to environment, i.e., active H generation and absorption
- CGR decreases with decreasing applied or crack-tip strain rate
- difficulty distinguishing dissolution and H effects makes development of mechanistic model difficult, so best approach is to develop suitable means for extrapolating experimental crack growth rate data, an effort that should include crack-tip strain rate

Comments:

A closely-argued paper that presents strong evidence in favour of some type of crack-tip strain rate ($\dot{\varepsilon_{CT}}$) model. The $\dot{\varepsilon_{CT}}$ component could explain the frequency dependence in the CF model approaches.
Argument that lifetime predictions should be based on some form of extrapolation of lab CGR's is consistent with current approach using CF models.

Ref. no.: 059
Title: Effects of pressure fluctuations on SCC propagation
Authors: J.A. Beavers, C.E. Jaske

Source: Pipeline Researcg Council International Report, Catalog no. L51872e	*Year:* 2004

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:
Dormancy, superposition model, corrosion fatigue

Results support R&D Guideline no.:
N100, N101, N102, N103, N104, N105, N106, N107

Comments:

Experimental and modelling study of the effects of cyclic loading on NpH SCC crack growth.

Experimental. Material: two separate X-65 (0.002 and 0.005% S). Specimens: pre-cracked CT, crack monitoring by dc potential drop. Solution: NS4, 5% CO_2/N_2. Test conditions: R ratios of 0.6, 0.8, 0.9; frequencies of 10^{-5}, 10^{-4}, 10^{-3}, 10^{-2} Hz, ΔK range 5.5 to 28 $MPa{\cdot}m^{1/2}$, K_{MAX} not given, also tested underloads and overloads, unload and reload, and gas pipeline spectrum

Key observations/conclusions:

- Specific conditions of R and frequency for which cracks either continue to grow or decelerate (and eventually become dormant?)

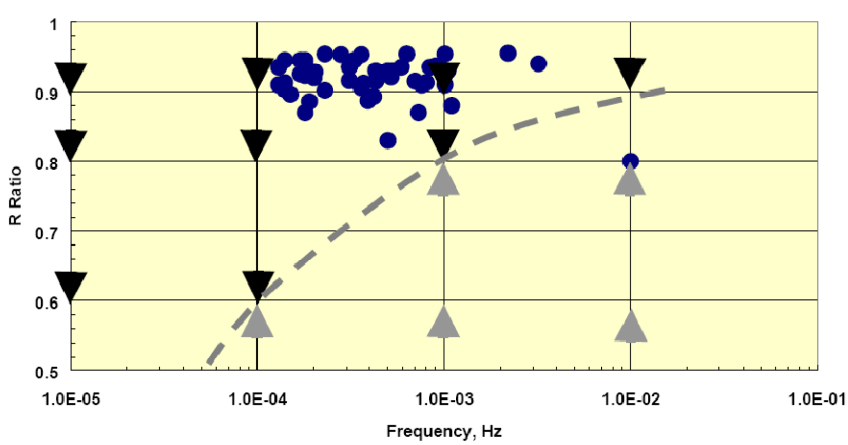


Figure 38. Summary of crack growth data, showing effects of R ratio and frequency on change in crack growth rate with time. Closed circles indicate operating conditions for gas transmission pipeline, taken from Figure 2.

- in lab tests with (gas transmission) field-relevant R values, initial CGR was ~0.6 mm/yr, but rapidly decreased
- cracks tend to decelerate at high R and low frequency

Check if additional Comments made ☒

Key observations/conclusions (continued):

- a modified super-position model, incorporating corrosion fatigue and an SCC component, was found to fit the lab data

  $\frac{da}{dN}\Big|_{total} = \frac{da}{dN}\Big|_{CF} + \frac{da}{dt}\Big|_{SCC} \cdot \frac{1}{f}$ where CF component involves $(\Delta K)^n$ term

  where $\frac{da}{dN}\Big|_{CF} = 6.9\ x\ 10^{-8}(\Delta K)^{3.0}$
- CF super-position model provides good fit to lab data for da/dt = 0.1 mm/yr, but does not give good fit to field data when used with gas transmission SCADA data
- failure to account for field observed rates may suggest that testing conditions are not sufficiently severe, i.e., NS4 may be less aggressive than field environments
- dormancy may be prevented by changes in environment or loading that sharpen crack
- low R values may sharpen crack
- most CF damage on gas transmission lines results from a small number of low R cycles (e.g., complete depressurization)
- relative contribution of CF will increase with increasing frequency and/or decreasing R
- threshold ΔK of ~10 $MPa \cdot m^{1/2}$ below which cracks become dormant

Comments:

An important study and one in which the authors were clearly struggling against dormancy of the cracks in the tests. Next stage in development of cyclic crack growth modelling following This implies that mechanical loading conditions on gas transmission lines are marginal for sustained crack growth.

Alternative explanation for failure to predict CGR's observed in field is that underestimating short crack growth rates. Conditions used here are appropriate for long cracks.

Ref. no.: 060	
Title: Crack size effects on the chemical driving force for aqueous corrosion fatigue	
Authors: R.P. Gangloff	
Source: Metall. Trans. A 16A, 953-969	*Year:* 1985
Relevant phase(s) in SCC Guidelines: NNpH SCC early-stage growth	
Sub-phase/keywords: Short cracks, hydrogen	
Results support R&D Guideline no.: N108, N109, N110	

Comments:

Experimental study of the corrosion fatigue of high strength 4130 steel in 3 wt.% NaCl solution. Compared growth rates of short (0.1-3 mm deep) surface elliptical or edge cracks were compared with long (15-40 mm deep) cracks in CT specimens. Samples subject to various ΔK values with maximum stress of 10-95% YS. Other experimental details not given here as not relevant to NNpH SCC environments.

Key observations:

- in vacuum or moist air, no difference in crack growth rate of short or long cracks
- in solution, (metallurgically) short cracks grew up to 500 times faster than long cracks at a given ΔK
- for HSS, difference in crack path for short (along prior austenite gb) and long (transgranular cracking associated with tempered martensite) cracks
- the acceleration of short cracks is greatest at small ΔK, and decreases with increasing crack length at a given stress or with increasing stress at a given crack size
- as rate of CF decreases, see increase in brittle transgranular cracking (shift from intergranular to transgranular)
- crack mouth opening (proportional to solution volume:crack surface area ratio), determines the environmental enhancement and the proportions of IG and TG cracking

Key conclusions:

- Short cracks are influenced by environmental factors to an equal or greater extent than mechanical factors
- "Environmental" enhancement is due to effect of cyclic loading on crack chemistry
- Short cracks have large surface area:volume ratio and, therefore, consume O_2 which otherwise is reduced to OH^- in crack and increases pH, thus decreasing H absorption
- in the case of HSS, Cr(III) hydrolysis is responsible for crack acidification

Comments:

- although on the face of it, this is a completely different system than NNpH SCC of pipeline steels, the conclusions present a possible explanation for the under-estimation of CGR for gas lines

Check if additional Comments made ☐

Ref. no.: 061

Title:
Effect of crack depth on fatigue crack growth rates for a C-Mn pipeline steel in a sour environment

Authors:
C.M. Holtam, D.P. Baxter, I.A. Ashcroft, R.C. Thomson

Source:	*Year:*
Int. J. Fatigue 32, 288-296	2010

Relevant phase(s) in SCC Guidelines:
NNpH SCC early-stage crack growth

Sub-phase/keywords:
Short crack, hydrogen, sour environment, sulphide

Results support R&D Guideline no.:
N112, N113

Comments:
Experimental study of fatigue crack growth in sour environments. Material: X-65, 0.003 %S. Specimens: square-section, single edge notched bend (SENB) specimens, fatigue-precracked to ~1.6 mm, crack growth monitored by DCPD. Loading: 3-point bending, R = 0.5, 0.1 Hz, most tests at constant ΔK, some with increasing or decreasing ΔK, ΔK range 9-19 MPa·m$^{1/2}$. Environment: 25^{o}C, sour environment, 5% NaCl, 0.4% Na acetate, pH 3.5, 7% H_2S/N_2.

Key observations:

- in sour environment, short cracks grow up to a factor of 10 faster than long cracks
- difference in rates for short and long cracks only observed at ΔK <11-12 MPa·m$^{1/2}$, but then cannot get larger ΔK with short cracks

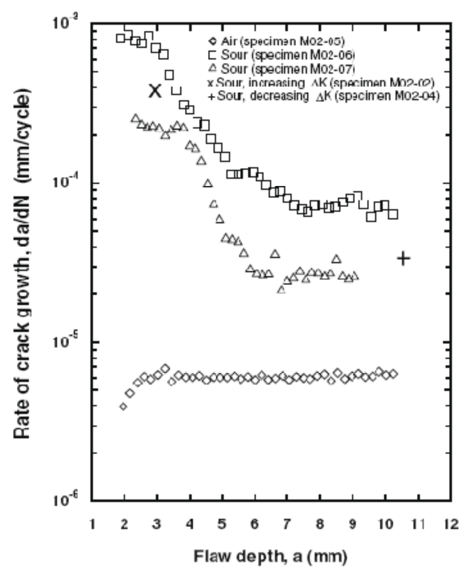


Fig. 5. Results of constant ΔK tests (~9 MPa m$^{0.5}$) in a sour environment and in air. Also plotted for comparison are the crack growth rates from the beginning and end of an increasing ΔK and a decreasing ΔK test, respectively.

Check if additional Comments made ☒

Key conclusions (continued):

- Possible explanation for increased crack growth rate for short cracks is environmental effect – lower crack-tip pH for short cracks
- Also possible that external charging of H is most important in sour environments so that, due to gradient of [H] across the wall, crack-tip [H] is higher for short cracks

Comments:

- Although in a sour environment, data offer useful insights into possible effects of short cracks for NNpH SCC
- Figure 5 , in particular, would explain why current super-position or CF-based CGR models appear to under-estimate crack growth for gas lines – i.e., we are using the wrong expression for small cracks. The same would also apply for liquid lines, but mechanical effects pick up sooner because of more-aggressive loading conditions.

Ref. no.: 062
Title: Test methodologies for the study of near neutral stress corrosion cracking in pipeline steels (EPRG)
Authors: E. Senigallia, M. Pontremoli

Source: Proc. 12th Biennial Joint Research Meeting on Pipeline Research, Groningen, The Netherlands, May 17-21, 1999.	*Year:* 1999

Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, crack growth
Sub-phase/keywords: Test procedure
Results support R&D Guideline no.: N114, N115, N116

Comments:

Development of test procedure for NNpH SCC based on flat tensile (initiation) and CT samples (crack growth). Round-robin tests involving four labs.

Experimental. Material: X-65. Specimens: tensile and CT – non-flattened samples with primer and internal epoxy ctg removed, original surface, tape-coated line. Environment: NS4, 10% CO_2/N_2. Loading: tensile – cyclic loading, R = 0.78, max stress 90% actual yield stress, saw tooth waveform, either 20 hrs load/80-120 mins unload (~1.3 x 10^{-5} Hz) or 2 hrs load/8-18 mins unload (~1.3 x 10^{-4} Hz), 40-60 cycles at low F, 700-1200 cycles at high f; CT specimens – K_{max} between 30 and 100 MPa·m$^{1/2}$, latter corresponding to K_{IC}, crack growth measurement by DCPD, 20-70 cycles at low f, 300-700 cycles at high f.

Key observations:

- tensile specimens
  - crack initiation observed in 12 of 21 samples, with depths of 2-70 μm
  - cracks initiated on 1 of 3 samples with tape coating still on
  - most cracks initiated on external surface, but some on internal surface
  - external cracks initiated from pits or areas of corrosion
  - slight tendency for crack initiation at higher frequency, although this also corresponds to greater number of cycles
- CT specimens
  - no macroscopic evidence for crack growth in any of the tests
  - some evidence for microscopic crack growth at lower f
  - crack growth rates in range 0.1-23 mm/yr, latter value at highest f and K_{MAX} of 100 MPa·m$^{1/2}$ and had fatigue-like features on fracture surface
- large variation in corrosion rate and E_{CORR} between labs (-0.52 to -0.794 V_{SCE})

Check if additional Comments made ☒

Key conclusions:

- inability to consistently get crack initiation of crack growth demonstrates stochastic nature of NNpH SCC
- cyclically loaded tensile technique suitable for studying susceptibility (and ranking) of new and vintage steels

Comments:

- tensile tests show that it is possible to get initiation in as little as 30 days under very realistic conditions of R and f. Therefore, initiation is not difficult to obtain under the right conditions.
- interesting that saw initiation without removing tape coating in one of three tests. Indicates that do not need large volume of solution to support initiation. Also, what is the distribution of potential like under such a coating?
- few details given regarding the corrosion potential in individual tests. This is a shame as the observed variation in e might explain the lack of consistency in observing initiation and crack growth
- I do not agree that lack of reproducibility is necessarily and indication of the stochastic nature of NNpH SCC. I think we are just not doing the experiments correctly.

Ref. no.: 063	
Title: Application of electrochemical techniques in investigation of the role of hydrogen in near-neutral pH stress corrosion cracking of pipleines	
Authors: Y.F. Cheng, L. Niu	
Source: J. Mater. Sci. 42(10), 3425-3434	*Year:* 2007
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: Technique development, hydrogen, mechanism	
Results support R&D Guideline no.: None	
Comments: Description of experimental techniques and their application to NNpH SCC.	

Check if additional Comments made ☐

Ref. no.: 064	
Title: Stress corrosion cracking of X-70 pipeline steels by electropulsing treatment in near-neutral pH solution	
Authors: B. Fang, J. Wang, S. Xiao, E.-H. Han, Z. Zhu, W. Ke	
Source: J. Mater. Sci. 40(24), 6545-6552	*Year:* 2005
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: SSRT	
Results support R&D Guideline no.: None	

Comments:

Experimental study of the susceptibility of two pipeline steels to X-70 NNpH SCC by SSRT. Materials: POSCO and Bao X-70 pipeline steels. Environment: XJ soil solution, 5% CO_2/N_2. Loaidng conditions: SSRT at strain rate of 2 x 10^{-6} s^{-1}. Samples subjhected to electropulsing (pulsed CP).

Key observations:

- UTS increased for electropulsed samples
- POSCO X-70 UTS enhanced more than for Bao steel
- SCC susceptibility increased with more-negative potentials

Comments:

- Conclsuiosn seem to be drawn based on effect of UTS. However, pipe will never be exposed to such extreme loading conditions.

Check if additional Comments made ☐

Ref. no.: 065

Title:
Hydrogen in stress corrosion cracking of X-70 pipeline steels in near-neutral pH solutions

Authors:
B. Fang, E.-H. Han, J. Wang, Z. Zhu, W. Ke

Source: J. Mater. Sci. 41(6), 1797-1803	*Year:* 2006

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:

Results support R&D Guideline no.:
N117

Comments:

Experimental study of effect of H on NNpH SCC. Materials: two different X-70 pipeline steels. Testing methods: monotonic SSRT, cyclic loading>

Key observations:
- susceptibility to SCC increased with cathodic polarization
- no sample failure during cyclic loading in elastic region
- samples failed by brittle fracture if cyclically loaded into plastic range
- H content high if samples loaded into plastic range

Key conclusions:
- NNpH SCC mechanism is related to H accumulation induced by plastic strain

Check if additional Comments made ☐

Ref. no.: 066

Title:
Microstructural features of environmentally assisted cracking in pipeline steel

Authors:
B.W. Williams, S.B. Lambert, X.Y. Zhang, A. Plumtree, R. Sutherby

Source:	*Year:*
Proc. Environmental Degradation of Materials & Corrosion Control in Metals (EDMCCM), 42nd Annual Conference of Metallurgists of CIM, Vancouver, BC, Canada, J. Luo, M. Elboujdaini, D. Shoesmith, P.C. Patnaik (eds.), pp. 87-99.	2003

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:
Green rust, crack environment, corrosion products

Results support R&D Guideline no.:
N118, N119

Comments:
Experimental study of growth of edge or surface cracks under cyclic loading. Material: X-60, from service, 0.018 %S. Samples: surface cracks or edge cracks grown by cyclic loading from notch or groove, crack depths 3.1 mm. Environment: NS4, 5% CO_2/N_2. Loading: frequencies of 6×10^{-6} to 0.06 Hz (0.5-5000 cycles/day) for 40 days; constant max load; R values of 0, 0.5, 0.8, 0.82, 0.9, 0.95, either at fixed or variable R values in a given test, ΔK in range 10-20 $MPa \cdot m^{1/2}$. Crack growth measured using reference microindents. Raman used to identify corrosion products. $E_{CORR} = -0.72\ V_{SCE}$.

Key observations:
- TG cracking observed at low frequency (10^{-5} Hz, 1 cycle/day) and high R ratios
- Corrosion fatigue observed at higher frequencies (0.06 Hz, 5000 cycles/day) and low R ratios and at 4.6×10^{-4} Hz (40 cycles/day) at R = 0
- Green rust found on crack walls and at crack tip, FeS and, possibly, $FeCO_3$ in solution
- at high frequencies, da/dN is slower than in air
- higher crack growth rate with variable amplitude loading (compared with constant R)

Key conclusions:
- corrosion products accumulate in crack and reduce crack tip opening displacement, thus slowing cracks
- variable amplitude loading causes crack-tip green rust film to rupture, thus promoting crack growth

Comments:
- conclusion re. rupture of crack-tip film is close to being a film-rupture model
- no mention of H
- observation of green rust in crack is interesting, whereas only Fe(II) species observed in bulk solution. E_{CORR} suggests adequate deaeration.

Check if additional Comments made ☐

Ref. no.: 067	
Title: Effect of MnS inclusions on stress corrosion cracking in low-alloy steels	
Authors: J. Kuniya, H. Anzai, I. Masaoka	
Source: Corrosion 48(4), 419-425	*Year:* 1992
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Inclusions	
Results support R&D Guideline no.: N120, N121, N122	

Comments:

Experimental study of MnS inclusions on SCC of low-alloy steel in 288^oC oxygenated pure water. Materials: four different steels studied with S contents between 0.004%-0.016%. Test environment: 288^oC, pure water, pH 6, 0.2 and 8 ppm O_2, 1.4 x 10^{-6} to 7 x 10^{-5} s^{-1} strain rate for SSRT. Polished samples.

Key observations:

- SCC initiation related to probability of MnS inclusion existing on surface, which increased with S content
- increased S contents result in elongated inclusions, whereas inclusions tend to be spherical at lower S content (A-1 0.004%S, A-2 0.014%S, B-1 0.004%S, B-2, 0.016%S)
- dissolution of elongated inclusion can create a "trench" in surface

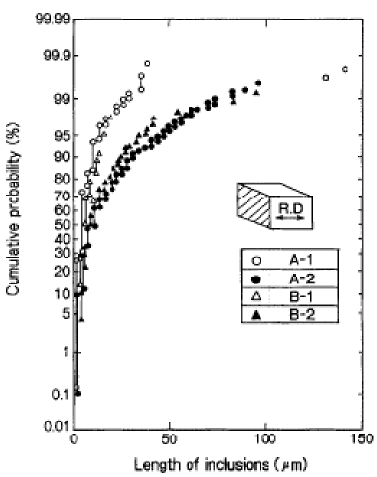


FIGURE 1. *Cumulative probability of length of inclusions.*

Comments:

- Associated here with NNpH SCC only because crack path is transgranular. Conclusion could apply to high-pH SCC initiation.
- Same question about relevance of observations on polished samples to initiation on mill-scale covered surfaces

Check if additional Comments made ☐

Ref. no.: 068	
Title: Effect of sulfide on stress corrosion crack growth in gas transmission pipe lines	
Authors: W.A. Van Der Sluys, M. Wilmott, K. Krist	
Source: Proc. 2nd International Pipeline Conference (ASME, New York, NY)	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: SRB	
Results support R&D Guideline no.:	

Comments:
Experimental study of effect of sulphide on NNpH SCC crack growth, either injected into crack or present in solution. NOVA: X-60 pipe from service containing field cracks, constant moment bending samples, 100% SMYS, reapplied weekly, corresponding to one R = 0.95 cycle per week, crack growth by analysis of surface crack extension, NS4 with 5% CO_2/N_2. Alliance: X-52, CT specimens, injection of H_2S at crack tip, R of 0.3, 0.5, or 0.8; freq 0.001, 0.01, 0.1 Hz; ΔK range 9-22 $MPa{\cdot}m^{1/2}$; 10-100 ppm H_2S

Key observations:

- % cracks showing growth from CMBR tests correlated with final SRB population
- average CMBR CGR 0.7 mm/yr
- environmental enhancement observed in Alliance tests for $\Delta K > 9$ $MPa{\cdot}m^{1/2}$

Comments:

- Alliance testing is under quite extreme conditions and may be related to the CF of C-steel in H_2S environments, rather than NNpH SCC
- NOVA work under much milder conditions, but indications for cracking are less apparent.

Check if additional Comments made ☐

Ref. no.: 069
Title: Corrosion fatigue and near-neutral pH stress corrosion cracking of pipeline steel in very dilute carbonate/bicarbonate with and without the presence of hydrogen sulfide using the compliance technique
Authors: R.L. Eadie, K.E. Szklarz, R.L. Sutherby
Source: Proc. CORROSION/2003, NACE International (Houston, TX), paper no. 03527 — *Year:* 2003
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth
Sub-phase/keywords: H_2S, sulphide, corrosion fatigue
Results support R&D Guideline no.: N022, N023, N024
Comments: Paper very similar to Eadie et al. (2005) (ref. no. 016)

Check if additional Comments made ☐

Ref. no.: 070	
Title: Development of a predictive model for the initiation and early-stage growth of near-neutral pH SCC of pipeline steels	
Authors: F. King, T. Jack, W. Chen, S.-H. Wang, M. Elboujdaini, W. Revie, R. Worthingham, P. Dusek	
Source: Proc. CORROSION/2001, NACE International (Houston, TX), paper no. 01214	*Year:* 2001
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N126, N127, N128, N129, N130	
Comments: Overview of GTI-funded program studying NNpH SCC crack initiation, dormancy and early-stage growth. Aim to develop materials-based model to supplement soils-based models for identifying SCC locations. Various experimental projects involved in program. Key observations: • Factors that lead to initiation: o inclusions o aligned defects o pre-existing defects at pipe surface o persistent slip bands produced by mechanical pre-treatment of the steel o coating disbondment o residual stress Comments: • Apparent that crack initiation can be achieved through high frequency (1 Hz) cyclic loading, but how relevant is this to pipeline operation • Usual comment re. use of polished samples to study crack initiation. Applies to both conclusion re. the effect of inclusions and aligned defects, which were observed along polishing lines on samples. • Work suggesting crack initiation at inclusions was performed at R = 0.4 and 1 Hz frequency for 470-1025 hrs. Is this a mechanical effect, or is there some effect of chemistry at this high frequency? • Cracks observed to initiate at edge (but still underneath) disbonded coating	

Check if additional Comments made ☐

Ref. no.: 071	
Title: The role of pressure and pressure fluctuations in the growth of stress corrosion cracks in line pipe steel	
Authors: M.J. Wilmott, R.L. Sutherby	
Source: Proc. 2nd International Pipeline Conference (ASME, New York, NY), Vol. 1, 409-421.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: SCADA, pressure fluctuations, short crack behaviour	
Results support R&D Guideline no.: N131, N132, N133, N134, N135	

Comments:

Experimental study using short field cracks, combined with analysis of P fluctuations. Material and samples: X-60 from service containing field colonies, 6.35 mm wall, surface crack length varied from 0.2-2 mm, surface water blasted. Mechanical testing conditions: loaded under constant-moment bending conditions, max load 40, 70, 100% SMYS, R = 0.98, 1 cycle/week (2 x 10^{-6} Hz), 240 days exposure. Environment: five different soils saturated with NS4, pH 6.4-7.5, simulated Plexiglas disbondments with 2 mm gap (trapped water pH 6.3-6.6). Determined surface crack extension from 10 MPI determinations before and after exposure. Weight-loss corrosion rates measured in five environments.

Key observations:

- 670 of 1761 (38%) of cracks showed statistically significant surface extension
- surface extension rates of 0.05-0.9 mm/yr
- no correlation between weight loss and crack growth rate
- no effect of maximum load on % of cracks growing or on growth rate
- characterized C/S discharge pressures to provide R values and strain rates for pressure cycles
    - strain rates 10^{-8} to 10^{-6} Hz
- range of K_I 4-15 MPa·m$^{1/2}$ (based on Newman and Raju, and assumption c = 2a)

Key conclusions:

- crack growth observed not thought to be due to corrosion (cracks did not widen)
- cracks within a colony grow at different rates due to crack interactions
- recognized that cracks can grow below K_{ISCC}, estimated to be ~9 MPa·m$^{1/2}$
- for shallow cracks, growth is independent of K_I

Comments:

- An important paper, both because of the recognition of the importance of cyclic loading and the need to characterize it and also because of the use of short cracks.
- Also indicates that crack growth is possible under static load or, at least under, minimal loading (ΔK in range 0.1-0.3 MPa·m$^{1/2}$ based on R = 0.98)

Check if additional Comments made ☐

Ref. no.: 072	
Title: Pipeline stress corrosion cracking: crack growth sensitivity studies under simulated field conditions	
Authors: M.J. Wilmott, T.R. Jack, G. Van Boven, R.L. Sutherby	
Source: Proc. CORROSION/96, NACE International (Houston, TX), paper no. 242	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Short crack behaviour	
Results support R&D Guideline no.: N136, N137, N138, N139, N140, N141	

Comments:

Experimental program aimed at investigating early-stage crack growth. Experimental details similar to paper 071, with additional electrochemical studies involving cyclic voltammetry and EIS. Addition of mixed culture of SRB and APB to test vessels. Six CMB specimens exposed to soils + NS4 for 212 days, with three specimens at OCP and three cathodically protected at -0.95 V_{CSE}.

Key observations:

- increase in SRB numbers in presence of CP
- 69 of 425 cracks (16%) showed statistically significant crack growth, with an average surface extension rate of 0.7 mm/yr
- % of cracks growing:
  - generally increases with increasing HCO_3^- concentration
  - increases with decreasing sulphate concentration
  - is independent of Cl^- concentration
  - is independent of potential in range -0.685 to -0.71 V_{SCE}
- 64% of the cracks showing growth were located at the edge of colonies, but grew at the same rate as cracks in centre of colony
- corrosion rates similar to crack extension rates

Key conclusions:

- similarity of corrosion rate and crack surface extension rate is consistent with dissolution mechanism
- successfully re-started growth on a relatively high fraction of field cracks

Comments:

- % of cracks that could be re-started in this and paper 071 (16% and 38%, respectively) is much higher than apparently non-dormant cracks in the field (~1-2%?)

Check if additional Comments made ☐

Ref. no.: 073

Title:
Environmental effects on near-neutral pH SCC

Authors:
J. Been, F. King, L. Yang, W. Chen, R. Sutherby, R. Worthingham

Source:	*Year:*
Proc. Northern Area Western Conference, NACE International (Houston, TX), February 3-6, 2003, Calgary, AB, Canada	2003

Relevant phase(s) in SCC Guidelines:
NNpH SCC initiation, crack growth

Sub-phase/keywords:
SSRT, organics

Results support R&D Guideline no.:
N142, N143, N144, N145

Comments:
Experimental study of effects of various environmental parameters on NNpH SCC. Material: X-65, NPS42, 0.016 %S, banded ferrite-pearlite microstructure. Specimens: transverse round tensile samples (gauge section corresponds to mid-wall), polished flat H perm specimens, CT with fatigue pre-crack. Environments: H-perm and SSRT in inorganic mixtures of HCO_3^-, Cl^-, $SO_\$^{2-}$, HSO_3^-, $S_2O_3^{2-}$, HS^-, AQDS; purge gas 0, 10, 100% CO_2/N_2, or 10% CO_2/N_2 with 10 or 100 vppm O_2. Cyclic load tests in NOTW, 5% CO_2/N_2, with 400-800 ppm organic acids in some tests. Mechanical testing: SSRT, 8 x 10^{-7} s^{-1} at E_{CORR} following pre-exposure at E_{CORR} to equilibrate with H, record time-to-failure, elongation to failure, and %RA. Cyclic load tests triangular waveform, R = 0.6, 0.005 Hz, ΔK = 13 MPa·$m^{1/2}$, K_{MAX} = 33 MPa·$m^{1/2}$, tests at E_{CORR}, DCPD for crack monitoring.

Key observations:

- CO_2: increased C_H^0, decreased %RA
- pH: increased C_H^0, decreased %RA
- HCO_3^-: no effect on C_H^0, decreased %RA
- Cl^-: no effect on C_H^0, no effect on %RA
- 3 mg/L SO_4^{2-}: decreased C_H^0, decreased %RA
- $\geq$30 mg/L SO_4^{2-}: decreased C_H^0, increased %RA
- SO_4^{2-}/Cl^-: decreases C_H^0, no effect on %RA
- HS^-: increased C_H^0, decreased %RA
- $S_2O_3^{2-}$: increased C_H^0, no effect on %RA
- 100 mg/L HSO_3^-: limited effect on C_H^0, decreased %RA
- 1000 mg/L HSO_3^-: limited effect on C_H^0, decreased %RA
- 100 vppm O_2: increased C_H^0, decreased %RA
- 1000 vppm O_2: limited effect on C_H^0, decreased %RA
- AQDS: decreased C_H^0, increased %RA
- humic acid: no effect on C_H^0, decreased %RA, lower CGR
- fulvic acid: no effect on C_H^0, decreased %RA, lower CGR
- humic + fulvic acids: no effect on C_H^0, decreased %RA, lower CGR

Check if additional Comments made ☒

Key conclusions:

- effect of pH was predominant
- HS^- detrimental (increased H perm and decreased ductility)
- model organics are generally inhibitive, although humic and fulvic acids did lead to decreased ductility

Comments:

- Question is what is being measured in the SSRT; simply the loss in ductility under severe plastic deformation due to H absorption or some measure of crack initiation and/or growth? In some cases, observed decreased C_H^0 and increased loss of ductility

Ref. no.: 074	
Title: Mechanistic studies of initiation and early-stage crack growth for near-neutral pH SCC on pipelines	
Authors: F. King, T. Jack, W. Chen, M. Wilmott, R.R. Fessler, K. Krist	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00361	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage growth	
Sub-phase/keywords: Electrochemistry	
Results support R&D Guideline no.: N146	
Comments: Summary paper of various electrochemical and H permeation studies in NNpH solutions. H permeation studies as a function of stress using hollow tensile specimen. Key observations: • characterized various aspects of voltammograms of C-steel in NOVA trapped water • rate of H permeation increases with increasing elastic stress >80% SMYS due to increase in C_H^0 • source of H evolution in NNpH solutions is reduction of H^+, rather than HCO_3^- or H_2O	

Check if additional Comments made ☐

Ref. no.: 075	
Title: Effect of surface scratch roughness and orientation on the development of SCC of line pipe steel in near neutral pH environment	
Authors: D. He, W. Chen, J. Luo, F. King, T. Jack, K. Krist	
Source: Proc. 3rd International Pipeline Conference (ASME, New York, NY), Vol. 2, 997-1004.	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N147	

Comments:
Study of effect of surface roughness and scratch orientation on NNpH SCC initiation. Material: X-65, flat tensiles, polished to 240- and 600-grit; scratch orientation parallel, perpendicular, or 45^{o} to loading axis, strain rate 10^{-6} s^{-1}. Electrolyte: soil extract with 5% CO_2/N_2. Tests conducted at E_{CORR} or -0.8 V_{SCE}. Susceptibility based on %RA.
 	
Key observations/conclusions:
• scratches aligned perpendicular to loading axis facilitate the development of SCC
• scratches aligned parallel to loading direction have little effect on SCC development
• degree of roughness has little effect at E_{CORR}, but is more significant at cathodic potentials
 	
Comments:
• Issues:
  o relevance of polished samples to millscale-covered pipeline steels?
  o is %RA a good measure of SCC susceptibility or even crack initiation?	

Check if additional Comments made ☐

Ref. no.: 076	
Title: Long seam welds in gas and liquids pipelines and near-neutral pH stress corrosion cracking and corrosion fatigue	
Authors: R. Eadie, L.W. Hunt, R. Sutherby, G. Roy, G. Shen, J. Luo, W. Chen. T.C. Hamré, F. King, T. Jack	
Source: Proc. 4th International Pipeline Conference (ASME, New York, NY), paper IPC2002-27118.	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.:	
Comments: Summary of CEPA study to investigate role of long-seam welds on NNpH SCC. Investigations included: measurement of residual stress, FEA stress analysis, electrochemical measurements of potential distribution around weld. Investigated four different pipes, including both double submerged arc weld (DSAW) and electric resistance welded (ERW). Key observations: • weld crown produces stress concentration factors of 1.2-2.8, with four of five welds with SCF > 2.0 • surface residual stress at toe of weld were compressive and ranged from -200 MPa to -650 MPa, but were close to neutral at a depth of >0.2 mm • elastic calculation of net stress during operation, taking into account SCF and residual stress, predicts net plastic tensile stress at toe of weld, primarily due to the SCF • estimated net stress varies significantly from pipe to pipe, suggesting significant variation in susceptibility • shot peening can impart such a high compressive residual stress, that net operating stress is still compressive near toe of weld • insignificant potential differences between weld metal, HAZ, and parent metal • material from weld toe is less susceptible to low temperature creep than parent metal Key conclusions: • for DSAW pipe, stress and stress concentration by weld crown is main contributing factor to longseam weld cracking	

Check if additional Comments made ☐

Ref. no.: 077	
Title: The role of stress intensifiers in near-neutral pH corrosion fatigue of line pipe	
Authors: J. Been, H. Lu, R. Eadie, G. Shen, RT. Sutherby	
Source: Proc. CORROSION/2004, NACE International (Houston, TX), paper no. 04552	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, early stage crack growth	
Sub-phase/keywords: Weld crown, pit	
Results support R&D Guideline no.: N150, N151	

Comments:

Study of factors associated with CF as applied to NNpH SCC, including estimation of "K_{ISCC}" and ΔK_{th} from literature. Limited experimental and FEA analyses of effect of stress raisers, with the latter estimating stress intensification for pit and weld crown as a function of the depth of an associated crack.

Key conclusions:

- literature reports for "K_{ISCC}" range from 20 MPa·m$^{1/2}$ at R = 0.5 to ~30 MPa·m$^{1/2}$ at R = 0.82
- literature reports for ΔK_{th} range from 2-10 MPam$^{1/2}$
- possible reasons for enhancement of short crack growth
  - electrochemical
  - smaller crack closure effects than for longer cracks
  - residual stress fields
  - stress concentration by stress raisers (this study)
- stress intensification by pit or weld crown diminishes with crack depth
  - at depth of 0.1 mm, factor of ~2 for weld crown and ~1.7 for pit
  - at depth of 1.1 mm, factor of ~1.2 for weld crown and ~1.2 for pit
- effect of stress raiser is to increase number of damaging cycles for short cracks

Comments:

- interesting analyses, but indicates apparently significant surface stress concentration diminishes quickly with increasing crack depth
- can stress intensification by a factor of 1.2 account for x10 increase in short crack growth rate?
- stress intensification may be more important for crack initiation than early stage growth

Check if additional Comments made ☐

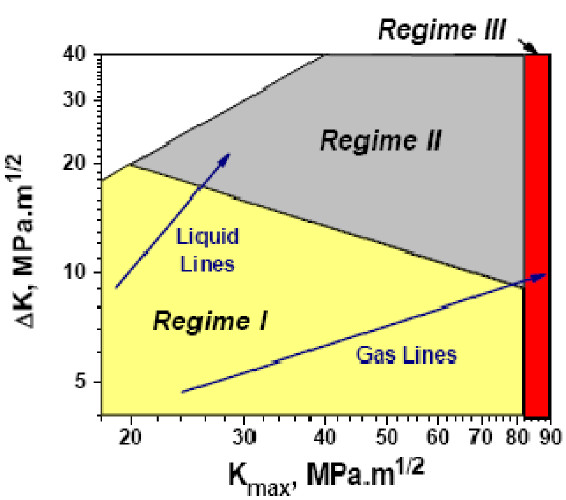
Ref. no.: 078	
Title: Prediction of environmentally assisted cracking on gas and liquid pipelines	
Authors: J. Been, R. Eadie, R. Sutherby	
Source: Proc. 6th International Pipeline Conference (ASME, New York, NY), paper IPC2006-10345.	*Year:* 2006
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N152, N153, N154, N155, N156, N157, N158, N159	

Comments:

Combined CEPA-funded experimental and modelling study of NNpH SCC focused on corrosion fatigue aspects. Material: X-65, 0.016 %S. Specimens: CT, 2.5 mm fatigue pre-crack, PD measurements of crack depth, cathodic polarized by 20 mV to simulate coupling to millscale. Dilute trapped water, 5% CO_2/N_2, pH 6.4. Cyclic loading: most expts at 0.005 Hz, some at 0.001 and 10^{-4} Hz, ΔK range 12-45 MPa·m$^{1/2}$, K_{MAX} range 20-100 MPa·m$^{1/2}$.

Key observations/conclusions:

- divided crack growth into different regimes based on K_{MAX} and ΔK values



- threshold ΔK in range 12-15 MPa·m$^{1/2}$
- dormancy occurred at ΔK below threshold value
- 20 mV cathodic polarization resulted in 2-5x higher CGR
- apparently dormant cracks could be re-started by resuming cyclic loading
- within the (extended) range of frequencies studied (10^{-5} to 0.01 Hz), da/dN decreased with increasing f, with da/dt increasing with increasing f

Check if additional Comments made ☒

Key observations/conclusions (continued):

- developed crack growth expressions for each of three regions in figure
  - o Regime III based on data measured at high K_I: da/dN = 2.57 X $10^{-4} \cdot K_{MAX}^{0.6}$
  - o Regime II based on non-linear fit to data at intermediate K_{MAX} and ΔK: da/dN = 3.27 x $10^{-8} \cdot \Delta K^{2.88} \cdot K_{MAX}^{0.42}$
  - o Regime I based on fit to data near threshold conditions to $\dot{\varepsilon_{CT}}$ model (because CF model gave unreasonably low CGR at low ΔK): da/dt = $0.0085 \cdot \dot{\varepsilon_{CT}}^{0.79}$
- threshold ΔK for CF mechanism a function of K_{MAX} with values of 20, 13, and 9 MPa·$m^{1/2}$ at K_{MAX} values of 20, 40, and 82 MPa·$m^{1/2}$, respectively.
- model accounts for SCC on liquid lines reasonably well (i.e., it produces credible times-to-failure), but predicts lifetimes >50 yrs for gas lines

Comments:

- Excellent approach to NNpH SCC modelling
- Although I am in agreement with adding a non-CF term at low ΔK to account for short crack behaviour, I am not sure the one proposed here is appropriate since, although it applies to low ΔK, was still measured using long crack son CT samples. Therefore, it may not include effects due to electrochemical or crack closure effects.

Ref. no.: 079

Title:
Near-neutral pH SCC: dormancy and re-initiation of stress corrosion cracks

Authors:
J.A. Beavers

Source:	*Year:*
Gas Research Institute Report GRI-7045	2004

Relevant phase(s) in SCC Guidelines:
NNpH SCC early-stage growth and dormancy

Sub-phase/keywords:

Results support R&D Guideline no.:

Comments:

Experimental study to determine the environmental, metallurgical, and mechanical conditions leading to dormancy and re-initiation. Material: X-65, two heats, 0.002% and 0.005% S. Specimens: 1/2 T CT, crack monitoring by DCPD. Environment: NS4, 5% CO_2/N_2, with higher CO_2 and added O_2 in some tests. Loading conditions: R = 0.9 (typical), 0.6, 0.8; frequency 10^{-5} Hz (typical), 10^{-2}, 10^{-3}, 10^{-4} Hz; K_{MAX} = 53-63 MPa·m$^{1/2}$. Started tests at R = 0.9, 10^{-5} Hz, ΔK ~5-6 MPa·m$^{1/2}$ which generally caused dormancy, then applied transient environmental (increased CO_2, O_2 addition) or mechanical event (e.g., simulated hydrotest, unload/reload), followed by resumption of initial conditions to determine whether crack re-started.

Key observations/conclusions:

- Two definitions of dormancy
  - A rate insufficient to cause failure during service life (0.06 mm/yr, 2 x 10^{-9} mm/s)
  - Rate equal to general corrosion rate (0.06 mm/yr, 2 x 10^{-9} mm/s)
  - Two definitions produce same estimated rate
- CGR related to crack-tip strain rate, but uncertainties in analysis and quality of correlation not considered good enough to use $\dot{\varepsilon}_{CT}$ to predict CGR on pipeline based on data from lab tests
- Propose that R ratio and frequency (which, in part, determine $\dot{\varepsilon}_{CT}$) can be used to rank whether dormancy will occur
- Propose that concept of a critical strain rate can be used to predict dormancy
- Unload-reload transients can increase the CGR and re-initiate dormant cracks
- Overloads had no consistent effect on CGR or re-initiation of dormant cracks
- Simulated hydrotests did not affect (near-) dormant cracks but did slow actively growing cracks
- For (near-) dormant conditions, increasing CO_2 or addition of O_2 can re-initiate cracks, as to can a decrease in O_2

Check if additional Comments made ☒

Comments:

- Some useful concepts, but difficult to quantify because of (i) variability between different $\dot{\varepsilon}_{CT}$ expressions, (ii) experimental variability associated with measuring such low crack growth rates
- However, still using long cracks, as indicated by high K_{MAX}, so not simulating geometry of short cracks and, hence, may not be representing all aspects of short-crack behaviour
- Figure below is basis for both threshold R/f for dormancy and a critical crack-tip strain rate

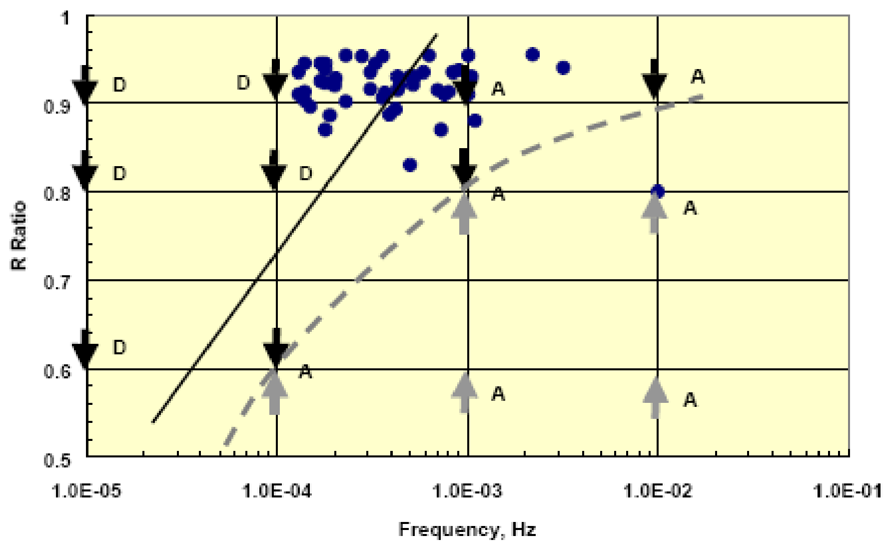


Figure 23. Figure 13 superimposed with the active/dormancy (A/D) predictions based strain rate calculated from Equation 11 and a critical crack tip strain rate of 9.6×10^{-6} sec^{-1}.

Ref. no.: 080	
Title: Evaluation of SCC susceptibility of X-70 steel in contact with various soil solutions at near neutral pH: comparison of laboratory predictions with field predictions	
Authors: T. Jack, M. Wilmott, W. Chen	
Source: Proc. 12th Biennial Joint Research Meeting on Pipeline Research, (Groningen, The Netherlands, May 17-21, 1999), Paper no. 11.	*Year:* 1999
Relevant phase(s) in SCC Guidelines: NNpH SCC suspcetibility	
Sub-phase/keywords: SSRT, H permeation	
Results support R&D Guideline no.: N169	

Comments:

Development of ranking technique based on SSRT and H-perm. Comparison with Marr soils model predictions. Material: X-70, 0.002% S. Specimens: polished tensiles and H-perm samples (1.5 mm thick). SSRT: 10^{-6} s^{-1}, %RA used as measure of SCC susceptibility. Environments: soil extracts obtained from six soil samples from sites, three of which had been characterized using Marr soils model, 5% CO_2/N_2. All measurements reported obtained at E_{CORR}.

Key observations/conclusions:

- sub-surface absorbed H concentration increases with decreasing potential
- %RA decreases with decreasing potential
- values of E_{CORR}, %RA, and C_H^0 rank in same order as Marr soils ranking

Comments:

- have to be careful with correlation of C_H^0 and %RA as it may simply reflect the loss of ductility with absorbed H, rather than increased susceptibility to SCC
- Marr soils model is a combination of various site factors of which the soil chemistry, the only one of relevance in this test, is just one parameter. Therefore, observed correlation may be fortuitous.

Check if additional Comments made ☐

Ref. no.: 081	
Title: Stress corrosion cracking of pipelines – its control or prevention	
Authors: R.N. Parkins	
Source: Proc. CORROSION/96, NACE International (Houston, TX), paper no. 249	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC	
Sub-phase/keywords: Remedies, control	
Results support R&D Guideline no.: H007, H008, H009, H010, H011	

Comments:

Overview of high-pH and NNpH SCC and of various remedies and approaches to the control of SCC that have been developed based on R&D.

High-pH SCC:

- Increasing temperature increases the rate of cracking and the width of the potential window for cracking
- Application of a cathodic current density to a mill-scaled or rusted surface polarizes the potential into the range for cracking
- On a cathodically polarized pipe, iR drop down the disbondment can result in some regions being within the potential window for cracking
- Overprotection at potentials more negative than -1.1 V_{SCE} can result in H_2 bubbles that block CP and shift potential into cracking range
- Decreasing the amplitude of pressure fluctuations leads to an increase in the threshold stress

Comments:

- Summary of conclusions from separate research studies.

Check if additional Comments made ☐

Ref. no.: 082	
Title: Testing methods for low-pH pipeline SCC: a comparison of SSRT and full-scale testing	
Authors: W. Zheng, R.W. Revie, F.A. MacLeod, D. Kiff, S. Rajan	
Source: Proc. CORROSION/95, NACE International (Houston, TX), paper no. 187	*Year:* 1995
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: SSRT	
Results support R&D Guideline no.: N170	
Comments: Summary of SSRT in NS1 and NS4 for various p_{CO2} and description of test design for full-scale testing. Material: X-65 and X-52. Specimen: tapered cylindrical tensiles; SCC severity assessed from maximum crack depth and number of cracks. Solutions: NS1, NS4, NS4 with added phosphate and ammonia for microbes. Key observations: • Unable to determine threshold stress for NNpH SCC because all cracks were restricted to the heavily necked region of the sample • Crack initiation/growth appears to occur at loads/strains beyond the yield point (based on interrupted test) • Significant variation in tests prevented any conclusions • Estimated CGR three orders of magnitude higher than observed in field • Concerns over relevance of SSRT	

Check if additional Comments made ☐

Ref. no.: 083	
Title: Electrochemical processes controlling SCC of underground pipelines	
Authors: R.B. Rebak, Z. Xia, R. Safruddin, Z. Szklarska-Smialowska	
Source: Proc. CORROSION/95, NACE International (Houston, TX), paper no. 184	*Year:* 1995
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: N028, N029, N030, N031, N032	
Comments: Same data as described in the more-extensive journal paper #021 above.	

Check if additional Comments made ☐

Ref. no.: 084	
Title: Low-pH stress corrosion cracking of natural gas pipelines	
Authors: B.A. Harle, J.A. Beavers, C.E. Jaske	
Source: Proc. CORROSION/94, NACE International (Houston, TX), paper no. 242	*Year:* 1994
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	

Comments:

Summary of approach to NNpH SCC based on J-integral. Description of work very much in the developmental stage. Material: X-65, 0.002% S. Solutions: NS4, 5% CO_2/N_2. Samples: ½ T CT specimens. J-integral can be thought of as the work required to grow a unit are of crack (incremental area under load-displacement curve divided by product of the incremental crack extension x crack (specimen) width).

Key observations/conclusions:

- monotonic relationship between J-integral and crack velocity

Comment:

- experimental development paper

Check if additional Comments made ☐

Ref. no.: 085	
Title: Application of the crack layer theory for understanding and modeling of stress corrosion cracking in high pressure pipeline steel	
Authors: A. Chudnovsky, B.-H. Choi, J. Fan, B. Zhang	
Source: Gas Research Institute Report, GRI-04/0169	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage growth	
Sub-phase/keywords: Model, statistical, crack colony	
Results support R&D Guideline no.: None	
Comments: Modelling and experimental study of the initiation and early-stage growth of NNpH SCC and colony development. Work was divided into four main tasks: 1. Statistical analysis and re-construction of an SCC colony 2. Numerical modelling of multi-crack interactions 3. Experimental measurements of individual SCC growth 4. Development of crack layer model Key observations/conclusions: • based on aspect ratio data presented, seem to have cracks which are deeper than semicircular • develop Monte Carlo model for crack initiation and growth, although details are not clear Comments: • Not an easy report to read or understand.	

Check if additional Comments made ☐

Ref. no.: 086	
Title: Theoretical and experimental study of stress corrosion cracking of pipeline steel in near neutral pH environment	
Authors: B. Zhang, J. Fan, Y. Gogotsi, A. Chudnovsky	
Source: Proc. 3rd International Pipeline Conference (ASME, New York, NY), Vol. 2, 1013-1020.	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage growth	
Sub-phase/keywords: Crack characterization	
Results support R&D Guideline no.: None	

Comments:

Summary of detailed program presented in ref. 085, describing combination of statistical modelling and experimental measurements.

Key observations/conclusions:

- Cracks always associated with pits, but not every pit initiates a crack. Percentage of pits associated with cracks 56%
- Poisson distribution of pits and Γ-distribution of crack lengths in a colony.
- Assumed completely random pit formation and probability of pitting, used constant crack growth rate and arrive at a crack and pit pattern that looks similar to what is observed in field
- Use thermodynamics of irreversible processes and conceptual model of process zone that includes three sub-zones: plastic deformation zone, H-affected zone, and electrochemical zone
- Develop a crack growth model based on plastic deformation and distribution of H – implicitly assuming that H distribution controls crack growth
- Accelerated testing at 1 Hz and R of 0.2, 0.4, 0.6, 0.8

Comment:

- Very difficult paper to follow
- Difficult to see how this work can be justified for use in predicting remaining lifetimes.

Check if additional Comments made ☐

Ref. no.: 087	
Title: Stress corrosion cracking under field simulated conditions. Part I: electrochemical studies of buried stress corrosion cracking environments	
Authors: M.J. Wilmott, G. Van Boven, T. Jack	
Source: Gas Research Institute Report, GRI-96/0452.1	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility, high-pH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Electrochemical study of high-pH and near-neutral pH environments with the aim of identifying rate-determining or important electrochemical processes in cracking systems. Key observations/conclusions: • Demonstrated active-passive transition in typical high-pH environment • Absence of active-passive transition in near-neutral pH environment • Corrosion rates of unstressed samples in near-neutral environments are lower than field-observed crack growth rates • Corrosion rates could be higher on stressed samples in near-neutral pH environments, so could not discount dissolution mechanism Comments: • Voltammetry in near-neutral pH environment was obscured by iR drop	

Check if additional Comments made ☐

Ref. no.: 088	
Title: Stress corrosion cracking under field simulated conditions. Part II: development of a crack tip model for stress corrosion cracking in carbon dioxide-rich near-neutral pH bulk solutions	
Authors: M.K. Watson, M.J. Wilmott, B. Erno	
Source: Gas Research Institute Report, GRI-96/0452.2	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, high-pH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N171, H012	

Comments:

Report of two models, a reactive-transport model to predict conditions inside a near-neutral pH SCC crack, and a thermodynamically-based model to predict the consequences of evaporative concentration of a bicarbonate solution.

Key observations/conclusions:

- NNpH SCC reactive-transport model
  - pH at crack tip is a minimum of one pH unit lower than that in bulk electrolyte outside crack
  - predicted crack-tip current density too low to account for field CGR, from which concluded that a dissolution model alone was not appropriate for NNpH SCC
  - complex interactions of MnS inclusions and crack solution chemistry
- Thermodynamic high-pH SCC evaporation model
  - simulated evaporation of $NaHCO_3$ solution in a closed system leads to the predicted precipitation of trona ($Na_3H(CO_3)_2{\cdot}2H_2O$) at 50°C and nahcolite ($NaHCO_3$) at 10 or 25°C
  - simulated evaporation of $NaHCO_3$ solution in equilibrium with CO_2 as in air predicts the precipitation of natron $Na_2CO_3{\cdot}10H_2O$ at 10, 25, and 50°C
  - simulated evaporation of $NaHCO_3$ solution in equilibrium with 5% CO_2 predicts the precipitation of nahcolite at 10, 25, and 50°C

Comments:

- NNpH SCC reactive-transport model awkward and not convincing, although prediction that pH is only one unit lower than bulk electrolyte is consistent with the fact that Fe is present as Fe(II) and that there are no other strongly hydrolysable cations present

Check if additional Comments made ☐

Ref. no.: 089	
Title: Investigation of pipeline stress corrosion cracking under controlled chemistry conditions	
Authors: M.J. Psaila-Dombrowski, A. Van Der Sluys, B.P. Miglin	
Source: Gas Research Institute Report, GRI-97/0001	*Year:* 1997
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Crack chemistry, sulphide	
Results support R&D Guideline no.: N172	

Comments:

Report of experimental studies in which species were injected into the crack of a CT specimen and the consequences on crack growth determined. Similar to studies report in # 068.

Key observations/conclusions:

- Injection of sulphide into crack tip accelerates crack up to 20x the rate in air
- Injection of $MgSO_4$ and CO_3^{2-}/HCO_3^- increase rates from 2-14x that in air

Comments:

- Effect of HS^- either be due to H or a CF process that involves the formation of FeS
- Effect of $MgSO_4$ could be due to acidification of the crack solution due to hydrolysis of Mg^{2+}
- The addition of CO_3^{2-}/HCO_3^- would tend to buffer pH in more-alkaline range

Check if additional Comments made ☐

Ref. no.: 090	
Title: Assessment of the aggressiveness of various types of soil towards low-pH SCC	
Authors: F. King, T. Jack, L. Yang	
Source: Gas Research Institute Report, GRI-04/0097	*Year:* 2004a
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords: Steel susceptibility, organics, soils model, soil extracts, soil solutions	
Results support R&D Guideline no.: N173, N174, N175, N176, N177, N178	

Comments:

Experimental study to assess the aggressiveness of various soils and the susceptibility of different steels using SSRT and H-permeation, supplemented by E_{CORR} and other analyses. Materials: five different steels, three from service (X-52 0.0143% S, X-65 0.016% S, X-70 0.002% S), all ferrite-pearlite and two unused (X-75 0.0053% S, X-70 0.0039% S) both acicular-ferrite. Samples: polished round tensiles and flat H-perm samples. Loading: SSRT at 10^{-6} s^{-1} at E_{CORR}. Environments: soil extracts from 13 soils, with one organic/sand soil providing an organic extract, a sand extract, and a 50:50 mixed extract. Equilibrated with 5% CO_2/N_2 or 1% CO_2/N_2. Field studies: NOVAProve *in situ* measurements of E_H, pH, temperature, soil resistivity.

Key observations:

- %RA decreases with increasingly negative E_{CORR} and increasing C_H^0
- Higher C_H^0 affects not only overall ductility but also severity of SCC
- Extract from organic component of mixed organic-sand soil inhibited aggressiveness of sand component
- No other soil property was found to correlate with loss of ductility
- Steels with more-negative E_{CORR} and higher C_H^0 exhibited greater loss of ductility
- Field observations indicated more-negative redox potentials at known SCC sites
- Evidence for brittle behaviour on fracture surfaces
- Modern, microalloyed, un-used steels were less susceptible than vintage ferrite-pearlite steels from service

Key conclusions:

- Results of lab tests in reasonable agreement with ranking based on soils model
- Results provide explanation for field observation that aggressiveness of organic soils depends on depth of organics
    - o organic soils have two effects: (i) tend to develop anaerobic conditions due to aerobic respiration and (ii) one or more organic components is inhibitive
    - o the inhibitive effect is dominant for pipes surrounded by organics, but the development of anaerobic conditions predominates for organics over sand
- E_{CORR} is a useful predictor of SCC susceptibility
- E_H may be a reasonable surrogate for E_{CORR}
- Depth of organics may be a useful indicator of soil aggressiveness
- For site selection, best to rely on overall "scenario" rather than a single parameter

Check if additional Comments made ☒

Comments:

- Question again is the relevance of SSRT to NNpH SCC under cyclic load as stresses nominally in the elastic range (notwithstanding stress concentrators and intensifiers, and residual stress). Authors suggest that, in addition to effect of H_2O on ductility, SSRT fracture surfaces also show evidence for brittle behaviour, suggesting some significance to SCC
- Relatively small sample of steels, but potentially useful evidence that modern steels are less-susceptible than vintage steels
- Possibly useful explanation for role of organics on SCC susceptibility
- Possibly useful correlation with E_{CORR}/E_H

Ref. no.: 091	
Title: Long-term environmental monitoring of near-neutral and high-pH SCC sites and the basis of an improved SCC site selection model	
Authors: F. King, K. Ikeda-Cameron, T. Jack, J. Been	
Source: Gas Research Institute Report, GRI-04/0098	*Year:* 2004b
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, high-pH SCC susceptibility	
Sub-phase/keywords: Field monitoring, NOVAProbe	
Results support R&D Guideline no.: H013, H014, N179, N180, N181	

Comments:

Report of an extensive field monitoring program of nine known Canadian NNpH (seven sites) and high-pH (two sites) SCC sites over a period of several years. Parameters monitored: pipe-depth NOVAProbe measurements (soil resistivity, redox potential, temperature, pH), corrosion coupons (CP conditions and native potential), miscellaneous data (pipe information; soil, groundwater, coating, and corrosion product samples; topography and land use; precipitation data; soil gas samples; SCADA pressure data; corrosion and SCC ILI information; CIS data; gas temperature (for high-pH SCC sites); and information about the nature of the SCC). Not all kinds od data were collected at all sites.

Key observations:

- NNpH SCC
  - associated with both permanently anaerobic and cyclic aerobic/anaerobic on tape lines
  - associated only with cyclic aerobic/anaerobic on asphalt lines (possibly due to need for aerobic microbial activity to break down complex organics in asphalt for subsequent use by simpler anaerobes or because aerobic cycles correspond with dry soils in which CP is lost or cause precipitation of carbonate in pores of ctg)
  - transitional nature of sites
    - temporal transitions involving seasonal changes in pipe-depth environment (resistivity, redox potential, soil-gas CO_2)
    - spatial transitions involving variation around pipe and along length of pipe or variations in height of water table
- High-pH SCC
  - both sites permanently aerobic, dry
  - transitional nature of sites
    - temporal transitions involving seasonal changes in pipe-depth environment (resistivity, redox potential, soil-gas CO_2)
    - spatial transitions involving variation around pipe

Check if additional Comments made ☒

Key conclusions:

- Temporal transitions imply cracking is not a continuous process, which has implications for lifetime prediction

Comments:

- Limited number of sites investigated, especially for high-pH SCC.

Ref. no.: 092	
Title: Coating deterioration as a precursor to SCC	
Authors: J. Been, F. King, F. Song, N. Sridhar	
Source: Gas Research Institute Report, GRI-04/0099	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, high-pH SCC susceptibility	
Sub-phase/keywords: Shielding coating, permeable coating	
Results support R&D Guideline no.: N182, N183, H015, H016, H017	

Comments:
Experimental and modelling study of the development of conditions for either NNpH SCC or high-pH SCC under shielding or permeable coatings, respectively. Experimental: NNpH SCC – model shielding disbondments (in triplicate) in each of three soils ranked by soils model. High-pH SCC: model permeable disbondment. In all cases, simulated disbondments were instrumented to measure time-dependent potential, pH, total carbonate concentration. Modelling: NNpH SCC – application of TECTRAN
 	
Key observations:
• NNpH SCC simulated disbondments
    o application of a small potential increased the disbondment pH and total CO_2 content slightly during long-term experiments
    o stabilization at near-neutral pH conditions occurred in the presence of minimal CP penetration into the disbondment and as a consequence of a decrease in the current reaching the steel at the disbondment site, most likely as a result of deposit formation at the mouth of the disbondment
    o differences in the nature of the trapped water environments for different soils were observed
        ▪ more-conductive clay till provided better current penetration into the disbondment, resulting in pH increase
        ▪ low conductivity sand with a low soil CO_2 content had little ability to buffer an increase in pH when a potential was applied, resulting in pH increase
    o drying of a soil may enhance the accessibility of the external environment to the trapped water, which could increase the absorbed CO_2 concentration
    o ranking of soils in terms of their ability to generate NNpH SCC conditions was in good agreement with soils model ranking
• NNpH SCC TECTRAN modelling
    o simulations suggest CO_2 permeation through tape coating may be important for maintaining near-neutral pH
    o degradation of the mastic may act as an additional source of CO_2	

Check if additional Comments made ☒

Key observations/conclusions:

- High-pH SCC permeable coatings
    - application of CP leads to an increase in pH in the simulated disbondment, but high CO_3^{2-}/HCO_3^- concentrations not observed with model porous membrane
    - pH and E in cracking region when current density was low or CP was interrupted
    - a greater supply of CO_2 is required to develop high CO_3^{2-}/HCO_3^- concentrations, possibly due to drying or holiday in coating

Comments:

- Uncomfortable with suggestion that pH increases under disbonded shielding coating. There is no evidence for this from the field, yet it is a common laboratory observation. I suspect we are somehow not properly simulating the disbondment geometry.
- Development of high-pH SCC environment should intuitively be a balance between the rate of pH increase at the interface (i.e., the applied cd) and the rate at which alkaline species can leave the disbondment (i.e., the porosity of the coating).
- Another possible reason for the lack of CO_3^{2-}/HCO_3^- concentration in the disbonded region is that CO_2 generation may occur within the disbondment itself, rather than only in the bulk soil environment, as was simulated experimentally in this project.

Ref. no.: 093	
Title: Initiation of stress corrosion cracking in pipeline steel	
Authors: M. Elboujdaini, Y.-Z. Wang, R.W. Revie, M. Shehata, G. de Silveira, R.N. Parkins	
Source: Gas Research Institute Report, GRI-05/0005	*Year:* 2005
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N126, N130	
Comments: Similar results to those reported by King et al. (2001) (record #070)	

Check if additional Comments made ☐

Ref. no.: 094	
Title: Correlation of soil conditions and SCC initiation phenomena to microbial induced corrosion	
Authors: T. Jack, L. Stehmeier, L. Yang, Y. Cheng, K. Ikeda-Cameron, R. Muwanga	
Source: Gas Research Institute Report, GRI-04/0160	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N184	

Comments:
Experimental study of the effect of prior exposure samples to active microbial medium followed by assessment of SCC initiation by SSRT. Material: X-65, 0.002% S. Samples: tapered tensile samples, polished to 600 grit on one side, millscale with adhesive on reverse. Testing: in duplicate, 2×10^{-5} s^{-1}, susceptibility based on %RA and number of secondary cracks on surface. Environments: pre-exposure to nitrate- or sulphate-reducing media in clay and peat soil for 33 days in anaerobic chamber under 5% CO_2/N_2 environment; similar solution used for SSRT testing. Controls also performed.
 	
Key observations:
• no effect on exposure to microbes on %RA
• secondary cracks in plastically deformed material near fracture
• larger number (~3x) of secondary cracks on samples pre-exposed to microbially active soil than controls
 	
Key conclusions:
• microbes could induce SCC initiation by:
  o preferential colonization on scratches, thus leading to linear pattern of defects
  o preferentially associating with inclusions	

Check if additional Comments made ☐

Ref. no.: 095	
Title: Environmental factors: effect on SCC growth	
Authors: G. Van Boven, T.R. Jack, F.King	
Source: Gas Research Institute Report, GRI-04/0161	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC, high pH SCC, suscpetibility	
Sub-phase/keywords: ILI, soils models, correlative model, soil resistivity	
Results support R&D Guideline no.: H018, N185, N186, N187	

Comments:

Attempt to correlate pipe-depth soil (resistivity, temperature, redox potential, pH, PSP) and terrain properties (drainage, soil type,) with ILI indications (both high-pH and NNpH SCC).

Key observations:
Only one verified high-pH SCC site on two lines studied. Site characteristics consistent with following conditions for finding SCC:

- inadequate CP
- high K/Na to Ca/Mg cation ratio
- high soil resistivity
- wet/dry cycles
- high temperature

Total of 59 NNpH SCC sites over a 90-km-long section. No SCC was observed at sites with soil resistivity greater than 14,000 ohm cm. No other single soil or site parameter correlated with SCC; however, higher probability of finding NNpH SCC under following conditions:

- level to gently sloping terrain
- low soil resistivity
- low redox potential
- poor CP
- poor drainage
- shallow peat deposits over glacial-lacustrine sediments susceptible to ponding

No NNpH SCC SCC was found:

- for soil resistivity >14,000 ohm cm
- at redox potentials of -0.32 to -0.68 V_{CSE}
- good CP

Comments:

- No unique soil characteristic (except perhaps for resistivity) for SCC. This is not surprising given the multivariate nature of SCC
- Small sample size, particularly for high-pH SCC

Check if additional Comments made ☐

Ref. no.: 096	
Title: Inhibitive effects of organics on near-neutral pH SCC	
Authors: J. Been, L. Yang, H. Lu, F. King	
Source: Gas Research Institute Report, GRI-04/0150	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC, susceptibility, initiation, early-stage growth	
Sub-phase/keywords: SSRT	
Results support R&D Guideline no.: N188	

Comments:

Experimental study of the effects of natural and model organic compounds, using SSRT, cyclic loading, H permeation, and electrochemical techniques.

Key observations:

- inhibitive effect of natural organics on SSRT
- inhibitive effect of organics on cyclic crack growth tests
- organics inhibit anodic reaction
- no effect of organics on H permeation
- inhibitive effect appears to depend on concentration of organics
- inhibitive effects of model organics on SSRT

Key conclusions:

- organics inhibit anodic dissolution
- redox-activity of organics thought to cause inhibition

Comments:

- if organics inhibit anodic reaction, then there should have been an effect of organics on H permeation at E_{CORR}

Check if additional Comments made ☐

Ref. no.: 097	
Title: Generation of near neutral pH and high pH SCC environments on buried pipelines	
Authors: T.R. Jack, B. Erno, K. Krist, R.R. Fessler	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00362	*Year:* 2000
Relevant phase(s) in SCC Guidelines: High pH SCC susceptibility, NNpH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: H019, H020, H021, H022, N189, N190	

Comments:

Review and synthesis of previous published work on mechanisms for generating high-pH and NNpH SCC environments.

Key observations:

Generation of NNpH SCC environments:

- compared with high-pH SCC, relatively little difference between groundwater and trapped water compositions for NNpH SCC
- what slight differences there are suggest precipitation of Ca (possibly due to CP at disbondment mouth) and loss of sulphate (possibly due to SRB), and increase in bicarbonate

Generation of high-pH SCC environments:

- can be generated by CP or evaporation
- under action of CP, Mg/Ca carbonates precipitate when they reach a region of high pH (possibly within ctg or at ctg/trapped water interface), resulting in Na/K-rich trapped electrolyte
- composition of trapped electrolyte depends on permeability of ctg, current density, and groundwater composition
- to attain permissive combination of potential and environment requires either an appropriate match of ctg permeability and current density, or the loss of CP for a permissive environment
    - in the latter case, potential would relax faster than the trapped water composition
    - implies a cyclic scenario of solution development and relaxation
- numerical evaporation leads to sodium bicarbonate precipitation at p_{CO2} >5% but pH is below the cracking window and sodium carbonate at lower p_{CO2} but pH is above the cracking window
    - implies a range of p_{CO2} for High-pH SCC
    - also requires that CP controls potential within cracking range

Comments:

- separation of Ca/Mg and Na/K due to precipitation of the former when they hit a region of high pH may be an effective way of concentrating K/Na in trapped water. Therefore, may not need high Na/K in groundwater as Beavers suggests

Check if additional Comments made ☐

Ref. no.: 098	
Title: Stress corrosion cracking study of microalloyed pipeline steels in dilute $NaHCO_3$ solutions	
Authors: A. Torres-Islas, J.G. Gonzalez-Rodriguez, J. Uruchurtu, S. Serna	
Source: Corros. Sci. 50, 2831-2839	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords: Microstructure, SSRT	
Results support R&D Guideline no.: N191	

Comments:

Experimental study of the effect of microstructure of X-70 pipeline steel to NNpH SCC in dilute $NaHCO_3$ solutions.

Key observations:

- greatest loss of ductility at potentials around E_{CORR} and within +50 mV anodic
- mild cathodic polarization (-100 mV) results in increased ductility compared with E_{CORR}
- large cathodic polarization (greater than -600 mV) results in decrease in ductility
- no consistent trend of heat treatment on suspcetibility

Key conclusions:

- propose a film rupture mechanism for as-received and water-sprayed conditions and a H mechanism for quenched and quenched and tempered heat treatments

Comments:

- differences in SSRT behaviour between the various heat treatments are minor and do not show consistent trends with potential or $NaHCO_3$ concentration
- no replicates or error in %RA provided
- is it likely that differences in heat treatment (microstructure) could result in a change in mechanism?

Check if additional Comments made ☐

Ref. no.: 099	
Title: Effect of precyclic loading on stress-corrosion-cracking initiation in an X-65 pipeline steel exposed to near-neutral pH soil environment	
Authors: W. Chen, S.-H. Wang, R. Chu, F. King, T.R. Jack, R.R. Fessler	
Source: Metall. Mater. Trans. A 34A, 2601-2608	*Year:* 2003
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Cyclic loading, X-65	
Results support R&D Guideline no.: N192	

Comments:

Experimental study of the effect of cyclic loading on the initiation of NNpH SCC on X-65 pipeline steel simulated trapped water solution. Cyclic loading equivalent to ~20 yrs service applied prior to exposure in corrosive environment

Key observations:

- micro-cracks observed following exposure to simulated trapped water environment following cyclic loading
- microcracks initiated at pits associated with grain boundaries, pearlite colonies, and banded phases
- strong preferential dissolution along banded structure, due to micro-galvanic effects
- cyclic loading with a peak stress of 80% YS resulted in fewer and shallower microcracks
- number and depth of micro-cracks increased with peak stress during cyclic loading for stress levels >80% YS
- modest increase in number and depth of micro cracks for peak stress during cyclic loading of 110% YS

Comments:

- specimens were polished prior to use, calling into question the relevance of the surface preparation
- if cyclic loading has an effect on crack initiation, then peak stress must be greater than 100% YS, i.e., significantly higher than 110% SMYS, implying a role for stress raisers
- to achieve 110% YS, load must be ~130% SMYS (actual YS not given in paper), which implies a stress concentration factor of 1.6 for a pipeline operating at 80% SMYS

Check if additional Comments made ☐

Ref. no.: 100	
Title: Microstructure dependence of stress corrosion cracking initiation in X-65 pipeline steel exposed to a near-neutral pH soil environment	
Authors: R. Chu, W. Chen, S.-H. Wang, F. King, T.R. Jack, R.R. Fessler	
Source: Corrosion 60, 275-283	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Cyclic loading, X-65	
Results support R&D Guideline no.: None	
Comments: Very similar to Metall. Mater. Trans A study (ref. no. 099).	

Check if additional Comments made ☐

Ref. no.: 101	
Title: Precyclic-loading-induced stress corrosion cracking of pipeline steels in a near-neutral-pH soil environment	
Authors: S.-H. Wang, W. Chen, F. King, T.R. Jack, R.R. Fessler	
Source: Corrosion 58, 526-534	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Cyclic loading, X-65, X-80	
Results support R&D Guideline no.: N193, N194	

Comments:

Experimental study of crack initiation on polished or mirror-polished X-65 and X-80 pipeline steels subject to cyclic loading prior to immersion in test electrolyte at constant load at E_{CORR} or under slight cathodic polarization.

Key observations:

- pre-cyclic loading causes crack initiation during subsequent corrosion exposure at constant load and cathodically polarized by 50 mV
- no microcracks were observed if the specimen was exposed to the corrosive solution at E_{CORR} because of general dissolution
- cracks observed at 45^o to loading direction or parallel to scratches for 600-grit polished specimens
- cracks only observed at 45^o to loading direction for mirror-polished specimens

Key conclusions:

- microcrack formation attributed to presence of localized deformation, such as persistent slip bands or polishing lines

Comments:

- not sure that dissolution at E_{CORR} would destroy all evidence for micro-crack initiation
- effect of cathodic polarization could be due to enhanced crack initiation due to H produced under cathodic polarization
- inference is that cyclic loading promotes crack initiation, but no quantitative relationship established by this study
- usual concerns about relevance of polished specimens

Check if additional Comments made ☐

Ref. no.: 102	
Title: The role of residual stress in neutral pH stress corrosion cracking of pipeline steels. Part I: pitting and cracking occurrence	
Authors: G. Van Boven, W. Chen, R. Rogge	
Source: Acta Mater. 55, 29-42	*Year:* 2007a
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage growth, dormancy	
Sub-phase/keywords:	
Results support R&D Guideline no.: N195, N196, N197, N198	

Comments:

Experimental study of the effect of residual stress on NNpH SCC crack initiation and growth under cyclic loading. Residual stress artificially induced through bending specimen. Residual stress characterized by n-diffraction.

Key observations:

- micro-pitting (up to a depth of 200 μm) occurred preferentially in areas with highest tensile residual stress (~300 MPa)
- little pitting or general corrosion in areas of compressive residual stress
- cracking occurred at bottom of micropits
- cracks tended to occur in areas with tensile residual stress of 150-200 MPa, but not in areas of highest tensile residual stress or compressive residual stress
- regions of highest tensile residual stress may have relaxed more during cyclic loading and, therefore, failed to support crack initiation
- evidence for crack blunting by dissolution and creep deformation at a specific depth at which rate of crack growth has slowed below dissolution rate because of decrease in residual stress
- crack growth rate increases with increasing residual stress
- threshold residual stress for crack growth of 150 MPa in short-term tests

Check if additional Comments made ☐

Ref. no.: 103	
Title: The role of residual stress in neutral pH stress corrosion cracking of pipeline steels. Part II: crack dormancy	
Authors: W. Chen, G, Van Boven, R. Rogge	
Source: Acta Mater. 55, 43-53	*Year:* 2007b
Relevant phase(s) in SCC Guidelines: NNpH SCC early-stage growth and dormancy	
Sub-phase/keywords:	
Results support R&D Guideline no.: N199, N200, N201, N202	

Comments:

Companion study to ref. no. 102.

Key observations:

- cyclic loading can attenuate both the magnitude and the gradient (through thickness) of residual stress
- although pitting occurs in regions of highest tensile residual stress, cracking is favoured is areas of moderate surface residual stress and low stress gradients
- crack initiation requires high stress gradient (this is contradictory to the previous statement)
- plastic deformation (creep) and extensive dissolution bunt cracks
- active cracks can become dormant as near-surface tensile residual stress decreases or becomes compressive in nature, due to re-distribution of stress as crack grows
- this dormancy mechanism often happens within 1 mm of surface
- factors that prevent dormancy include:
    - large tensile stress gradient extending deep into wall
    - specific microstructures/materials properties producing low-temperature creep deformation
    - environments that promote HIC of dormant cracks

Comments:

- interesting paper and technique, but a number of the conclusions are contradictory or difficult to follow.

Check if additional Comments made ☐

Ref. no.: 104	
Title: Residual stress and stress corrosion cracking of high pressure hydrocarbon transmission pipelines	
Authors: G. Van Boven, R. Rogge, W. Chen	
Source: Proc. IPC 2006, ASME (New York, NY), paper IPC2006-10486	*Year:* 2006
Relevant phase(s) in SCC Guidelines: NNpH SCC early-stage growth and dormancy	
Sub-phase/keywords:	
Results support R&D Guideline no.: N195, N196, N197, N198, N199, N200, N201, N202	
Comments: Summary of more-detailed results in Ref. no. 102 and 103.	

Check if additional Comments made ☐

Ref. no.: 105	
Title: Stress corrosion crack initiation in X-65 pipeline steel under disbonded coating with cathodic protection	
Authors: B. Fang, A. Eslami, R. Kania, R. Worthingham, J. Been, W. Chen	
Source: Proc. IPC 2008, ASME (New York, NY), paper IPC2008-64476	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Coating, CP	
Results support R&D Guideline no.: N203, N204, N205	

Comments:

Experimental simulation of a disbonded region in a NNpH SCC electrolyte with the application of CP with or without purging with 5% CO_2/N_2 (location of purge not identified, i.e., in bulk solution or within crevice simulating disbondment). Used C2 solution (Ca-rich 33 ppm, high Cl^-, poorly buffered, 51 ppm HCO_3^-), shown elsewhere to maintain sharp crack tip. Gap between steel plate and simulated ctg 10 mm. pH microelectrode used to measure pH in crevice. Experiment performed for 64 days with CP of -1.2 V_{SCE}, with CO_2 purging for first 37 days (Stage I) and then stopped (Stage II) (no applied stress). Second experiment with cyclic loading (R = 0.8, σ_{MAX} = 100% SMYS, strain rate 8.7 x 10^{-8} s^{-1}), continuous 5% CO_2/N_2 purge.

Key observations:

- Acidification of disbonded region with CO_2 bubbling in Stage I, but increase in pH in absence of CO_2 purge
- pH lowest nearest mouth of disbondment, with a minimum value of pH 4.2 compared with ~pH 6 for the bulk solution
- acidified disbondment solution pH rose to value in bulk solution after 25 days
- upon cessation of CO_2 bubbling, pH in disbondment increased to as high as pH 11
- less corrosion near mouth of disbondment due to effective CP, pitting in mid-range of sample, and general corrosion furthest from disbondment mouth
- under cyclic load, crack-like features appeared to initiate from cracks in mid region of sample
- density of pits and cracks a maximum 8-10 cm from mouth of disbondment

Key conclusions:

- environment under disbondment will vary seasonally in accordance with the rate of CO_2 generation
- cracking most likely some distance away from mouth of disbondment

Comments:

- the report of acidification in the disbonded region does not make physical sense
- the proposed acidification mechanism involving preferential H^+ migration is implausible as, if true, the cathodic would be more acidic than the anode
- furthermore, if the reported pH measurements are correct, there is a 2 pH unit discontinuity between the mouth of the disbondment and the bulk solution
- no indication of initial surface treatment of steel plate.

Check if additional Comments made ☐

Ref. no.: 106	
Title: Low temperature creep behaviour of pipeline steels	
Authors: W. Chen, H. Zhu, S-H. Wang	
Source: Can. Met. Quart. 48, 271-284	*Year:* 2009
Relevant phase(s) in SCC Guidelines: High-pH SCC, NNpH SCC, susceptibility	
Sub-phase/keywords: Cyclic loading	
Results support R&D Guideline no.: N206	

Comments:

Experimental study of low-temperature creep behaviour of X-52, X-70, X-80, and X-100 pipeline steels.

Key observations:

- detailed room-temperature creep studies show that cyclic loading can induce burst of creep strain at room temperature in pipeline steels
- creep strain varies for different materials/microstructures

Comments:

- creep burst of potential relevance for crack initiation and growth

Check if additional Comments made ☐

Ref. no.: 107	
Title: Environmental aspects of near-neutral pH stress corrosion cracking of pipeline steel	
Authors: W. Chen, F. King, T.R. Jack, M.J. Wilmott	
Source: Met. Mat. Trans. A 33A, 1429-1436	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: SSRT, soil extracts, pH, CO_2	
Results support R&D Guideline no.: N207, N208	

Comments:

Experimental study of susceptibility to NNpH SCC in soil extracts using SSRT. Susceptibility to SCC assessed based on relative time-to-failure.

Key observations:

- time-to-failure decreased with:
  - decreasing potential (regardless of soil type, pH)
  - increasing pH (at E_{CORR}) up to pH 7.5, decreasing pH in more alkaline solution
  - maximum susceptibility at pH 7.5
  - E_{CORR} increases with decreasing pH

Key conclusions:

- aggressiveness of a soil can be judged from the difference in pH in N_2 and CO_2-purged solution – the narrower the pH range the more-aggressive the soil
- for a given soil, aggressiveness increases with decreasing pH (increasing p_{CO2}), although no evidence presented to support this claim

Comments:

- concerns about the relevance of SSRT for determining SCC susceptibility, especially when using time-to-failure as a measure of susceptibility
- interesting suggestion that range of pH for a given soil indicates aggressiveness, which might imply that highly-buffered soil extracts are most aggressive
- suggestion that susceptibility to SCC increases with increasing p_{CO2} difficult to reconcile on basis of evidence provided

Check if additional Comments made ☐

Ref. no.: 108	
Title: Laboratory simulation of hydrostatic test in near-neutral pH soil environments	
Authors: W. Chen, R. Sutherby	
Source: Proc. IPC 2006, ASME (New York, NY), paper IPC2006-10477	*Year:* 2006
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: N209, N210	

Comments:

Experiemtnal study of crack growth during hydrotesting monitored using potential drop technique and CT specimens. Specimens exposed to one of two simulated NNpH SCC solutions during simulated hydrotest.

Key observations/conclusions:

- observed crack growth in solution, but not in air during simulated hydrotest
- amount of crack growth depends on crack morphology, crack depth, and environment
  - more crack growth in C2 solution than in NOVA trapped water
  - more growth for shorter cracks
- hydrostatic testing reduces the subsequent growth rate during return to service, at least temporarily
  - level of reduction depends on magnitude of cyclic loading, with greater reduction for more mild cyclic loads

Comments:

- observation of crack growth during hydrotest can explain pressure reversals during hydrotesting
- the C2 electrolyte again appears to be very aggressive, primarily by maintaining a shapr crack tip. Is this solution representative of anything or just a laboratory contrivance? Need to understand reason for sharpness of crack in C2 solution.
- crack growth rate must have been high during simulated hydrotest in order to have been able to measure it during a relatively short period of time, notwithstanding the fact that hydrotest represents severe loading conditions – must be a very severe enevironemntal effect for it to be appararent over such a short time period

Check if additional Comments made ☐

Ref. no.: 109	
Title: Hydrogen permeation behavior of X-70 pipeline steel in a near-neutral pH soil environment	
Authors: W. Chen, T.R. Jack, F. King, M.J. Wilmott.	
Source: Proc. International Pipeline Conf. 2000 (ASME International, New York, NY), pp. 953-960	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N211	

Comments:

Experimental study of H permeation through a pipeline steel in a range of electrolytes under both galvanostatic and potentiostatic conditions.

Key observations/conclusions:

- Diffusible H concentration increases with increasing cathodic polarisation
- Diffusible H concentration a factor of 3-10 times below threshold for blistering of X-70
- Diffusivity apparently a function of potential

Comments:

- reported <u>diffusible</u> H concentrations are much higher than solubility of H in steel and probably represent a total H concentration

Check if additional Comments made ☐

Ref. no.: 110	
Title: R. Sutherby, W. Chen	
Authors: Deflected stress corrosion cracks in the pipeline steel	
Source: Proc. International Pipeline Conf. 2004 (ASME International, New York, NY), paper IPC04-0600	*Year:* 2004
Relevant phase(s) in SCC Guidelines: High-pH SCC, crack growth	
Sub-phase/keywords: Microstructure, hardness	
Results support R&D Guideline no.: H023, H024	

Comments:

Results of metallographic examination and analysis of crack path in pipe removed from service.

Key observations/conclusions:

- transgranular cracks deviate from normal direction of propagation at various depths through pipe wall
- relatively wide crack
- angle of "deflection" variable, but typically between 30^o and 60^o
- segment normal to hoop stress generally less than 1.5 mm long (15% pipe wall)
- "sandwich" type microstructure, with harder areas near inner and outer surfaces and progressively softer centre
- distribution of hardness may have caused complex loading condition, allowing yielding of softer material
- crack growth may then be possible influenced by shear stress

Comments:

- unusual observation of wide, corroded intergranular cracks, corrosion in crack generally being associated with transgranular NNpH SCC
- is this high-pH SCC or a distinctly different form of cracking
- could this be an example of a transition from high-pH to near-neutral pH SCC conditions?

Check if additional Comments made ☐

Ref. no.: 112	
Title: Environmental effect of crack growth rate of pipeline steel in near-neutral pH soil environments	
Authors: W. Chen, R. Sutherby	
Source: Proc. International Pipeline Conf. 2004 (ASME International, New York, NY), paper IPC04-0449	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords: Corrosion fatigue, C2 solution	
Results support R&D Guideline no.: N212, N213, N214, N215	

Comments:.

Experimental study of NNpH SCC crack growth in two different synthetic soil solutions. Crack growth using cyclically loaded CT specimens. Aggressive loading with R = 0.5-0.7, frequency 0.1-0.0025 Hz, K_{MAX} 35-55 MPa·m$^{1/2}$, ΔK 10-28 MPa·m$^{1/2}$. C2 (pH 6.3) and NOVA TW (pH 7.1), 5% CO_2.

Key observations/conclusions:

- nature of environment makes no difference at high ΔK (>15 MPa·m$^{1/2)}$, although CGR higher than in air
- at low ΔK (<15 MPa·m$^{1/2}$), CGR is strongly dependent on environment but not on ΔK
- effect of environment and loading is consequence of corrosion and RT creep on crack-tip sharpness and crack width
    - o paradoxically, low-corrosivity solutions result in blunt crack tips and wide cracks, resulting in lower K_I and less crack-closure effect, respectively
    - o less RT creep also results in sharper crack tip
- C2 solution results in sharper crack tip and 3x crack growth than in NOVA TW
- suggested that the more-corrosive C2 solution produces higher absorbed H concentrations that lead to microcracks at the crack tip where H accumulates, maintaining a sharp crack
- slower the crack growth rate, more time for RT creep to blunt crack tip

Comments:

- clearly an effect of the environment at low ΔK
- no clear explanation of role of solution chemistry – requires further study
- paper lists recipe for HC4 solution, but speaks of C2!

Check if additional Comments made ☐

Ref. no.: 113	
Title: Transgranular crack growth in the pipeline steels exposed to near-neutral pH soil aqueous solutions: the role of hydrogen	
Authors: W. Chen, R. Kania, R. Worthingham, G. Van Boven	
Source: Acta Materialia 57, 6200-6214	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC early-stage growth and dormancy	
Sub-phase/keywords: Dormancy, crack-tip blunting, hydrogen	
Results support R&D Guideline no.: N216, N217, N218, N219, N220, N221	

Comments:

Experimental crack growth study in HC4/C2 and NOVA TW solutions using cyclically loaded CT specimens (similar, same?, experimental data as ref. no. 112?). Also includes detailed discussion of factors leading to blunting and dormancy.

Key observations/conclusions:

- two competitive processes – blunting due to either RT creep or dissolution and sharpening due to fatigue and hydrogen effects
- under static loading, crack tip blunting is predominant, promoting dormancy
- under cyclic loading, less blunting but enhanced sharpening due to H-facilitated slip
- since gas lines operate under nearly constant load, crack growth must be due to intermittent bursts of growth between periods of dormancy.
    - implies that during periods of growth, CGR must be much higher than the time-averaged rate
- development of crack colony requires high residual stress and NNpH environment
- presence of external H promotes crack growth (ie, H from general corrosion or CP), with internal H produced at crack tip having a secondary effect

Comments:

- interesting paper, containing many suggestions for the cracking mechanism
- discussion tends to be loosely argued
- evidence that externally produced H is more important than H produced in crack is unclear. No discussion of H pick-up ratios, which are likely to be higher in a (slightly) acidified crack solution than on external surfaces, especially in the presence of CP and subsequent passive film formation
- discussion of short crack growth behaviour ignores any environmental effects and focuses only on residual stress

Check if additional Comments made ☐

Ref. no.: 114	
Title: Pit to crack transition in X-52 pipeline steel in near neutral pH environment Part 1 – formation of blunt cracks from pits under cyclic loading	
Authors: B.Y. Fang, R.L. Eadie, W.X. Chen, M. Elboujdaini	
Source: Corros. Eng. Sci. Technol. DOI 10.1179/147842208X386304	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords: Artificial pits	
Results support R&D Guideline no.: N222, N223, N224, N225, N226, N227	

Comments:

Experimental study of the initiation of cracks from artificial pits under cyclic loading.

Key observations/conclusions:

- crack initiation from pits is much easier in NNpH solutions than in air, occurring at fractions of a % of the number of cycles
- pits initiated in solution were wide, consistent with a dissolution mechanism
- not all pits initiated cracks
- crack initiation more likely from larger pits and with increasing depth:width ratio
- increasing probability of pit initiation with increasing peak stress
- increasing probability of pit initiation with smaller stress ratio
- exposure of pre-pitted samples to solution resulted in additional pits and transition to cracks at smaller pit sizes
- corrosive CS solution reduces pit-to-crack transition probability, probably by removing stress raising pits
- increased number of inclusions increased pit initiation

Comments:

- usual issue with relevance of polished specimens

Check if additional Comments made ☐

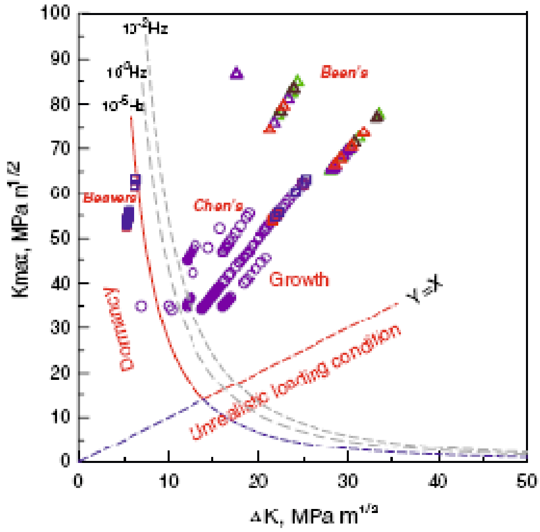
Ref. no.: 115	
Title: Crack growth behavior of pipeline steel in near-neutral pH soil environments	
Authors: W. Chen, R.L. Sutherby	
Source: Met. Mater. Trans. A, 38A, 1260-1268	*Year:* 2007
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth, dormancy	
Sub-phase/keywords: Corrosion fatigue	
Results support R&D Guideline no.: N228, N229. N230, N231	

Comments:

Experiemntal study of crack growth under cyclcic loading in various synthetic soil solutions. Aggressive loading with R = 0.6-0.8, frequency 0.1-0.00125 Hz, K_{MAX} 35-55 MPa·m$^{1/2}$, ΔK 10-28 MPa·m$^{1/2}$. X-65 steel from service, CT specimens with crack monitoring by potential drop. Various electrolytes used, including C1, C2, C3, and NOVA TW of increasing pH.

Key observations/conclusions:

- NNpH SCC involves a CF mechanism
- CGR decreased with increasing pH
- correlated crack growth behaviour from various sources with dependence on $\Delta K^2 K_{MAX}/f^{0.1}$
- threshold value of $\Delta K^2 K_{MAX}/f^{0.1}$ of 8500 (MPa·√m)^3/Hz$^{0.1}$
- frequency-dependent envelope for onset of dormancy



-
- threshold $\Delta K^2 K_{MAX}/f^{0.1}$ value may be environment and material dependent

Check if additional Comments made ☐

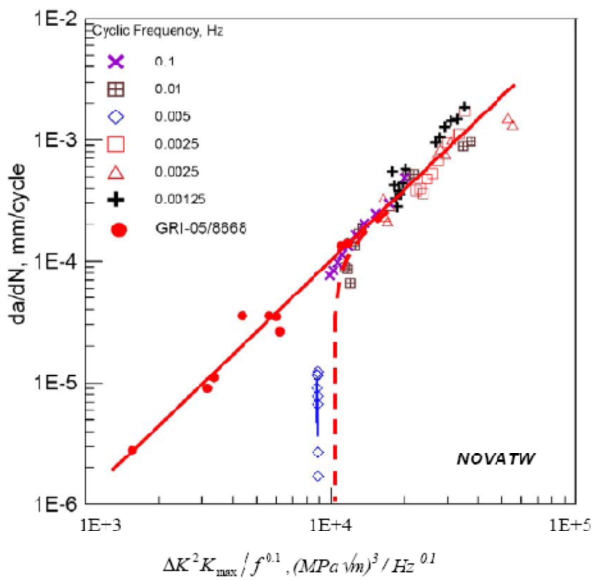
Ref. no.: 116	
Title: Crack growth model of pipeline steels in near-neutral pH soil environments	
Authors: W. Chen, R. Kania, R. Worthingham, S. Kariyawasam	
Source: Proc. International Pipeline Conf. 2008 (ASME International, New York, NY), paper IPC2008-64475	*Year:* 2008
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth, dormancy	
Sub-phase/keywords: Short cracks	
Results support R&D Guideline no.: N232	

Comments:

Presents similar model to that in ref. no. 115, but also includes discussion of behaviour of short cracks from full-scale tests.

Key observations/conclusions:

- as for ref. no. 115
- short cracks in full-scale tests grow below the threshold value of $\Delta K^2 K_{MAX}/f^{0.1}$ of 8500 $(MPa\cdot\sqrt{m})^3/Hz^{0.1}$
- short crack growth attributed to effects of residual stress of stress concentration



Comments:

- explanation for growth of short cracks below threshold ignores any effect of the crack chemistry/electrochemistry
- threshold $\Delta K^2 K_{MAX}/f^{0.1}$ of 8500 $(MPa\cdot\sqrt{m})^3/Hz^{0.1}$ applies only to lab CT specimens

Check if additional Comments made ☐

Ref. no.: 117

Title:
Role of hydrogen in crack growth in pipeline steels exposed to near neutral pH soil environment

Authors:
W. Chen, R. Kania, B. Worthingham, S. Kariyawasam

Source: Proc. Int. Conf. on Fracture (ICF 12), Ottawa, ON, July 12-17, 2009, paper T19.005	*Year:* 2009

Relevant phase(s) in SCC Guidelines:
NNpH SCC crack growth

Sub-phase/keywords:

Results support R&D Guideline no.:
N233, N234, N235, N236, N237

Comments:

Experimental study of crack growth of CT specimens under cyclic loading. Used masking of specimen sides to investigate role of bulk and crack-tip H.

Key observations/conclusions:

- corrosion in the crack tends to blunt the crack tip and lead to dormancy
- under benign mechanical loading conditions, CGR is determined by lattice H concentration around crack tip
- crack sharpening due to high H from corrosive solution overcomes blunting effect of corrosive environment
- H from general corrosion of pipe surface and CP more important than H generated within crack
- cracks may become dormant because of limited supply of H from external surface
- dormant cracks can be re-initiated by increasing lattice [H], eg, by increasing CP or corrosiveness of electrolyte (eg increasing p_{CO2})

Comments:

- suggestion that surface H is important is inconsistent with observation that CP can suppress cracking
- no discussion of H pick up efficiencies on bare surface compared with crack tip
- suggestion that cracks can become dormant because flux of H from surface becomes small is not credible. Flux of crack 20% through wall is 80% of that at the surface. Why would such a small decrease in H flux have such a dramatic effect on crack growth?

Check if additional Comments made ☐

Ref. no.: 118	
Title: Role of prior cyclic loading in the initiation of stress-corrosion cracks on pipeline steels exposed to near-neutral pH environment	
Authors: S-H. Wang, W. Chen, T. Jack, F. King, R.R. Fessler, K. Krist	
Source: Proc. International Pipeline Conf. 2000 (ASME International, New York, NY), vol. 2, pps. 1005-1011	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N238	
Comments: Experimental study of crack initiation on polished round tensile samples, X-52 and X-80 pipeline steels (S content not given), NS4 solution, 5% CO_2/N_2, cyclic loading R = 0.5-0.9, 5 x 10^{-5} s^{-1} strain rate, 8000 cycles in blocks to simulate gas line operation. Key observations/conclusions: • cyclic loading enhances crack initiation in solution • cracks initiate at pits, along polishing lines, and at persistent slip bands (45^o angle) • pits and micro-cracks only observed under slight cathodic polarization • no pits of cracks at OCP Comments: • conclusion that slight cathodic polarization is required for crack initiation is likely an artifact of the use of polished steel samples	

Check if additional Comments made ☐

Ref. no.: 119
Title: SCC in areas of local deformation
Authors: M.P.H. Brongers, J.A. Beavers
Source: Gas Research Institute report GRI-04/0127 — *Year:* 2005
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility
Sub-phase/keywords:
Results support R&D Guideline no.: N239, N240

Comments:

Combination of pipeline company survey, literature review, and limited FEA model of stress distribution around dents.

Key observations/conclusions:

- SCC in dents observed on both gas and liquid pipelines
- NNpH SCC more prevalent at dents than high-pH SCC
- cracking tended to occur around shoulder of dent where metallurgical changes are minimal, but cyclic and maximum stresses are high
- most failures occur in dents on bottom of pipe, suggestive of rock dents
- constrained dent may aggravate stress conditions
- presence of rocks in dent can shield CP
- FEA modelling shows complex stress distributions affected, in part, by the asymmetry of the dent, the presence of residual stress
- dent acts as a stress concentrator as well as imparting residual stress
- FEA modelling suggests:
    - highest stresses occur at the time the indenter impacts the steel
    - longitudinal indenter induces a larger area of residual stress than a spherical indenter

Check if additional Comments made ☐

Ref. no.: 120	
Title: Effects of O_2 and CO_2 on near-neutral-pH stress corrosion crack propagation	
Authors: J.T. Johnson, C.L. Durr, J.A. Beavers, B.S. Delanty	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00356	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords: Gas pipeline	
Results support R&D Guideline no.: N241, N242	

Comments:

Experimental study of the effects of O_2 and CO_2 on the electrochemical, H-permeation, and cyclic crack growth behaviour of X-65 pipeline steel in NS4 solution. Cyclic loading: R 0.89-0.9, 10^{-5} Hz, K_{MAX} = 64 MPa√m (large sub-critical crack)

Key observations/conclusions:

- increasing CO_2 (0-15%)
  - increased the corrosion rate
  - increased hydrogen permeation
  - accelerated crack growth
- increasing O_2 (0-20%)
  - no effect on corrosion rate
  - decreased rate of H permeation
  - increased CGR
- electrochemistry
  - indications of anodic film formation in NS4
  - E_{CORR} and i_{CORR} increase with increasing CO_2
  - E_{CORR} increased with increasing O_2 but no effect on i_{CORR}
- H-permeation
  - H permeation rate increases with CO_2, but decreased with O_2
- crack growth
  - increased with increasing CO_2, especially in range 0-5%
  - effect of O_2 (0-20%) minor in comparison to CO_2

Comments:

- simulated deep crack
- cracks look wide with significant crack wall corrosion
- evidence for crack deceleration in some tests, despite increase in CO_2
- suggestion that CGR increases with p_{CO2} is based on just three gas comps, 0%, 5%, 15% and difference between 5% and 15% is minimal. Therefore, could also indicate that simple presence of CO_2 increases CGR, as per other studies

Check if additional Comments made ☐

Ref. no.: 121	
Title: Mechanistic studies on near-neutral-pH SCC on underground pipelines	
Authors: J.A. Beavers, C.L. Durr, S.S. Shademan	
Source: Proc. Materials for Resource Recovery and Transport, L. Collins (ed.), The Metallurgical Society of CIM (Montreal, Canada), pp. 51-69	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Electrochemistry, H permeation	
Results support R&D Guideline no.: N243	

Comments:

Review of electrochemical, H permeation, and crack propagation studies.

Key observations/conclusions:

- electrochemical behaviour consistent with active dissolution in NS4 solution
- no evidence for active-passive transition necessary for slip dissolution model
- CO_2 significantly affects electrochemical behaviour (increased E_{CORR} and i_{CORR}) and increases H permeation
- increasing cathodic polarization increase H permeation rates but effect is offset by accompanying increase in pH
- cyclic loading required for crack growth, but no apparent effect of frequency
- crack velocity decreases with increasing R value
- observations consistent with a H mechanism

Comments:

- some of the conclusions from this work were contracted by later work by Beavers and others (eg, lack of frequency effect on CGR)
- these results must be considered as preliminary
- good example of early implementation of cyclic load testing

Check if additional Comments made ☐

Ref. no.: 122	
Title: Low-pH stress corrosion crack propagation in API X-65 line pipe steel	
Authors: B.A. Harle, J.A. Beavers	
Source: Corrosion 49, 861-863	*Year:* 1993
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords: J-integral	
Results support R&D Guideline no.: None	
Comments: Technical note on early studies applying J-integral approach to quantifying effect of cyclic loading on crack growth in NNpH SCC environments. Key observations/conclusions: • observed significant crack growth in NNpH electrolyte • J-integral is a useful measure of the crack driving force	

Check if additional Comments made ☐

Ref. no.: 123	
Title: Low-pH stress corrosion cracking of natural gas pipelines	
Authors: B.A. Harle, J.A. Beavers, C.E. Jaske	
Source: Proc. CORROSION/94, NACE International (Houston, TX), paper no. 242	*Year:* 1994
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Description of the results of early studies on replicating NNpH SCC using cyclic loading using the J-integral as a measure of the crack driving force. Key observations/conclusions: • confirmed ability to replicate crack growth in NNpH environment in the laboratory • monotonic relationship between crack growth and J-integral, suggesting the latter is useful as a measure of the driving force for crack growth • experimental conditions significantly more severe than experienced by operating pipelines • further work required	

Check if additional Comments made ☐

Ref. no.: 124	
Title: Near-neutral pH SCC: crack propagation in susceptible soil environments	
Authors: J.A. Beavers, C.L. Durr, B.S. Delanty, D.M. Owen, R.L. Sutherby	
Source: Proc. CORROSION/2001, NACE International (Houston, TX), paper no. 01217	*Year:* 2001
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, late-stage crack growth	
Sub-phase/keywords: Soils models, Marr, natural soil extracts	
Results support R&D Guideline no.: N244, N245, N246, N247, N248, N249	

Comments:

Experimental study to determine the aggressiveness of synthetic soil extracts from sites considered to be highly susceptible based on Marr soils model and to compare with aggressiveness of NS4. Soils ranked based on E_{CORR}, i_{CORR}, H permeation rate, crack velocity, microbial population. Tests performed using a synthetic soil solution based on analysis of centrifuged extract with addition of a "teabag" of actual soil. Study done in part to determine whether NS4 is representative of actual soil solutions.

Key results/observations:

- electrochemical behaviour is soil solution similar to that in NS4
- presence of soil teabag caused reproducible peak in H permeation current for several tests not observed in synthetic solution
- CGR higher in soil solution than in NS4
- CGR rate increases in less corrosive environments (decreasing i_{CORR} and E_{CORR})
- no correlation between field ranking and lab CGR
- no correlation between microbial population and any measured parameter, including H perm and CGR
- organics over clay soil gave by far highest CGR

Comments:

- current peak during H permeation is due to damage to steel allowing more H entry, typically due to microcracks or blisters associated with presence of sulphide
- correlation of i_{CORR} and E_{CORR} suggests active system
- absence of correlation between soil ranking and CGR does not necessarily indicate that soils models are not useful as crack growth is only one aspect of overall process
- K_{MAX} close to that for near-critical flaw, yet still saw effect of environment on CGR
- microbial population well known not to correlate with corrosion kinetics – rather, it is microbial activity that is important

Check if additional Comments made ☐

Ref. no.: 125	
Title: Materials factors influencing the initiation of near-neutral pH SCC on underground pipelines	
Authors: J.A. Beavers, J.T. Johnson, R.L. Sutherby	
Source: Proc. International Pipeline Conf. 2000 (ASME International, New York, NY), vol. 2, pps. 979-988	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords: Residual stress, surface roughness, cyclic stress-strain behaviour, inclusions, microhardness	
Results support R&D Guideline no.: N250, N251, N252, N253, N254, N255, N256, N257, N258, N259	

Comments:

CEPA study to correlate areas of initiated cracks on pipe from service with various metallurgical parameters, including: residual stress, surface roughness, cyclic stress-strain behaviour, inclusions (number, area, composition), microhardness, steel chemical composition, local galvanic behaviour. Fourteen pipe samples ranging from NPS8 to NPS 42, X-52 to X-70, 1950's-1970's vintage.

Key observations/conclusions:

- strong correlation between residual stress and presence of NNpH SCC colonies
  - residual stress increased with increasing depth, being near zero or negative at surface in some cases
  - no evidence for decrease in residual stress at depths <2 mm
  - residual stress decreased with increasing distance from SCC colonies
  - mean residual stress for SCC colonies 220 MPa, without SCC colonies 100 MPa
- microhardness is also higher in SCC colonies than in control areas
- possible correlation of SCC to surface roughness
  - rougher surface correlates to SCC
- no statistically significant correlation between occurrence of SCC colonies and:
  - steel composition
  - cyclic stress-strain behaviour
  - inclusion properties (S contents ranged from 0.003 to 0.021 ppm)
  - local galvanic behaviour

Comments:

- interesting that inclusion properties do not correlate with SCC colonies, given the overwhelming R&D evidence that cracks initiate from inclusions. This may indicate that, as noted elsewhere, that initiation studies on polished surfaces are of marginal relevance
- no evidence for decrease in residual stress between 1-2 mm is not consistent with argument that cracks become dormant due to exhaustion of residual stress

Check if additional Comments made ☐

Ref. no.: 126	
Title: Near-neutral pH SCC in pipelines: effects of pressure fluctuations on crack propagation	
Authors: J.A. Beavers, C.E. Jaske	
Source: Proc. CORROSION/98, NACE International (Houston, TX), paper no. 257	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N260, N261, N262, N263	
Comments: Experimental study of crack growth in NS4 solution using CT specimens and potential drop. Key observations/conclusions: • prior loading history has significant effect on crack growth behaviour o overloading inhibits subsequent crack growth o underloading stimulates cracking on reloading o hydrostatic testing, which involves both overloading and underloading, caused some crack extension but reduced subsequent crack velocity • cracking only occurs during loading part of cycle • CGR decreases with decreasing R value	

Check if additional Comments made ☐

Ref. no.: 127	
Title: Near-neutral pH SCC: mechanical effects on crack propagation	
Authors: J.A. Beavers, E.L. Hagerdorn	
Source: Proc. 9th Linepipe Symposium, Pipeline Research Council International, Catalog No. L51746, paper 24	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N260, N261, N262, N263	
Comments: Same data and conclusions as ref no. 126.	

Check if additional Comments made ☐

Ref. no.: 128	
Title: Mechanical and metallurgical effects on low-pH stress corrosion cracking of natural gas pipelines	
Authors: B.A. Harle, J.A. Beavers, C.E. Jaske	
Source: Proc. CORROSION/95, NACE International (Houston, TX), paper no. 646	*Year:* 1995
Relevant phase(s) in SCC Guidelines: NNpH SCC late-stage crack growth	
Sub-phase/keywords: Microstructure, welds	
Results support R&D Guideline no.: N264, N265	

Comments:
 	
Experimental study of effect of displacement rate and metallurgical parameters on crack growth as part of continued study of NNpH SCC applying J-integral approach.
 	
Key observations/conclusions:
• crack growth rate decreases with decreasing displacement rate
• crack growth rate depends on metallurgy
  o ERW weld material exhibits high crack growth rate and poor fracture resistance
  o HAZ exhibits higher crack growth rate than base metal
• overloads are beneficial for reducing subsequent crack growth
 	
Comments:	

Check if additional Comments made ☐

Ref. no.: 129	
Title: Stress corrosion cracking of linepipe steels in near-neutral pH environment: a review of the effects of stress	
Authors: W. Zheng, R. Sutherby, R.W. Revie, W.R. Tyson, G. Shen	
Source: In ASTM Special Technical Publication, STP 1401, Environmentally Assisted Cracking Predictive Methods for Risk Assessment and Evaluation of Materials, Equipment and Structures, R.D. Kane (ed.), American Society for Testing and Materials (West Conshohocken, PA), pp. 473-483	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC	
Sub-phase/keywords: Residual stress, net total stress, stress raiser	
Results support R&D Guideline no.: N266, N267, N268	

Comments:

Review of stress-related effects on NNpH SCC based on studies in literature.

Key conclusions:

- net total stress may be greater than nominal operating stress due to residual stress and stress raisers
- for maximum loads below the yield stress, cyclic loading is required for crack initiation and growth
- crack growth rates increase with increasing dJ/dt
- at loads close to yield stress, cracks may develop with very minor pressure fluctuations
    - low-T creep can then provide sufficient plastic strain for crack growth, aided by the presence of H
- hydrostatic testing retards subsequent crack growth, likely through the introduction of compressive residual stress

Check if additional Comments made ☐

Ref. no.: 130	
Title: Recent progress in the study of transgranular SCC in line pipe steels	
Authors: W. Zheng, F.A. MacLeod, R.W. Revie, W.R. Tyson, G. Shen, D. Kiff, M. Skaff, E-W. Wong	
Source: Proc. 2nd International Conference on Corrosion-Deformation Interactions-CDI '96 (European Federation of Corrosion Report No. 21), paper 28, pp. 282-292	*Year:* 1997
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N269	

Comments:

Experimental study of crack growth in actual silty clay soil environment using pre-cracked NPS20 X-60 or X-52 pipe. Initial cracks 1.3-2.5 mm deep (20-40% through wall). Trapezoidal loading with period of static load at maximum stress between unload/reload cycles.

Key observations/conclusions:

- No crack growth observed at R = 1.0 or 0.97 at 80% YS
- no effect of environmental conditions on growth of individual cracks within ranges studied (pH 6.9-7.0), [SO_4^{2-}] 31-49 ppm, [Cl^-] 18-27 ppm
- crack growth rate increases with increasing dJ/dt
- conclude a H mechanism based on fractography and fact that maximum observed crack growth rate of 10^{-6} mm/s is too high for dissolution mechanism

Check if additional Comments made ☐

Ref. no.: 131	
Title: Early stages of stress corrosion crack development of X-65 pipeline steel in near-neutral pH solution	
Authors: Y.Z. Wang, R.W. Revie, M.T. Shehata, R.N. Parkins	
Source: Proc. Materials for Resource Recovery and Transport, L. Collins (ed.), (Metallurgical Society of Canadian Institute of Mining, Metallurgy and Petroleum (CIM), Montreal, QC), p. 71-93.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N270, N271, N272	

Comments:

Experiemntal study of NNpH SCC initiation and early-stage growth using cyclically loaded polished tensiles in NS4 solution.

Key observations/conclusions:

- many types of crack initation sites with differing degrees of ease of initiation
  - pits formed from inclusions, but not all cracks have pits and not all pits initiate cracks
  - other surface geometrical discontinuities
  - at a later stage, sites generated by cyclic deformation
- crack initiation is a competitive process, with crack initiating first at the most favourable sites and subsequently at less-favourable locations
- number of cracks increase with test time
- for dense cracks that develop later, crack interaction and coalescence increases crack propagation
- cracks of a given size exhibit a wide range of growth rates
- stress range is more important for crack initation than maximum stress
- reducing magnitude of pressure fluctuations could be a method for controlling SCC

Comments:

- very aggressive cyclic loading at R as low as 0.4, 1 Hz
- releavance to pipeline operation, particularly given the use of polished samples

Check if additional Comments made ☐

Ref. no.: 132	
Title: Initiation of environment induced cracking in pipeline steel: microstructural correlations	
Authors: Y.Z. Wang, R.W. Revie, M.T. Shehata, R.N. Parkins, K. Krist	
Source: Proc. International Pipeline Conf. 1998 (ASME International, New York, NY), vol. 1, pps. 529-542	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N273	

Comments:

Experimental study of NNpH SCC crack initiation on polished samples under aggressive cyclic loading conditions. Similar in content to ref. no. 131, but with additional information.

Key observations/conclusions:

- multiple types of crack initiation site
- initiation is a competitive process, with cracks initiating first at the most favourable sites
- pits are the most favoured initiation sites and initiate first, but cracks may not remain longest cracks at later
- subsequent cracks form from local sites of microplastic deformation induced by cyclic loading, possibly as a result of slip dissolution at crystallogaphic planes
- dynamic loading maintains sharp crack during cracking process
- plasticity localization and localised dissolution mutually enhance each other, with absorbed H possibly enhancing plasticity localization

Comments:

- as with ref. no. 131, very aggressive (low R, high frequency) loading

Check if additional Comments made ☐

Ref. no.: 133	
Title: Pipeline SCC in near-neutral pH environment: effects of environmental and metallurgical variables	
Authors: W. Zheng, R.W. Revie, O. Dinardo, F.A. MacLeod, W.R. Tyson, D. Kiff	
Source: Proc. 9th Linepipe Symposium, Pipeline Research Council International, Catalog No. L51746, paper 22	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords: Microstructure, effects of CO_2, potential	
Results support R&D Guideline no.: N274, N275, N276, N277	

Comments:

Experimental study of NNpH SCC crack growth using pre-cracked NPS20 X-52 pipe in soil box. Effects of CO_2, potential, and metallurgical segregation reported.

Key observations/conclusions:

- cracks grow faster when CO_2 is admitted directly to crack site
- crack arrests when 100 mV cathodic polarisation applied
- some cracks grew in more-susceptible microstructure at 200 mV cathodic polarisation
- cracks slowed down during passage across pearlite-rich zones (high mid-wall hardness), possibly due to its higher yield strength
- evidence of K_{ISCC} of ~37 MPa√m at R = 0.6

Comments:

- re-activation of cracks at -200 mV polarization may indicate shift to HIC mechanism
- possible "sweet spot" of 0 to -100 mV polarization
- lower susceptibility of pearlite would suggest that banded microstructure should be beneficial, but not generally found
- could pearlite induce dormancy?

Check if additional Comments made ☐

Ref. no.: 134	
Title: Stress corrosion crack initiation processes: pitting and microcrack coalescence	
Authors: M. Elboujdaini, Y.-Z. Wang, R.W. Revie, R.N. Parkins, M.T. Shehata	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00379	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Recap of data from ref. no. 131, 132. No new data.	

Check if additional Comments made ☐

Ref. no.: 135	
Title: Mechanistic aspects of stress corrosion crack initiation and early propagation	
Authors: Y-Z. Wang, R.W. Revie, R.N. Parkins	
Source: Proc. CORROSION/99, NACE International (Houston, TX), paper no. 143	*Year:* 1999
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N278, N279, N280, N281, N282, N283	

Comments:

Contains some data from ref. no. 131 and 132 and new data.

Key new observations/conclusions:

- original surface is more susceptible to crack initiation than polished surface
- cracks initiated at:
    - depressed regions or valleys
    - pre-existing defects
    - non-metallic inclusions
- critical balance between solution corrosivity and severity of mechanical loading for crack development
    - at low R value, more and deeper cracks in more corrosive environment
    - at high R, cracks can be removed by general dissolution
- Mild CP (100 mV) has different effects on different crack sizes
    - accelerates growth of large coalesced cracks
    - slows growth of smaller individual cracks compared with rate at OCP

Comments:

- implies optimum conditions for early-stage crack is a combination of corrosive environment and low R
- interesting effect of CP, implies change of mechanism for early-stage growth from dissolution to H at point that cracks coalesce. Coalescence may correspond to point at which cracks become more mechanically driven.

Check if additional Comments made ☐

Ref. no.: 136	
Title: Pipeline SCC in near-neutral pH environment: results of full-scale tests	
Authors: W. Zheng, R.W. Revie, W.R. Tyson, G. Shen, F.A. MacLeod, D. Kiff,	
Source: Proc. CORROSION/96, NACE International (Houston, TX), paper no. 253	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N284, N285	

Comments:

Early report of experimental data from full-scale tests with NPS20 X-52 and X-60 pipe.

Key observations/conclusions:

- dynamic crack-tip strain is an important factor for crack growth
- no crack growth under static loading at 97% SMYS (80% YS)
- K_{ISCC} ~27 MPa√m
- observed crack growth at 78% SMYS (67% YS)

Comments:

- noteworthy that no cracking was observed under constant load at values of 97% SMYS

Check if additional Comments made ☐

Ref. no.: 137	
Title: Methodology for realistic full-scale testing of linepipe for stress-corrosion cracking	
Authors: R.W. Revie, W. Zheng, F.A. MacLeod, D. Kiff	
Source: Pipeline Technology, Vol. I, R. Denys (ed.), Elsevier (Amsterdam), pp. 571-576.	*Year:* 1995
Relevant phase(s) in SCC Guidelines: NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Description of development of full-scale testing rig. No experimental data reported.	

Check if additional Comments made ☐

Ref. no.: 138
Title: Low pH SCC: environmental effects on crack propagation
Authors: W. Zheng, R.W. Revie, F.A. MacLeod, O. Dinardo, D. Kiff, J. McKinnon

Source: Pipeline Research Council International report, Catalog. no. L51791e	*Year:* 1998

Relevant phase(s) in SCC Guidelines: NNpH SCC early-stage crack growth
Sub-phase/keywords:
Results support R&D Guideline no.: N286, N287, N288, N289, N290

Comments:

Experimental study of the environmental effects on NNpH SCC crack growth using the pre-cracked full-scale test facility. Similar experimental set-up as described elsewhere. Many results same as those in ref. no. 129, 130, 133, 136.

Key observations/conclusions:

- cathodic polarization of up to 200 mV was found to inhibit crack growth in base material, but no effect in more-sensitive microstructure such as ERW hard zone
- 100 mV anodic polarization slows cracks in ERW because of lower H production
- primary role of CO_2 is to control pH in NNpH range
- under cyclic loading, presence of CO_2 increased crack growth rate
- crack growth observed for R = 0.9 or lower
- cyclic loading pre-requisite for crack growth in base material and weld zone
- log (da/dt) proportional to log ($K \cdot \Delta K/\Delta t$), where $\Delta K/\Delta t$ is rate of increase in K during loading part of cycle
    - o same amount of crack growth for slow P fluctuation ($\Delta K/\Delta t$) at high load (K) as a fast P fluctuation at low load

Comments:

- benefit of anodic polarization raises possibility of anodic protection
- interesting relationship between da/dt and $\Delta K/\Delta t$

Check if additional Comments made ☐

Ref. no.: 139	
Title: The involvement of hydrogen in low pH stress corrosion cracking of pipeline steels	
Authors: R.N. Parkins	
Source: Proc. 12th Biennial Joint Research Meeting on Pipeline Research, Groningen, The Netherlands, May 17-21, 1999, paper no. 10	*Year:* 1999
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth	
Sub-phase/keywords: Hydrogen, trapped hydrogen	
Results support R&D Guideline no.: N291, N292, N293, N294, N295, N296	

Comments:

Experimental study of H permeation through pipeline steels using Devanathan-type cell.

Key observations/conclusions:

- H enters pipeline steels over a wide range of potentials and pH, including those associated with NNpH SCC
- H entry is enhanced by CO_2
- trapped H has no effect on ductility, since pre-charged specimens strained when exposed to air exhibit same ductility as non-charged specimens
- diffusible H does affect ductility, which is reduced when pre-charged (or specimens charged *in situ*) are tested in solution
- no evidence for H-enhanced plasticity
- most probably mechanism involves some unknown synergistic effect of H and dissolution
- increasing c_0^H leads to less reduction in area (ie, increased brittleness) in SSRT

Comments:

- H trap density cannot be used to rank susceptibility of different steels to NNpH SCC

Check if additional Comments made ☐

Ref. no.: 140	
Title: The initiation and early stages of growth of stress corrosion cracks in pipeline steel exposed to a dilute, near-neutral pH solution	
Authors: R.N. Parkins, B.S. Delanty	
Source: Proc. 9th Linepipe Symposium, Pipeline Research Council International, Catalog No. L51746, paper 19	*Year:* 1996
Relevant phase(s) in SCC Guidelines: NNpH SCC initiation, early-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N297, N298, N299, N300	

Comments:

Experimental study involving cyclic loading of flat tensile samples at 93% SMYS with R = 0.85 at 4.3 x 10^{-4} Hz, or range of σ_{MAX} and R at 0.074 Hz.

Key observations/conclusions:

- many small cracks initiate from pits but then grow laterally and re-from as pits with a maximum depth of 20 μm
- a few cracks continue to grow and then come under influence of σ and $\Delta\sigma$, but generally only grow under loading conditions more severe than those experienced by operating pipelines
- because of stochastic nature of pitting and scatter in observed crack growth rates, need to treat NNpH SCC stochastically
- small cracks can become dormant at pearlite bands (which are harder and will not exhibit the same plastic strain at a given stress level)
- if crack tips avoid pearlite then cracks can grow until such time that mechanical loading drives cracks regardless of microstructure
- field P fluctuations may be more severe than typical lab P spectra because they involve a random series of fluctuations of different sizes and strain rates

Comments:

- suggestion that small cracks only grow under loading conditions more severe than those experienced by operating pipelines may not take into account effects of residual stress and stress raisers
- crack arrest by pearlite would suggest that heavily banded steel should be less susceptible, but this does not appear to be the case
- suggestion of thousands of initiation events, most of which corrode to form pits, with only a fraction of cracks remaining as cracks of which the vast majority become dormant, resulting in few deep cracks

Check if additional Comments made ☐

Ref. no.: 141

Title:
Environment sensitive cracking of high-pressure pipelines in contact with carbon dioxide-containing solutions

Authors:
R.N. Parkins

Source:	*Year:*
Topical report to Line Pipe Research Supervisory Committee of the American Gas Association, NG-18 Report no. 205 (draft)	1992

Relevant phase(s) in SCC Guidelines:
NNpH SCC susceptibility, initiation, early-stage crack growth

Sub-phase/keywords:

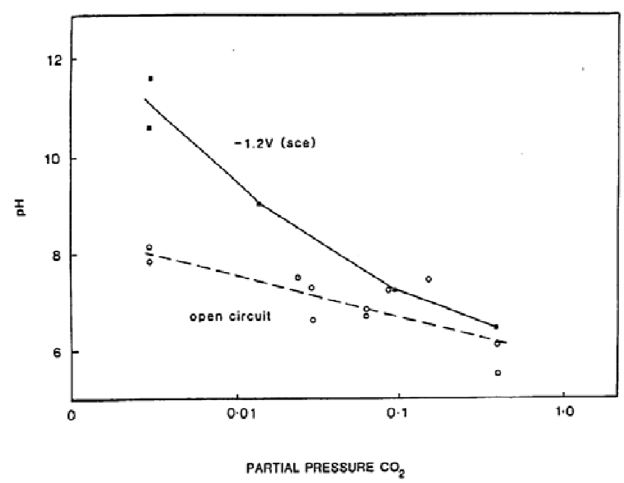
Results support R&D Guideline no.:
N301, N302, N303, N304, N305, N306, N307, N308

Comments:

Experimental study of effects of environment on SSRT behaviour of pipeline steel in CO_2-containing environments.

Key observations/conclusions:

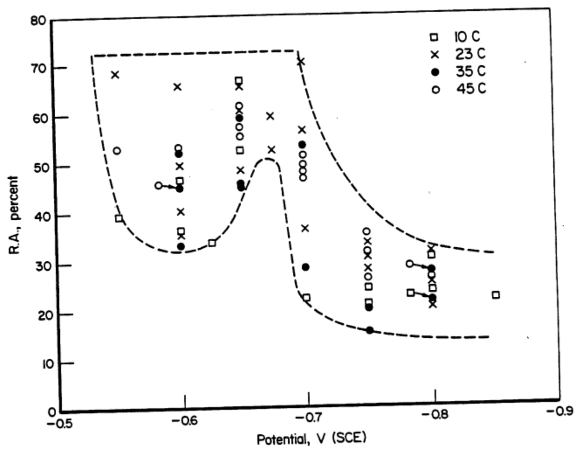
- pH associated with NNpH SCC in the field is inconsistent with significant CP reaching the pipe

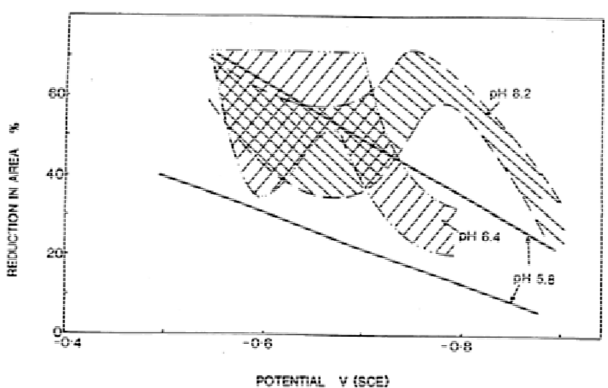


- CO_2 is important factor in NNpH SCC, based on failure time of SSRT
- No temperature dependence of SSRT data between 5 and 45^{o}C
- cyclic loading over a wide range of stress and stress ranges produces cracking similar to that observed in field
- mechanism involves both H and dissolution
- evidence that cracks form in bands suggesting that cracks initiate just ahead of existing cracks
- crack coalescence occurs early in crack life with later stages involving increase in crack depth

Check if additional Comments made ☒

- considerable scatter in both field and lab data, the latter being unreproducible
- coalescence of both field and lab cracks occurs for y < 0.14·(2a)
- cracks initiate in pits because these represent regions of low pH





Comments:

- under anaerobic (i.e., Fe(II)) conditions, won't get too much acidification of pits. Oxidation of MnS inclusions would acidify fit, but need O_2 or Fe(III)
- 5-10% CO_2 (pH 6.4) shows distinctly different behaviour of %RA = f(E) than 100% CO_2 (pH 5.8)

Ref. no.: 142	
Title: Effects of hydrogen on low pH stress corrosion crack growth	
Authors: R.N. Parkins	
Source: Report to Line Pipe Research Supervisory Committee of the American Gas Association, final report, PR-232-9704	*Year:* 1998
Relevant phase(s) in SCC Guidelines: NNpH SCC suscpetibility	
Sub-phase/keywords: H permeation	
Results support R&D Guideline no.: N291, N292, N293, N294, N295, N296	

Comments:

Experimental H permeation study of X-52 and X-60 steels in NS4 solution purged with N_2 (pH 8.3), 10% CO_2 (pH 6.3), or 100% CO_2 (pH 5.1).

Key observations/conclusions:

- H enters steel at OCP in NNpH environments
- H entry increases with increasing CO_2 partial pressure
- presence of corrosion product reduces, but does not prevent, H entry
- trap density varies from steel to steel
- H pre-charged specimen tested in air is ductile
- H pre-charged specimen tested in solution exhibits brittle behaviour
- steady-state H permeation flux increases with increasingly negative potential

Comments:

- essentially similar study and results/conclusions as ref. no. 139

Check if additional Comments made ☐

Ref. no.: 143	
Title: A review of stress corrosion cracking of pipelines in contact with near-neutral (low) pH solutions	
Authors: R.N. Parkins	
Source: Report to Line Pipe Research Supervisory Committee of the American Gas Association, PR-232-9701	*Year:* 1999
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, early-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: N309, N310, N311, N312, N313, N314, N315, N316, N317, N318, N319	

Comments:

Review of field and experimental (mostly based on SSRT) evidence on NNpH SCC.

Key observations/conclusions:

- although relatively modern FBE, urethane, and liquid epoxy coatings appear to have improved properties, situation for new multilayer coatings is unclear
- pipe surface prep plays a large role in avoiding cracking
- cracking can be obtained in pure water with CO_2, so role of Cl^- and sulphate is uncertain
- cracks initiate more readily on the original pipe surface, regardless of whether that surface has been water blasted or pickled
- cracks frequently grow from pits, often associated with non-metallic inclusions
- crack initiation is not random, and is often found around a central pit or at the edge of tape coating – directed initiation
- dormant cracks can be reactivated by coalescing with growing crack
- static load near yield stress is insufficient to initiate cracks
- cyclic loading is required for crack initiation, with decreasing R favouring cracking
- simulated hydrotest enhances cracking during test, but reduces crack growth upon return to normal P fluctuations
- pearlite grains can cause crack arrest
- HAZ of ERW is particularly susceptible to cracking
- mechanism involves a synergistic effect of H and dissolution
- no correlation between C_0^H and susceptibility as measured by SSRT
- H probably leads to decohesion, but some evidence for HELP (H-assisted RT creep)

Comments:

- additional observations/conclusions as in ref. no. 141, 142

Check if additional Comments made ☐

Ref. no.: 144	
Title: Microbial effects on stress-corrosion cracking of line-pipe steels in low-pH environments	
Authors: G.O. Davis, R.N. Parkins	
Source: Report to Line Pipe Research Supervisory Committee of the American Gas Association, NG-18 Report No. 202	*Year:* 1992
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation, early-stage crack growth	
Sub-phase/keywords: SRB, sulphide	
Results support R&D Guideline no.:	

Comments:

Experimental study involving X-65 SSRT (5 x 10^{-7} s^{-1}) in Postgate B medium with and without added SRB. 10% CO_2, pH 6-7. Susceptibility based on %RA and TTF.

Key observations/conclusions:

- no difference in SSRT behaviour with or without SRB
- CGR lower with SRB than without
- based on these tests, no indication that SRB are either necessary for, or enhance, NNpH SCC

Comments:

- possible that Postagte B contains an SCC (of anodic or cathodic) inhibitor, since it contains phosphate, lactate, and yeast extract
- SRB may produce inhibiting biofilm – explanation for lower apparent CGR with SRB
- Redvers himself was dismissive about the depth of this study

Check if additional Comments made ☐

Ref. no.: 145	
Title: Stress corrosion cracking in areas of local deformation	
Authors: M.P.H. Brongers, W. Kovacs, C.S. Scott, J.A. Beavers	
Source: Pipeline Research Council International report, Catalog no. TBD	*Year:* 2009
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth	
Sub-phase/keywords: Dent, CTOD, hydrotest	
Results support R&D Guideline no.: N321, N322	

Comments:

Experimental study of the effect of cyclic loading on crack growth in the shoulder of an unconstrained dent and specifically during a hydrotest. Studied mechanical component only, without the presence of an environment.

Key observations/conclusions:

- bending stresses more important than hoop stresses for crack in dent
- unlike undented regions, hydrotesting may not be beneficial for SCC associated with a dent

Comments:

- exclusion of environment raises questions about whether all effects have been taken into account, since other work shows an effect of the environment on deep cracks
- project largely involved development of methodology

Check if additional Comments made ☐

Ref. no.: 146	
Title: Raman spectral and electrochemical studies of surface film formation on iron and its alloys with carbon in $Na_2CO_3/NaHCO_3$ solution with reference to stress corrosion cracking	
Authors: M. Odziemkowski, J. Flis, D.E. Irish	
Source: Electrochim. Acta, 39, 2225-2236	*Year:* 1994
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords: Passive film, magnetite, iron carbonate	
Results support R&D Guideline no.: H025	

Comments:

Detailed electrochemical and surface analytical study of passivation and film formation of iron and steel in $Na_2CO_3/NaHCO_3$ solution at 75°C.

Key observations/conclusions:

- active region $FeCO_3$ or $FeCO_3 \cdot H_2O$, stated by authors to correspond to region of TGSCC
- active-passive transition: Fe_3O_4 and $FeCO_3$ (or $FeCO_3 \cdot H_2O$)
- passive region: FeOOH
- Fe_3O_4 specifically forms at -0.7 V_{SCE}, close to region of maximum susceptibility to IGSCC
- SCC is favoured by electrochemical conditions at which Fe(III) oxides or oxyhydroxides are in equilibrium with Fe_3O_4 and/or Fe(II) species

Comments:

- question is always what is chemical environment and potential inside crack and, especially, at the crack tip? Are they significantly different from those on/at the exposed surface?
- not certain that last conclusion is necessarily valid – although reduction of Fe(III) corrosion products does occur at -0.7 V_{SCE} during cathodic stripping, does this necessarily mean that the Fe(III) layer is in equilibrium with Fe_3O_4 or Fe(II0 species?

Check if additional Comments made ☐

Ref. no.: 147	
Title: Physico-chemical characterization of corrosion layers formed on iron in a sodium carbonate-bicarbonate containing environment	
Authors: J.M. Blengino, M. Keddam, J.P. Labbe, L. Robbiola	
Source: Corros. Sci. 37, 621-643	*Year:* 1995
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Electrochemical and surface analytical study of film formation in high-pH SCC environments. Studied effect of temperature. Key observations/conclusions: • films are thick (>1 μm), have a bilayer structure, are mixed anionic-cationic conductors, and behave like capacitors • siderite ($FeCO_3$) is main constituent of corrosion product at -0.7 to -0.65 V_{SCE} at 80°C • little Fe_3O_4 observed (unlike other studies), but authors attribute this to short-term nature of these current experiments • SCC said to be related to Fe(II):Fe(III) ratio in film • results suggest that immediate composition of film following repair of defected layer is different from original film – aged film is composed most of oxides, whilst new film comprises carbonates • initial layers poorly protective compared with aged layers Comments: • underlying scientific study with little of relevance for practical guidelines	

Check if additional Comments made ☐

Ref. no.: 148	
Title: Overview of intergranular stress corrosion cracking research activities	
Authors: R.N. Parkins	
Source: Report to Line Pipe Research Supervisory Committee of the American Gas Association, PR-232-9401 (draft)	*Year:* 1994
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation, early-stage crack growth, late-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H026-H077	

Comments:

Overview of 30 years of R&D on high-pH SCC, supplemented with observations and interpretations of field data. An invaluable resource.

Key observations/conclusions:

- Reducing the gas outlet temperature is an effective way of mitigating high-pH SCC as it
    - delays coating deterioration
    - slows the generation of the high-pH environment
    - reduces the range of potentials over which cracking occurs
    - reduces the rate of crack growth
- Overprotection of the pipe (<-1.1 V_{SCE}) should be avoided as otherwise H_2 gas bubbles form, partially block the coating/pipe crevice resulting in iR drops and a possible shift of the pipe potential into the cracking range
- Differing susceptibility of pipe steels is likely due to differing cyclic stress-strain behaviour rather than any effect of chemical composition
- Lifetime prediction will require a stochastic approach to deal with the inherent scatter and variability of the cracking process
- High-pH SCC is significantly less common on liquid lines (because of the lower temperature), although three cases from Saudi Arabia are known
- At failure (rupture), cracks are typically 75% through wall
- High-pH SCC follows an intergranular path
- Field evidence indicates that crack faces are covered by Fe_3O_4 with traces of $FeCO_3$
- Pipeline steels passivate in 1N-1N solution, with the potential range for cracking on the passive side of the active-passive transition (figure)

Check if additional Comments made ☒

Comments (continued):

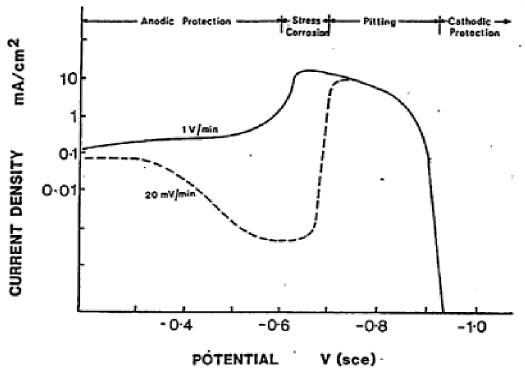


Figure 4. Fast and slow sweep rate polarization curves for pipeline steel in 1N Na_2CO_3 + 1N $NaHCO_3$ solution at 75°C, showing the domains of corrosion behaviour.

- High-pH SCC has been observed:
  - on NPS8 to NPS34 pipe
  - wall thicknesses ranging from 4.6 mm to 12.7 mm
  - on submerged arc, flash, and electric-resistance weld pipe, as well as seamless pipe
  - as short as 6 years following the start of operation, to a maximum of 40 years, with an average of 15-20 years service
  - 90% of failures have been within 10 miles (16 km) of the upstream compressor station as a result of the higher temperatures and more-severe loading conditions in this region
  - gas temperatures at the time of failure have ranged from 10 to 60°C with the majority >35°C, although temperatures may have been hotter earlier in service
  - 70% of failures initiated at the bottom of the pipe where coating damage is more likely
  - there has generally been no correlation with soil characteristics, with one exception being the Moomba to Sydney pipeline where cracking occurred primarily in low conductivity wet clay pans
  - failures have occurred in steels with a wide range of chemical compositions (0.07-0.35 C, 0.40-1.33 Mn, 0.006-0.062 S)
  - failures have occurred at hoop stresses of 46-76% SMYS, with all but one occurring at >60% SMYS
  - there is no evidence for any role of stress raisers, unlike NNpH SCC, although high-pH SCC has occurred in dents
  - the pipe-to-soil potential at the time of failure ranged from -0.85 to -2.0 V_{CSE}
  - most failures have occurred on lines coated in the field with a combination of coal tar primer and a coal tar enamel/fiberglass felt, although some failures have occurred on asphalt- and tape-coated lines (need to be normalized wrt to installed miles of each type of coating)
  - failures have also occurred on bare lines 1-17 years after the application of CP following a period of 9-16 years unprotected, during which a layer of corrosion product had built up
  - field electrolytes are carbonate/bicarbonate based with concentration of the order of 0.1 mol/L (0.5-1 wt.%)

Comments (continued):

- the high-pH SCC electrolyte can be generated electrochemically, but a constant supply of CO_2 is required as otherwise the pH will exceed pH 11 (see figure ref. no. 141) and lie outside the pH range for cracking, presumably because the rate of film repair exceeds the rate of film breakdown. The amount of CO_2 required depends on the applied current density, but typically is of the order of a few vol.%. Too little CO_2 and the pH >11, too little CO_2 and pH <8. This need for a constant supply of CO_2 speaks against seasonal effects
- the high-pH SCC environment can also be generated by the evaporation of a pH 6.5 solution, which results in a pH 9-10 aHCO_3/Na_2CO_3 solution
- cracking occurs in a window of potentials, with the width of the window a function of temperature, strain rate, electrolyte composition, and pH.

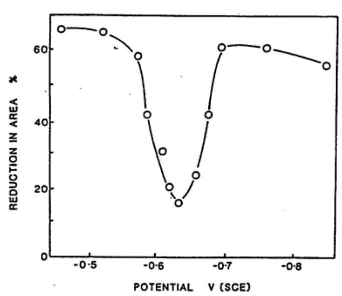


Figure 8. Slow strain rate stress corrosion test results for pipeline steel in the 'standard' carbonate-bicarbonate solution at 75°C and various potentials. Increasing susceptibility to SCC is associated with decreasing reduction in area.

- Cracking stops below a threshold strain rate, with the threshold being potential dependent
- crack growth rate is a function of temperature, with a range of reported activation energies of 20-67 kJ/mol and a best estimate of 42 kJ/mol

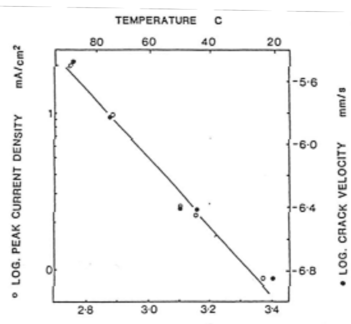


Figure 10. Temperature dependencies of SCC velocity and peak current density from fast sweep rate polarization curves for pipeline steel in carbonate-bicarbonate solution.

- the upper pH threshold for cracking is ~pH 10.5, at which the potential window for cracking closes (see figure below)

Comments (continued):

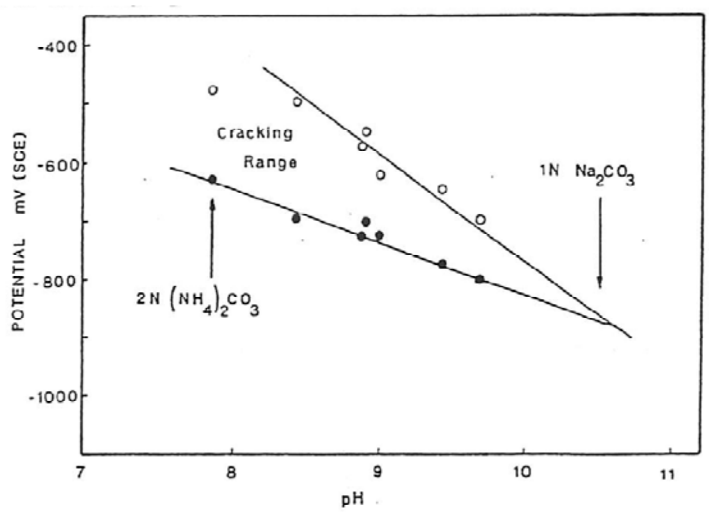


Figure 11. The pH dependence of the intergranular SCC range for pipeline steel in various in various carbonate-bicarbonate solutions at 75°C, from pre-cracked specimen tests.

- the threshold stress for cracking is a function of R value, decreasing with decreasing R (see figure below)

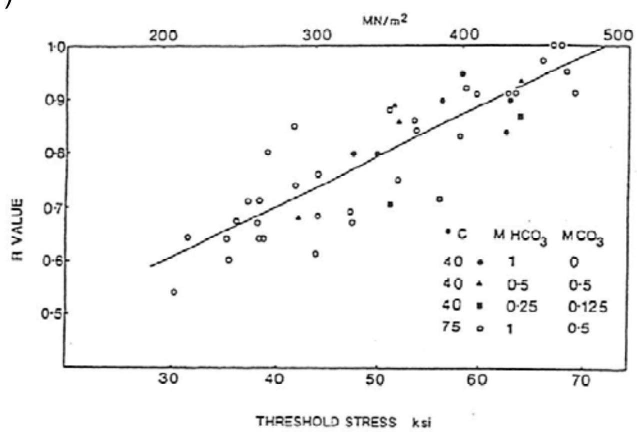


Figure 13. Threshold stresses for a X-70 steel from tapered specimen tests in various solutions at different R values.

- the threshold stress for cracking is independent of electrolyte composition
- the threshold stress for cracking is independent of temperature
- presence of Cl^- and sulphate in electrolyte has no apparent effect on high-pH SCC
- E_{CORR} lies in the passive region and is more-positive than the cracking range
- Application of adequate CP will shift the potential to values more-negative of the cracking range, indicating that some source of iR drop is necessary for cracking
- On millscale-covered pipe, there is a range of current density that will poise the potential in the cracking range (e.g., ~60 μA/cm^2 in 1N-1N at 75^{o}C)

Comments (continued):

- removal of millscale will prevent potential from falling in potential range for cracking under galvanostatic conditions (unless pipe subsequently becomes covered in corrosion product)
- there will be a potential drop along the disbondment with the magnitude of the iR drop depending on time, disbondment height, and electrolyte conductivity
- increasing disbondment gap causes potential to move through the cracking range faster, as does a polished surface
- disbondment chemistry and potential distribution is time dependent
- if CP is lost, potential drifts back through the cracking range and can be in range for months (figure)

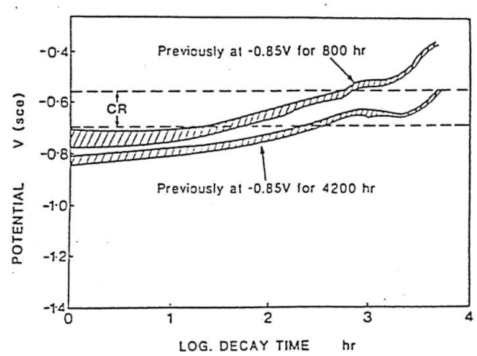


Figure 24. Decay of potential along a crevice after potential control switched-off; mill scaled steel surface in 'standard' solution. The more negative side of the scatterband represents the potential at the holiday and the less negative side the potential 20 cm from the holiday.

- H_2 bubbles in disbondment cause iR drop and increase potential, especially is bubbles are at the mouth of the disbondment. Therefore, should not polarize surface into HER region (<-1.1 V_{SCE}), which will also minimize electrochemical generation of high-pH SCC environment
- threshold stress (stress intensity factor) above which cracks show sustained growth (1N-1N, 75-90°C, -0.65 V_{SCE}: K_{ISCC} ~21 MPa√m, σ_{th} ~305 MPa)
- cracks may initiate and grow below threshold, but CGR decreases with time and cracks become dormant
- K_{ISCC} and σ_{th} are functions of electrolyte composition, T, and loading conditions
- Whether crack growth occurs is determined by relative rates of film formation and film rupture, the latter determined by the crack-tip strain rate ($\dot{\varepsilon_{CT}}$)
- Crack-tip strain rate determines whether cracks become dormant, which implies a threshold $\dot{\varepsilon_{CT}}$ for sustained crack growth, with the threshold value being a function of electrolyte composition, potential, and temperature
- Implies strain rate, not stress or stress range, is most important loading characteristic for high-pH SCC
- under constant load, controlling parameter is the effective strain rate, as determined by the creep rate

Comments (continued):

- on operating pipelines, creep should be exhausted prior to the establishment of high-pH SCC environmental conditions, but cyclic loading sustains creep
- for a given maximum stress, creep rate is higher under cyclic (under-)loading conditions than under constant load
- cyclic loading promotes creep at a maximum stress at which sustained loading would not
- at ambient temperature, creep is limited by work hardening, but the effect can be overcome by cyclic loading (see figure)

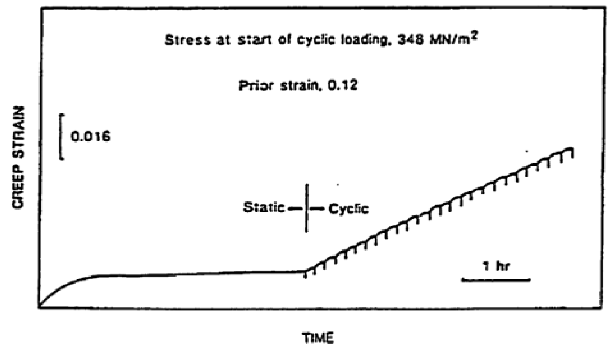


Figure 32. Creep behaviour of a pipeline steel at 20°C involving initial loading at 348 MN/m² (50.5 ksi), followed by a period of repetitive unloading and reloading at 10 minute intervals with an unloading hold time of 1 minute.

- under cyclic loading, therefore, SCC will occur at lower stress than under static loading
- threshold stress decreases with decreasing R (increasing stress range) (figure)

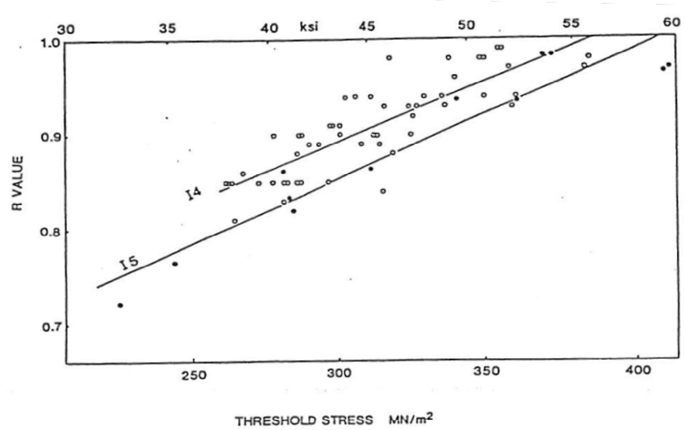


Figure 39. Effect of R ratio on the threshold stresses for two line pipe steels exposed to the 'standard' solution at 75°C and -0.65 V(SCE). The data points were calculated from the mean load.

- threshold stress is only weakly dependent on frequency – does this indicate that initiation is independent of frequency, but that propagation is not?
- increase in work hardening may lead to a decrease in CGR with increasing number of cycles

Comments (continued):

- higher stress promotes higher crack density in shorter times
- rate of crack initiation would be expected to decrease with time due to shielding effects and strain hardening, but the total number of cracks is expected to continue to increase with time and promote crack coalescence
- periodic unloading/reloading prevents dormancy of high-pH SCC cracks
- prior strain to 105% YS, as in a hydrotest, neither accelerates nor decelerates subsequent crack growth under cyclic loading conditions
- grit blasting increases threshold stress for cracking, possibly due to the removal of millscale but more likely due to the introduction of compressive residual stress, with the extent of increase depending on the duration and conditions of blasting (e.g., an increase from 60% to 80% SMYS with 2 mins treatment)
- under static load, the threshold stress is of the order of the actual yield stress
- under cyclic load, the threshold stress decreases by 60-80 MPa for each 0.1 reduction in R
- cyclic loading promotes microplastic deformation at stress levels below those for monotonic loading
- the more-resistant steels are those with improved cyclic stress-strain behaviour
- rarely observe cracks under adherent millscale, unless the millscale itself is cracked
- additions of Ti, Mo, Cr, and Ni reduce the susceptibility to SCC, but this is of limited practical use as the amounts of alloying elements required would make the steel prohibitively expensive
- cracking follows a slip dissolution mechanism
- CGR is proportional to the crack-tip strain rate $\dot{\varepsilon}_{CT}$
- the maximum crack growth rate is determined by the Faradaic limit under film-free conditions, estimated to be $5\pm2 \times 10^{-6}$ mm/s (160 ± 60 mm/yr)
- crack growth is discontinuous with even large cracks becoming dormant for long periods, with other cracks growing and nucleating around them
- crack aspect ratio changes with depth
  - shallow cracks (<0.5 mm) are long (2a/c = 10-20)
  - intermediate depth cracks (0.5 < c < 1.5 mm) are short (2a/c = 2-10)
  - deep cracks (>1.5 mm) are long (2a/c = 3-20)
  - implies that intermediate depth cracks are stress driven and deeper cracks grow by coalescence
- crack coalescence occurs later in life (depths > 1 mm)
- cracks coalesce when their growing tips pass one another
- coalescence rules for high-pH SCC are the same for lab and field samples and the same as for NNpH SCC, suggesting that it is largely mechanics driven
- coalescence occurs for $y \leq 0.14(2a)$
- coalescence can cause dormant cracks to re-activate
- coalescence is of fundamental importance for lifetime prediction
- Battelle model for crack growth based on
  - cyclic stress-strain behaviour
  - slip dissolution CGR expression
  - condition for coalescence

Comments (continued):

- Battelle model (continued)
    - o consider a surface layer of decreased stiffness (restraint) that can undergo greater microplastic strain than the bulk material
    - o cyclic stress-strain behaviour of steel determines strain for a given stress
    - o upon encountering the stiffer inner layer, a crack may become dormant if the strain and strain rate are insufficient to sustain cracking
    - o it is found that only cracks in sparse colonies grow to a depth of concern
- Newcastle model for crack growth is based on
    - o power-law dependence of strain associated with cyclic loading
    - o condition for crack coalescence
    - o the first condition leads to a cycle-dependent diminishing rate of crack growth and of crack initiation; $da/dN = 0.026N^{-0.822}$ mm/cycle, $n_C = 98.4N^{-0.803}$ cracks/cm^2/cycle, where N is the number of cycles and the coefficients are obtained from experimental data
    - o model is one in which the growth rate of nucleated cracks decreases with increasing N, with crack extension eventually determined by coalescence
    - o failure is assumed to be rapid once a crack has grown to a surface length of 6 mm, which is large enough to exceed K_{ISCC} with relatively rapid growth to failure after that.
- in all matters of prediction there is variability which needs to be accounted for stochastically in models
- four stages in crack growth (figure)

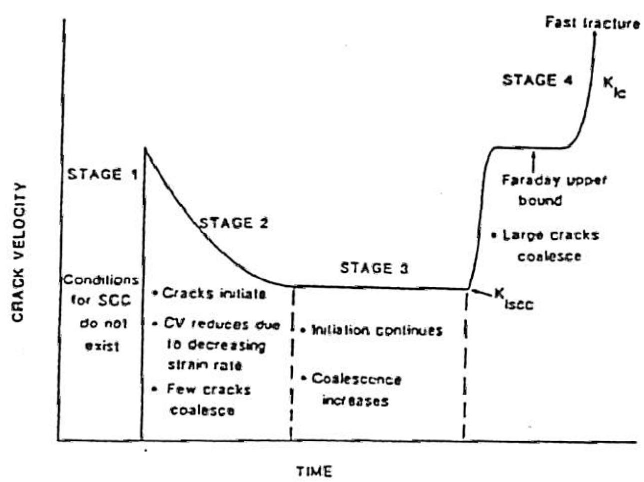


Figure 70. Schematic illustration of the effect of time upon SCC velocity.

Comments (continued):

- lowering the temperature has the benefits of:
    - slowing coating deterioration
    - slowing evaporative concentration of the electrolyte
    - reducing the crack growth rate
- avoiding over-protection, especially within 20 km of the C/S is recommended, with an acceptable range of potentials of:
    - -0.85 to -1.1 V_{SCE} (-0.9 to -1.2 V_{CSE})
- minimizing pressure fluctuations will reduce the probability of SCC, with a R value >0.90 at 72% SMYS posing little risk of cracking
- shot blasting the surface of new pipe is beneficial

Ref. no.: 149	
Title: Stress Corrosion Cracking Life Predcition Model – SCCLPM Version 1.0 user's manual and softwar	
Authors: B.N. Leis, T.P. Forte, N.D. Ghadiali	
Source: Report to Line Pipe Research Supervisory Committee, NG-18 Report No. 217	*Year:* 1995
Relevant phase(s) in SCC Guidelines: High-pH SCC crack growth	
Sub-phase/keywords: Model, prediction	
Results support R&D Guideline no.: None	

Comments:

Software manual and user's guide to SCCLPM.

Key conclusions:

- SCCLPM accounts for:
  - crack growth on the assumption that the environment has been generated
  - ductile flaw growth during hydrotesting
  - use of ductile flaw growth model to define critical flaw size
  - failure due to a single or dominant crack
  - X-52 pipeline
  - simple pressure histories (maximum pressure, pressure cycles)
  - cyclic softening
  - stochastic nature of material properties, such as flow stress, fracture toughness
  - stochastic distribution of neighbouring cracks in colony
  - crack coalescence

Check if additional Comments made ☐

Ref. no.: 150	
Title: Validation of a high pH stress-corrosion cracking life prediction model (SCCLPM) for gas-transmission pipelines	
Authors: B.N. Leis	
Source: Report to Line Pipe Research Supervisory Committee, Program PR 3-9531	*Year:* 1997
Relevant phase(s) in SCC Guidelines: High-pH	
Sub-phase/keywords: Model, prediction	
Results support R&D Guideline no.: H078	

Comments:

Report of validation of SCCLPM against field data from US gas transmission pipeline.

Key conclusions:

- SCCLPM can account for trends in
    - crack growth with time
    - colony shape
    - crack spacing
    - coalescence
    - crack aspect ratio
    - time to failure
    - crack depth
    - relative number of dense and sparse colonies
    - observed colony shapes and sizes
    - both pipe body colonies and colonies near LSW
    - failure pressures from hydrotests
- recommended practices to reduce cracking were:
    - reduce the frequency and amplitude of pressure cycling
    - reduce gas discharge temperature

Check if additional Comments made ☐

Ref. no.: 151	
Title: Effect of microstructure and microchemistry on the SCC behaviour of pipeline steels in a high pH environment	
Authors: M.J. Danielson, R.H. Jones, K. Krist	
Source: Proc. CORROSION/2000, NACE International (Houston, TX), paper no. 00359	*Year:* 2000
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords: Steel susceptibility	
Results support R&D Guideline no.: H079	

Comments:

Experimental study of six vintage X-52 (SMYS 359 MPa) steels with varying C, S, P contents from Battelle bone yard. Steels selected to allow statistical analysis of effects of alloying impurities. Crack growth studies of K_{ISCC} and stage II cracking using CT specimens in 1N-1N solution at 75°C at -0.65 V_{SCE}. Cyclic loading at R = 0.82, initial K_{MAX} 32 MPa√m, 400 cycles/day. Auger electron microscopic investigation of distribution of impurity elements to grain boundaries.

Key observations/conclusions:

- steels have varying material properties (ASTM grain size 4-10, actual yield 283-434 MPa, Charpy 35-172 J; 0.09-0.29 C, 0.012-0.028 P, 0.007-0.023 S)
- little variation in K_{ISCC} (32-43 MPa√m) or stage II crack growth rate (1-2 x 10^{-7} mm/s)

Check if additional Comments made ☐

Ref. no.: 152	
Title: Effect of microstructure and microchemistry on the SCC behavior of archival and modern pipeline steels in a high pH environment	
Authors: M.J. Danielson, R.H. Jones, P. Dusek	
Source: Proc. CORROSION/2001, NACE International (Houston, TX), paper no. 01211	*Year:* 2001
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords: Modern steels, cyclic softening, cyclic stress-strain behaviour	
Results support R&D Guideline no.: H080, H081, H082	

Comments:

Follow-on study from ref. no. 151, extending study to include three modern steels (X-65, X-70, X-80). Same experimental procedure as ref. no. 151. X-65 (0.034 C, 0.0090 P, 0.0053 S), Charpy (-60°C) 163 J, 462 MPa YS; X-70 (0.045 C, 0.0085 P, 0.0039 S), Charpy (-60°C) 22 J, 537 MPa YS; X-80 (0.0325 C, 0.0109 P, 0.0041 S), Charpy (-60°C) 24 J, 565 MPa YS.

Key observations/conclusions:

- Three modern steels have significantly lower K_{ISCC} (< 25 MPa√m) compared with vintage X-52 steels
- Two of the modern steels have similar CGR to the vintage X-52 steels, with the X-80 exhibiting a slightly lower rate
- Lower K_{ISCC} may be due to:
    - absence of high-strength pearlite phases in modern steels, which might affect local plasticity or crack-tip strain rate
    - segregation, or lack of, of elements to grain boundaries
    - enhanced cyclic softening
    - artifact of this one particular manufacturer
- crack-tip strain rate is required for crack propagation
- CGR decrease with time as creep exhausted
- cyclic loading enhances crack growth through cyclic softening, resulting in higher crack-tip strain rate

Comment:

- should examine cyclic stress-strain behaviour of modern steels

Check if additional Comments made ☐

Ref. no.: 153

Title:
Assessment of the effects of surface preparation and coatings on the susceptibility of line pipe to stress-corrosion cracking

Authors:
J.A. Beavers

Source:	*Year:*
Report to Corrosion Supervisory Committee, PR186-917, Final Report	1992

Relevant phase(s) in SCC Guidelines:
High-pH SCC susceptibility, NNpH SCC susceptibility

Sub-phase/keywords:
FBE, CTE, PE tape

Results support R&D Guideline no.:
H083-H087, N323-N327

Comments:

Experimental study of the susceptibility of different coatings to high-pH SCC and, in particular, whether FBE-coated line is immune/less susceptible. Assessed: (i) resistance of coating to disbondment, (ii) CP permeability, (iii) effect of surface prep. Tests performed to assess these factors included: CD disbondment, measurements of potential gradients under disbonded coatings, measurement of current passing through ctg, and tapered-tensile tests in 1N-1N solution at 25-75°C. SCC tests performed on coated and uncoated samples prepared in lab, as well as uncoated but grit blasted samples from coating mills.

Key observations/conclusions:

- primary factors affecting the SCC susceptibility are:
    - resistance to disbondment
    - ability of coating to pass CP
- FBE – high resistance to SCC (high resistance to CD, CP permeable)
- PE tape – poor resistance to SCC (poor resistance to CD, shielding)
- CTE – intermediate resistance (intermediate resistance to CD, CP permeable)
- CTE applied to a millscale-covered surface is more-resistant to disbondment than FBE
- did not observe significant iR drop down coating disbondment, although increases with length of disbondment and decreasing solution conductivity
- can get inadequate protection under disbonded PE ctg if there is adjacent bare millscale-covered pipe, but CP is more evenly distributed for CTE-coated pipe. Grit blasted surface naturally attain E_{CORR} more-negative than cracking range so lack of CP is not an issue. However, if grit blasted surface corrodes then E_{CORR} can be posied in cracking range.

Check if additional Comments made ☒

Comments (continued):

- grit blasting at level imparted in coating mills can be either beneficial or detrimental
    - blasting increased resistance to CD for CTE and FBE, but not PE
    - blasting resulted in shift in E_{CORR} to potentials more-negative than cracking range
    - blasting either increased or decreased threshold stress, depending upon intensity of blasting
        - increasing Almen strip deflection leads to increased threshold stress
        - a deflection >2.9 mm is required to increase threshold stress above that for millscaled surface
        - white surface finish leads to increase in threshold stress
        - any traces of remaining rust/millscale increase SCC susceptibility
        - older FBE lines may have had insufficient grit blasting to render them immune to SCC
        - near-white surface finish may be inadequate to impart significant compressive residual stress

Comment:

- implications for NNpH SCC although only high-pH SCC environment was used

Ref. no.: 154	
Title: Mechanics and material aspects in predicting serviceability limited by stress-corrosion cracking	
Authors: B.N. Leis, R.N. Parkins	
Source: Fatigue Fract. Eng. Materials Struct., 21, 583-601	*Year:* 1998
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, crack growth	
Sub-phase/keywords: Model, lifetime prediction	
Results support R&D Guideline no.: H054, H071, H088, H089, H090, H091	

Comments:

Detailed discussion of Battelle predictive model.

Key observations/conclusions:

- differences in steel behaviour due to different cyclic stress-strain behaviour
- microplastic straining characteristics of steel primarily determine cracking behaviour
- at SIF between K_{ISCC} and the fracture toughness K_Q, crack propagates at a maximum rate determined by the rate of dissolution under film-free conditions
- static creep is unlikely to be responsible for cracking because the initial creep response will be exhausted prior to the development of the cracking environment
- pipeline steels can become "softer" due to cyclic loading, resulting in more strain for a given stress level
- shallow cracks prefer to propagate along the surface rather than in the depth direction because there is less constraint to deformation in the surface layer
- cracks may become dormant as they propagate depthwise through the surface layer due to the stiffer underlying material

Check if additional Comments made ☐

Ref. no.: 155	
Title: A mechanics-based analysis of stress-corrosion cracking of line-pipe steel in a carbonate-bicarbonate environment	
Authors: B.N. Leis, W.J. Walsh	
Source: Environmentally Assisted Cracking: Science and Engineering, ASTM STP 1049, W.B. Lisagor, T.W. Crooker, and B.N. Leis (eds.), American Society for Testing and Materials (Philadelphia, PA), pp. 243-265	*Year:* 1990
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage crack growth	
Sub-phase/keywords: Model	
Results support R&D Guideline no.: H071	
Comments: Experimental study and modelling development of what was to become the Battelle predictive model. Experimental study based on SSRT and TTT in 1N-1N at 75°C.	

Check if additional Comments made ☐

Ref. no.: 156	
Title: Modelling stress-corrosion cracking of high-pressure gas pipelines	
Authors: B.N. Leis, R.N. Parkins	
Source: In 8th Symposium on Line Pipe Research, American Gas Association Catalog No. L51680, paper no. 19	*Year:* 1993
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage crack growth	
Sub-phase/keywords: Model, lifetime prediction	
Results support R&D Guideline no.: H071, H072, H092, H093, H094, H095, H096, H097	

Comments:

Review of experimental and mechanics basis for Battelle and Newcastle lifetime prediction models. Models presume that the SCC environment is present.

Key conclusions:

- dense colonies are a result of widespread microplastic behaviour at stresses above yield
- sparse, banded collinear colonies are a result of localized plasticity due to stresses just below of above yield
- nucleation and growth requires surface microplasticity and depends, in part, on steel response to cyclic loading
- surface microplasticity (inelastic behaviour) can be induced by normal pipeline operating conditions
- as crack grows depthwise, growth behaviour becomes controlled by fracture mechanics
- coalescence is a key factor in the overall process

Check if additional Comments made ☐

Ref. no.: 157	
Title: Role of microstructures on stress corrosion cracking of pipeline steels in carbonate-bicarbonate solution	
Authors: H. Asahi, T. Kushida, M. Kimura, H. Fukai, S. Okano	
Source: Corrosion 55, 644-652	*Year:* 1999
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility	
Sub-phase/keywords: Microstructure, TMCP, modern, vintage	
Results support R&D Guideline no.: H098, H099, H100, H101, H102, H103	

Comments:

Experimental study of the effect of microstructure and other manufacturing processes on susceptibility of modern, vintage, and lab-prepared steels. TTT in 1N-1N solution at 75^{o}C, -650 mV_{SCE}, 14 days, triangular cyclic loading, 10^{-3} Hz, σ_{MAX} = 100%YS, R = 0.7. Steels: five pipeline steels X-65, X-80 TMCP; X-52, X-65 controlled rolled; X-65 Q&T; three lab steels with 0.02, 0.05, 0.08 C. Millscaled and polished surfaces SCC resistance defined by σ_{th}/σ_{YS}.

Key observations/conclusions:

- Maximum crack depth observed between 85 and 90% YS
- TMCP steels less susceptible than vintage controlled-rolled steels
- CGR higher for controlled-rolled steels than TMCP steels, although lots of scatter in data
- threshold stress for ferrite-pearlite microstructure is lower than that for bainite-ferrite or bainite, the latter from TMCP
- materials with mixed microstructures and/or coarse grain size are more likely to undergo local plastic deformation at lower stresses than uniform microstructures
- threshold stress on millscale surfaces lower than on polished surfaces
- removal of millscale by pickling did not change threshold stress, implying that roughness or some other factor other than the actual presence of the millscale was important
- softer decarburized surface layers are particularly susceptible and also contain coarser grains
- grit blasting prevented cracking due to introduction of a hard surface layer, with possible additional role of compressive residual stress
- increased surface roughness leads to a decrease in threshold stress

Comments:

- greater resistance of modern TMCP steels in contrast to findings of Danielson et al., but the latter related only to K_{ISCC}. Perhaps modern steels more resistant to initiation and early-stage growth.

Check if additional Comments made ☐

Ref. no.: 158	
Title: The investigation on stress corrosion cracking in a carbonate-bicarbonate solution and its mechanism from metallurgical aspects	
Authors: H. Asahi, T. Kushida, M. Kimura, H. Fukai, S. Okano	
Source: Proc. 9th Linepipe Symposium, Pipeline Research Council International, Catalog No. L51746, paper 17	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility	
Sub-phase/keywords: Microstructure, TMCP, modern, vintage	
Results support R&D Guideline no.: H098, H099, H100, H101, H102, H103	
Comments: Identical to ref. no. 157	

Check if additional Comments made ☐

Ref. no.: 159	
Title: Chances for high-pH SCC in Gasunie's transmission system	
Authors: W. Sloterdijk	
Source: Proc. 9th Linepipe Symposium, Pipeline Research Council International, Catalog No. L51746, paper 18	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords: Newcastle model, lifetime prediction	
Results support R&D Guideline no.: H104, H105, H106	

Comments:

Assessment of susceptibility of Gasunie's system to high-pH SCC based on (i) consideration of system and operating conditions, (ii) experimental measurements of properties of steels from system, and (iii) application of the Newcastle high-pH SCC model.

Experimental studies based on TTT on X-56 and X-60 steels from hot-taps

Key observations/conclusions:

- No field-applied coatings in system, and little PE tape
- Compared with historical conditions for high-pH SCC, regional lines not susceptible as they operate at <45% SMYS
- Operational data indicates potentially susceptible portions of system operate at 65-72% SMYS, R = 0.82-0.93, current max temp 34-45^{o}C
- Experimentally, observed cracking on vintage X-56 and X-60 steels but not on two modern steels
- Measured cycle-dependent nucleation and crack growth rates in standard 1N-1N solution (?) – expts done by RNP so assume he used the standard conditions
- Applied Newcastle model as described in ref. no. 150
- Predicted lifetimes for different lines were >16 yrs, >500 yrs, and not susceptible
- Argued that >16 yrs was overly conservative

Check if additional Comments made ☐

Ref. no.: 160	
Title: Conditions that lead to the generation of SCC environments	
Authors: R.R. Ramsingh, R.W. Revie	
Source: Report for the Corrosion Supervisotry Committee of PRCI, contract PR-230-9914, draft report	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, high-pH SCC suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Very concise review of factors leading to high-pH and near-neutral pH SCC. Key observations/conclusions: • five main factors to consider: o pipe surface preparation o coating type o "initial corrosion morphology" o CP level o CO_2 partial pressure	

Check if additional Comments made ☐

Ref. no.: 161	
Title: Initiation of stress-corrosion cracking on gas transmission piping	
Authors: B.N. Leis, J.A. Colwell	
Source: Effects of the Environment on the Initiation of Crack Growth, ASTM STP 1298, W.A. Van Der Sluys, R.S. Piascik, R. Zawierucha (eds.), American Society for Testing and Materials (Philadelphia, PA), pp. 34-58	*Year:* 1997
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage growth, near-neutral pH SCC initiation, early-stage growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H107, H108, H109, H110, H112, N328, N329, N330, N331	

Comments:

Field and laboratory study of the initiation and early-stage growth of high-pH and NNpH SCC, with a focus on microstructural and mechanical aspects. Mostly refers to high-pH SCC.

Key observations/comments:

- dense crack patches (defined as those with a spacing in the hoop direction of <20% wt) tend to go dormant because of shielding
- sparse crack patches (defined as those with a spacing >20% wt) tend to grow
- a patch is not the same as a colony, the latter being defined more by the size and shape of the disbondment
- there can be several patches within a colony, and which may be sparse or dense
- there is a complex 3-D interaction of stresses within patches and stress intensity at crack tip can increase, decrease, or remain constant under different circumstances
- high-pH and NNpH SCC show similar crack size, shape, and spacing tendencies
- spacing of cracks within a patch in general decreases with increasing stress, but there can be local differences due to microscale differences
- cracking is associated with microplastic deformation of grains and this microscale variation in properties has a large impact on crack spacing

Comments:

- the apparent importance of microscale variation in material properties (e.g., orientation of gb, local changes in hardness, etc.) in determining crack initiation and growth and ultimately crack spacing would seem to make it impossible, *a priori*, to predict crack spacing; albeit that it is possible to replicate the type of crack pattern observed through suitable model(s). Such models, however, are interpretive rather than predictive

Check if additional Comments made ☐

Ref. no.: 162	
Title: The role of coatings in the generation of high- and near-neutral pH environments that promote environmentally assisted cracking	
Authors: J. Been, F. King, L. Yang, F. Song, N. Sridhar	
Source: Proc. CORROSION/2005, NACE International (Houston, TX), paper no. 05167	*Year:* 2005
Relevant phase(s) in SCC Guidelines: NNpH SCC, high-pH SCC, susceptibility	
Sub-phase/keywords: Modelling, soils model	
Results support R&D Guideline no.: N332, N333	

Comments:

Experimental and modelling study of the development of both high- and near-neutral pH SCC environments. Simulated instrumented disbondments exposed to three soils associated with NNpH SCC and monitored for CP penetration and time-dependent changes in trapped water composition. Permeable membranes used to determine the balance between CP and coating properties in the development of high-pH environments. Permeable Coating Model and TECTRAN used to simulate field conditions for high-pH and NNpH SCC, respectively.

Key observations/conclusions:

- for NNpH SCC
  - minimal penetration of CP along simulated disbondment
  - trapped water pH increased with CP level (up to 3 V), suggesting some transport of OH^- into disbondment and/or some penetration of CP
  - TECTRAN suggests that CO_2 permeation through PE coating is important in maintaining a NNpH environment
- for high-pH SCC
  - development of high-pH environment determined by the balance between OH^- production and its loss by transport through the coating
  - without rapid CO_2 transport, tend to develop a NaOH solution rather than a HCO_3^-/CO_3^{2-} solution
  - PCM predicts effects of competition between OH^- formation and transport

Comments:

- one of the few studies in which CP did not penetrate disbondment
- if you need continuous CO_2 permeation through PE ctg to maintain a NNpH environment, then why don't you end up with a concentration HCO_3^- solution?

Check if additional Comments made ☐

Ref. no.: 163	
Title: High-pH SCC: temperature and potential dependence for cracking in field environments	
Authors: J.A. Beavers, C.L. Durr, B.S. Delanty	
Source: Proc. IPC 1998, ASME (New York, NY), Vol. 1, pp. 423-437	*Year:* 1998
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords: Electrolyte composition	
Results support R&D Guideline no.: H115, H116, H117, H118, H119	

Comments:

Experimental study of the temperature and potential dependence of high-pH SCC in representative field solutions. Simulated field electrolytes prepared containing 12-37 (pH 9.8), 18-28, 23-20 (pH 10.3) g/L Na_2CO_3-g/L $NaHCO_3$ and compared with results using more-concentrated 1N-1N solution (53 g/L Na_2CO_3-83 g/L $NaHCO_3$). Smooth cylindrical SSRT tensile samples prepared from X-52 NPS42 pipe, 5 x 10^{-7} s^{-1}. Fast and slow voltammetry to identify cracking range for subsequent SSRT. Test temperatures 25, 40, 55, 75^{o}C.

Key observations/conclusions:

- high Na/K, but low Mg/Ca, in trapped electrolytes
- all simulated field electrolytes less potent than 1N-1N
- peak current on fast scan increases with increasing T
- peak potential shifts to more active values with increasing T
- peak potential for 12-37 electrolyte is ~30 mV more negative than that for 1N-1N
- maximum CGR for 12-37 and 1N-1N same at 15^{o}C but that for 1N-1N increases more rapidly with increasing T and is 50% higher than for 12-37 at 75^{o}C
- width of potential window for cracking increases with temperature, from ~50 mV at 25^{o}C to ~150 mV at 75^{o}C
- width of potential window is ~30% wider for 1N-1N than for 12-237
- cracking range is within 120 mV of -850 mV at 40^{o}C but only 30 mV at 75^{o}C

Comments:

- assumption that the more-negative the potential range for cracking the more likely cracking is to occur on a protected pipe as it requires a smaller iR drop

Check if additional Comments made ☐

Ref. no.: 164	
Title: Stress-corrosion and hydrogen-stress cracking in buried pipelines	
Authors: R.R. Fessler, T.P. Groeneveld, A.R. Elsea	
Source: In Proc. Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys, NACE-5, NACE International (Houston, TX), pp.135-146	*Year:* 1977
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility	
Sub-phase/keywords: Field data	
Results support R&D Guideline no.: H120	

Comments:

One of the original sources for much of the field observations reported by Parkins in ref. no. 150.

Also discusses potential mitigation strategies:

- Reduce coating disbondment and defects
- Add inhibitor to suppress cracking over entire potential range (shifting E_{CORR} or potential range for cracking is unlikely to be a satisfactory mitigation strategy as some part of the pipe would always be in the cracking range)
- Reduce stress (uneconomic)
- Increase resistance of steel (but alloying additions in economical amounts have limited effect)
- Effective CP
- Reduce temperature

Check if additional Comments made ☐

Ref. no.: 165	
Title: Combination of conditions causes stress-corrosion cracking	
Authors: R.R. Fessler	
Source: Oil and Gas J. , February 16, 1976 edition, pp. 81-83	*Year:* 1976
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation, early-stage growth	
Sub-phase/keywords: Threshold stress	
Results support R&D Guideline no.: H121	

Comments:

Review of field experience and laboratory findings, many of which are in the summary by Parkins (1994) (ref. no. 150).

Key observations/conclusions:

- Under the action of small cyclic loads (±1.5-5% of mean stress), threshold stress decreases with decreasing frequency (X-52 steel, 1N-1N, 82^{o}C, -650 mV_{SCE})

Comment:

- Thus, for initiation, opposite effect of strain rate compared with crack growth, for which rate increases with increasing frequency. For initiation, material becomes more susceptible with decreasing frequency.

Check if additional Comments made ☐

Ref. no.: 166	
Title: Test method for defining susceptibility of line pipe steels to stress-corrosion cracking	
Authors: J.A. Beavers, R.N. Parkins, G.H. Koch, W.E. Berry	
Source: Report to Line Pipe Research Supervisory Committee NG-18, Report No. 146	*Year:* 1985
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation and early-stage growth	
Sub-phase/keywords: TTT, millscale	
Results support R&D Guideline no.: H122, H123, H124	

Comments:

Description of the development of the TTT for high-pH SCC. Experimental studies in 1N-1N at 75°C at -650 mV_{SCE}, with millscale attached. Two types of X-52. Test conditions: frequency 0.0002 to 0.2 cycles/min; stress range 1.5-15 ksi; time 7, 28 days; stressing rate 5 x 10^{-6} to 0.05 ksi/s.

Key observations/conclusions:

- threshold stress:
  - decreases with increasing stress range (decreasing R)
  - no obvious trend with frequency
  - no obvious trend with $d\sigma/dt$
- crack growth rate
  - no strong trend with stress range, although some indication with one steel for a decrease in CGR with increasing $\Delta\sigma$
  - slight tendency for CGR to increase with increasing frequency
  - no obvious trend with $d\sigma/dt$
  - decreases with duration of test
- crack density
  - no strong trend with stress range, although some indication with one steel for a decrease in crack density with increasing $\Delta\sigma$
  - no trend with frequency
  - no trend with $d\sigma/dt$
  - crack density increases with duration of test

Check if additional Comments made ☐

Ref. no.: 167	
Title: Standard test procedure for stress corrosion cracking threshold stress determination	
Authors: J.A. Beavers, W.E. Berry, R.N. Parkins	
Source: Corrosion 42, 9-17	*Year:* 1986
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation and early-stage growth	
Sub-phase/keywords: TTT	
Results support R&D Guideline no.: H122, H123, H124	
Comments: Journal version of detailed study reported in ref. no. 166	

Check if additional Comments made ☐

Ref. no.: 168	
Title: An evaluation of the resistance of pipeline steels to initiation and early growth of stress corrosion cracks	
Authors: I, Černý, V. Linhart	
Source: Eng. Fract. Mech. 71, 913-921	*Year:* 2004
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H125, H126	
Comments: Experimental study of the susceptibility of base metal, HAZ, and weld metal from a banded ferrite-pearlite X-60 and a normalized C-steel with a ferrite microstructure, both from service. Susceptibility based on number and total length of cracks on samples exposed to 1N-1N at 10°C or 75°C for 245 days at E_{CORR} following various pre-strains: 1% plastic deformation, 0.5% plastic deformation, 95% YS, or cyclic loading at R = 0.63 (no indication of max stress, number of cycles, or frequency). Also no indication of specimen geometry or whether the samples were exposed to the 1N-1N in the stressed or unstressed conditions, or whether stressing was done in the environment. Key observations/conclusions: • no significant effect of different pre-straining conditions • 1% deformation with HAZ exhibited the highest susceptibility • no effect of pre-strain on base material • pre-cyclic loading enhanced susceptibility • weld metal was least susceptible • ferrite microstructure more resistant than ferrite-pearlite microstructure Comments: • apart from the lack of key experimental details, unclear why they exposed samples at E_{CORR}. Based on all other work, E_{CORR} is <u>outside</u> the cracking range!! Treat the results/conclusions with caution • how can they conclude that pre-cyclic loading enhanced susceptibility when both materials were taken from service!	

Check if additional Comments made ☐

Ref. no.: 169	
Title: Initiation of stress corrosion cracking for pipeline steels in a carbonate-bicarbonate solution	
Authors: Z.F. Wang, A. Atrens	
Source: Met. Mater. Trans. A, <u>27A</u>, 2686-2691	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: H127, H128, H129	
Comments: Experimental study of high-pH SCC initiation using linearly increasing stress test (LIST), similar to CERT but under stress instead of displacement control ($d\sigma/dt$ = 0.0191 to 0.000191 MPa/s). 1N-1N at 70°C, flat tensiles with original surface on one side. Steels: three types of X-65, X-52, X-46, X-42. Key observations/conclusions: • cracking at potentials more negative than -800 mV_{SCE} due to HE • SCC in range -700 to -550 mV_{SCE} due to anodic dissolution mechanism • threshold stress for initiation is greater than the YS and requires plastic deformation • resistance to initiation decreased with increasing strength (i.e., $\sigma_{init}/\sigma_{YS}$ tends to 1 with increasing YS) • HE initiates below YS, at a stress equivalent to ~0.1% strain • original surface more susceptible than polished surface	

Check if additional Comments made ☐

Ref. no.: 170	
Title: Applicability of ESEM in SCC studies	
Authors: A. Atrens, Z.F. Wang, N. Kinaev, D.R. Cousens, J.Q. Wang	
Source: Proc. 13th Int. Corrosion Congress, Melbourne, Australia, paper no. 233	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: H130	

Comments:

Experimental study of the earliest stages of the initiation of high-pH SCC

Key observations:

- stages in crack initiation (on polished surfaces)
    - solution etches gb
    - sample becomes oxide covered
    - film cracks at gb
    - SCC initiates at cracks in oxide at gb
- cracks also initiate at pits, but most pits do not initiate cracks

Check if additional Comments made ☐

Ref. no.: 171	
Title: A new probabilistic model for high-pH stress-corrosion cracking	
Authors: A. Francis, C. Jandu	
Source: J. Pipeline Integrity 5, 5-24	*Year:* 2006
Relevant phase(s) in SCC Guidelines: High-pH SCC crack growth	
Sub-phase/keywords: Lifetime prediction, model	
Results support R&D Guideline no.: H131	

Comments:

Probabilistic model based on slip dissolution mechanism and expression for crack-tip strain rate. Introduce probability distributions for various parameters.

Key aspects of model:

- the model is based on:
    - Shoji expression for crack-tip strain rate
    - expression for crack growth rate for discontinuous slip dissolution mechanism
    - fatigue growth of deep defects
- probabilistic aspects/probability distributions
    - crack depth prior to coalescence
    - probability of coalescence
    - crack depths after coalescence
    - probability of failure
- model accounts for
    - effects of temperature, potential, cyclic load, mean stress
- model predicts
    - time-dependent defect depth
    - effect of T, potential, stress range, mean stress, R on defect depth
    - probability of coalescence and the effects of T, potential, stress range, mean stress, R on defect depth on that probability

Comments:

- many of the probability distributions are related to coalescence. However, (i) coalescence is perhaps one of the most well-defined parameters for high-pH SCC, (ii) seem to distribute depth before and after coalescence, whereas coalescence is determined by surface spacing

Check if additional Comments made ☐

Ref. no.: 172	
Title: Conceptual understanding and life prediction for SCC of pipelines	
Authors: R.N. Parkins	
Source: Proc. Life Prediction of Structures Subject to Environmental Degradation, Research Topical Symposium, CORROSION/96, NACE International (Houston, TX), pp. 1-49.	*Year:* 1996
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage crack growth	
Sub-phase/keywords: Lifetime prediction	
Results support R&D Guideline no.: H132, H133	

Comments:

Review of experimental and mechanistic basis for high-pH SCC predictive model. Covers much the same ground as ref. no. 150.

Additional observations/conclusions:

- further improvement of model would include directed initiation
- even deep cracks can become dormant due to stress shielding
- over-emphasis in literature in measuring late-life crack velocities since vast majority of crack life is spent below K_{ISCC}

Check if additional Comments made ☐

Ref. no.: 173	
Title: Predictive approaches to stress corrosion cracking failure	
Authors: R.N. Parkins	
Source: Corros. Sci. 20, 147-166	*Year:* 1980
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage crack growth	
Sub-phase/keywords: Lifetime prediction	
Results support R&D Guideline no.: None	
Comments: Review of predictive approaches for SCC and their experimental basis. Covers much of same material as ref. no. 150.	

Check if additional Comments made ☐

Ref. no.: 174	
Title: The stress corrosion cracking of C-Mn steel in CO_2-HCO_3^--CO_3^{2-} solutions. I: Stress corrosion data	
Authors: R.N. Parkins, S. Zhou	
Source: Corros. Sci. 39, 159-173	*Year:* 1997
Relevant phase(s) in SCC Guidelines: High-pH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: H134, H135, H136, H137, H138, H139, H140, H141	

Comments:

Experimental study of the cracking of low C-steel (0.05C, 0.035S), 23°C with some at elevated T, SSRT, monotonic strain rate of 2 x 10^{-6} s^{-1}, some with cyclic loading. Solution: $NaHCO_3$/Na_2CO_3 solutions of varying concentration and pH (adjusted using CO_2), some tests in NS4.

Key results/observations:

- observed both IGSCC and TGSCC over wide ranges of potential and pH (figure)
- in pH range for high-pH SCC, only cracking observed was IGSCC in potential range associated with this form of SCC

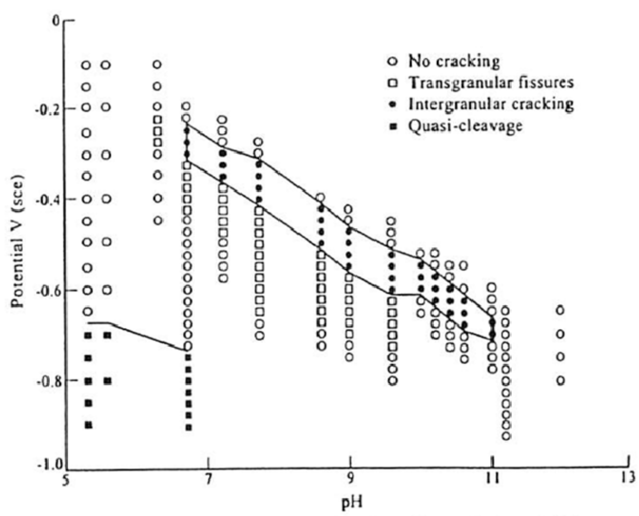


Fig. 12. Showing the modes of fracture resulting from the application of different potentials in SSRT on low-carbon steel in solutions of various pH values at ambient temperature.

Check if additional Comments made ☒

Comments (continued):

- in pH range associated with NNpH SCC, only observed quasi-cleavage at potentials associated with this form of cracking, with some TG fissuring at potentials 400 mV more positive
- at intermediate pH (7-9.5) observed both transgranular fissures (at more-negative E) and IGSCC at more-positive E
- IGSCC observed in entire range pH 7-11, associated with potentials at which active-passive transitions could occur, with different passivating solids – cracking range shifts to more-negative potentials with increasing pH
- for high-pH 1 mol/L Na_2CO_3 + x mol/L $NaHCO_3$ solution (pH 10-11) at room temperature
    - peak CGR decreases with increasing pH (decreasing $NaHCO_3$)
    - width of potential window is fairly constant at 60-90 mV
    - cracking window shifts to more-negative values with increasing pH
- peak CGR for high-pH SCC shifts to more-negative potentials with increasing T

Comments:

- interesting coexistence of IGSCC and TGSCC over narrow ranges of pH and potential, except at those pH's associated with either high-pH or NNpH cracking
- quasi-cleavage only observed below the HER but, for the conditions of these tests at least, need to be 100 mV below the equilibrium line for 1 atm H_2
- why is no IGSCC reported in the field at lower pH/higher potentials?

Ref. no.: 175	
Title: The stress corrosion cracking of C-Mn steel in CO_2-HCO_3^--CO_3^{2-} solutions. II: Electrochemical and other data	
Authors: R.N. Parkins, S. Zhou	
Source: Corros. Sci. 39, 175-191	*Year:* 1997
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H142, H143, H144	
Comments:	

Experimental study of the electrochemical properties of C-steel in carbonate/bicarbonate solutions.

Key observations/conclusions:

- based on comparison of fast and slow scans, factor of 10 difference in current in potential range for high-pH SCC, but little or no difference in current in potential range for TGSCC

Comments:

- fast/slow scan voltammetry seems to be a good method for identifying potential regions for slip dissolution mechanism
- correlation between nature of attack on gb on unstressed samples and nature of corresponding cracking – observe gb etching under IGSCC conditions, but only gb attack under TGSCC conditions
- E-pH conditions for IGSCC bounded by electrochemical couples involving a dissolved and solid species suggesting the possibility of active-passive transition
- IGSCC occurs over a much wider range of potentials (-200 to -700 mV_{SCE}), pH (7-11), and solution composition (0.1-2.0 mol/L) than normally associated with high-pH SCC
- of the two species, bicarbonate dominates over carbonate
- crack growth rate increases with increasing [HCO_3^-]

Check if additional Comments made ☐

Ref. no.: 176	
Title: Stress corrosion cracking of high-pressure gas transmission pipelines	
Authors: R.N. Parkins, R.R. Fessler	
Source: Materials in Engineering Applications 1, 80-96	*Year:* 1978
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Historical summary of observed conditions for high-pH SCC and mechanistic information available to that date. Similar information to that covered in part in ref. no. 150.	

Check if additional Comments made ☐

Ref. no.: 177

Title:
Characterization of axial flaws in pipelines, with a focus on stress corrosion cracking

Authors:
B.N .Leis

Source:	*Year:*
Report to the Line Pipe Research Supervisory Committee, NG-18 Report No. 212, PRCI Catalog No. L51807	1997

Relevant phase(s) in SCC Guidelines:
High-pH SCC initiation, crack growth

Sub-phase/keywords:

Results support R&D Guideline no.:
H107, H108, H110, H146, H147, H148, H149, H150

Comments:

Review of field observation and laboratory investigations of the metallurgical and mechanical aspects of high-pH SCC flaws. Some aspects could also apply to NNpH SCC cracks, but evidence comes mainly from field evidence and lab studies focused on high-pH SCC.

Key observations/conclusions:

- NNpH and high-pH SCC colonies exhibit similar crack size, shape, and spacing
- cracks spacings greater than 20% wall thickness were associated with failures and are termed "sparse" crack patches
- crack spacing less than 20% wall thickness were found away from the site of failure and are termed "dense" crack patches
- cracks spaced circumferentially closer than 20% wall thickness tend to go dormant, while more-widely spaced cracks continue to grow
- operating factors, such as the maximum pressure, control the initial crack spacing, with operating and other factors subsequently determining the crack spacing
- maximum stress determines the circumferential crack spacing at initiation
- cracking can occur at <MAOP for a Class I location (ie, 72-80%SMYS)
- dense and sparse crack patches can form at the same maximum stress due to variation in mechanical properties at a microscopic scale
- parallel cracks with a circumferential spacing of less than 20% wall thickness are not likely to grow
- Mode II loading (in-plane shear) controls growth direction during coalescence
- mechanics, rather than metallurgical or environmental factors, determine the SCC crack patterns observed, including the effect of coalescence
- coalescence is determined by the crack length, applied pressure, pipeline properties, and (implicitly) on crack depth
- once dormant, cracks in dense patches stay dormant
- cracks in dense patches become dormant after very little growth in depth direction because driving force drops to zero

Check if additional Comments made ☒

Comments (continued):

- typical pre-cracked specimens only represent Stage 4 and represent a small fraction of the total lifetime
- high pressure hydrotests (test pressures >110% SMYS) represent an effective means of avoiding in-service failures
- hydrotests at lower pressures are increasingly ineffective
- short but deep SCC flaws will tend to leak and in modern high-toughness pipe may not be removed by hydrotesting

Ref. no.: 178	
Title: Susceptibility to stress corrosion cracking for low-carbon steel welds in carbonate-bicarbonate solution	
Authors: H. Mitsui, R. Takahashi, H. Asano, N. Taniguchi, M. Yui	
Source: Corrosion 64, 939-948	*Year:* 2008
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation, early-stage growth	
Sub-phase/keywords:	
Results support R&D Guideline no.:	

Comments:

Experimental study of the susceptibility of C-steel welds in 1N-1N at 80^{o}C for nuclear waste storage containers. Potential range -700 to -625 mV_{SCE}. SSRT 8 x 10^{-7} s^{-1}, susceptibility determined from strain to failure and crack growth rate. Weld types studied: TIG, MAG, EBW.

Key observations/conclusions:

- SCC morphology strongly dependent on microstructure
- in ferrite-pearlite base metal, cracks mainly propagated along ferrite-ferrite or ferrite-pearlite grain boundaries
- in fine-grained weld metal, cracks avoided pearlite or pearlite-dispersed regions and propagated along ferrite-ferrite boundaries
- CGR in base metal higher than in weld metal
- weld less susceptible to SCC than base metal, presumably due to finer-grained material
-

Comments:

- EBW not relevant to pipelines, but findings that fine-grained weld metal is less susceptible than coarser grain base metal is important

Check if additional Comments made ☐

Ref. no.: 179	
Title: Line pipe stress corrosion cracking – mechanisms and remedies	
Authors: R.N. Parkins, R.R. Fessler	
Source: Proc. CORROSION/86, NACE International (Houston, TX), paper no. 320	*Year:* 1986
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	
Comments: Historical summary of observed conditions for high-pH SCC and mechanistic information available to that date. Similar information to that covered in part in ref. no. 150.	

Check if additional Comments made ☐

Ref. no.: 180	
Title: Stress corrosion crack coalescence	
Authors: R.N. Parkins, P.M. Singh	
Source: Corrosion <u>46</u>, 485-499	*Year:* 1990
Relevant phase(s) in SCC Guidelines: High-pH SCC initiation, early-stage crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H154, H155, H156, H157, H158, H159, H160	

Comments:

Experimental study of crack initiation, early-stage growth, coalescence and continued growth, based on analysis of crack patterns on C-reduced C-steel tensile specimens subject to cyclic loading in standard 1N-1N solution.

Key observations/conclusions:

- cyclic loading (R = 0.9) enhances crack initiation by reducing threshold stress
- threshold stress lower on as-received (millscale) surface
- density of cracks increases with increasing load
- crack growth rate decreases with time, expressed on a per cycle basis - crack growth per cycle = $0.0065N^{-0.822}$ mm/cycle
- crack initiation continues at a decelerating rate, expressed on a per cycle basis – number of cracks per mm per cycle = $2.46N^{-0.803}$
- condition for crack coalescence given by $y < 0.025 + 0.14(2a)$
- decreasing CGR with time are accompanied by continued crack nucleation
- dormant cracks are reactivated by coalescence with new cracks

Comments:

- seminal work on crack coalescence and its role in continued crack propagation and failure

Check if additional Comments made ☐

Ref. no.: 181	
Title: Stress corrosion cracking characteristics of a range of pipeline steels in carbonate-bicarbonate solution	
Authors: R.N. Parkins, E. Belhimer, W.K. Blanchard, Jr.	
Source: Corrosion <u>49</u>, 951-966	*Year:* 1993
Relevant phase(s) in SCC Guidelines: High-pH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: H161, 162, 163, 164, 165, 166	

Comments:

Experimental study of crack initiation, time-dependent crack growth rate under cyclic loading conditions for 14 pipeline and C-steels with varying YS (214-496 MPa), grain size (5.5-54 μm), and chemistry (0.05-0.27C, 0.004-0.049S). Both tapered and parallel-sided tensile samples exposed to 1N-1N at 75°C and -650 mV_{SCE}. Cyclic loading at frequencies of 0.0043 or 0.00015 Hz, R 0.4-1.0).

Key observations/conclusions:

- threshold stress increases with increasing R
- under static load, threshold stress is approximately the same as the yield stress
- cyclic load decreases yield point and stress for a given strain in plastic region (ie, increased strain for a given stress) due to cyclic-softening (cyclic stress-strain behaviour)
- magnitude of softening effect increases with increasing stress range
- the stress at which the cyclic stress-strain curve differed from that for monotonic loading approximated the threshold stress for cracking
- cyclic stress-strain behaviour strongly implies that microplastic deformation caused by load cycling is responsible for the reduction in threshold stress
- number of cracks nucleated increases with time and number of cycles and the stress, but is independent of loading frequency
- crack growth rate decreases with time and number of cycles, with the time dependence a function of stress
- decrease in crack growth rate with time is probably due to work hardening and/or strain ageing
- conditions for crack coalescence are $y \leq 0.14(2a)$
- for modelling purposes, the time dependence of the number of cracks nucleated per mm is $N = 0.01$ to $0.5t^{-0.4 \text{ to } -0.8}$ where t is in hours and the time dependence of the crack growth rate given by $G = 0.0007t^{-0.45 \text{ to } -0.55}$ mm/hr

Check if additional Comments made ☐

Ref. no.: 182

Title:
The application of stress corrosion crack growth kinetics to predicting lifetimes of structures

Authors:
R.N. Parkins

Source:	*Year:*
Corros. Sci. 29, 1019-1038	1989

Relevant phase(s) in SCC Guidelines:
High-pH SCC early-stage growth, late-stage crack growth

Sub-phase/keywords:
Lifetime prediction

Results support R&D Guideline no.:
H167

Comments:

Approach to lifetime prediction for high-pH SCC based on slip dissolution mechanism and related expressions. Also takes into account time-dependent decrease in CGR and coalescence.

Key observations/conclusions:

- rejected method based only on slip dissolution model because of predominance of crack coalescence in determining lifetime.

Check if additional Comments made ☐

Ref. no.: 183
Title: Stress corrosion cracking of X-60 line pipe steel in a carbonate-bicarbonate solution
Authors: A.K. Pilkey, S.B. Lambert, A. Plumtree

Source: Corrosion 51, 91-96	*Year:* 1995

Relevant phase(s) in SCC Guidelines: High-pH SCC late-stage crack growth
Sub-phase/keywords:
Results support R&D Guideline no.: H168, H169, H170

Comments:

Experimental study of the crack growth kinetics of a pipeline steel in 1N-1N at 75°C and -650 mV_{SCE} using cyclic loading of pre-cracked samples at R = 0.82 and either 40 cycles/day or 400 cycles per day.

Key observations/conclusions:

- maximum average crack growth rate 2.7 x 10^{-7} mm/s (8.5 mm/yr)
- threshold stress intensity factor K_{ISCC} ~25 MPa√m
- results in agreement with film-rupture model
- estimated a Faradaic crack growth rate of 7.5 x 10^{-7} mm/s (but this is highly dependent on the value of the current and surface area used)
- used an expression for the crack-tip strain rate from Parkins and Greenwell of

$$\dot{\epsilon}_{CT} = \frac{1}{2t}\frac{(\Delta K)^2}{WG\sigma_y}$$

Comments:

- Parkins would suggest that this sort of study is unnecessary as pipe spends so little of its lifetime in Stage 4 – based on reported rate, this is correct!!
- reported rate is of the order that one would expect for the Faradaic upper limit

Check if additional Comments made ☐

Ref. no.: 184	
Title: The influence of soil chemistry on SCC of underground pipelines	
Authors: J.A. Beavers, R.G. Worthingham	
Source: Proc. 4th International Pipeline Conference (ASME, New York, NY), paper IPC2002-27146.	*Year:* 2002
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, NNpH SCC susceptibility	
Sub-phase/keywords: Groundwater composition groundwater pH	
Results support R&D Guideline no.: H171, H172, H173, N334, N335	

Comments:

Analysis of the soil conditions where high-pH and NNpH SCC have been found on the TCPL system, with a focus on the composition of the groundwater, in particular the concentration of cations.

Approach was to statistically analyse trends based on analyses of soil extracts and trapped electrolytes from several hundred TCPL dig sites.

Key observations/conclusions:

- historically, there has been no consistent groundwater or other soil indicator for either high-pH or NNpH SCC
- the meq/L cation ratio (Na+K)/(Ca+Mg) in the soil for high-pH SCC sites was statistically higher (mean 0.46) for high-pH SCC sites than for high-pH SCC at which no SCC was found (mean 0.40), for NNpH SCC sites (0.33) and for NNpH SCC sites with no SCC (0.25)
- the meq/L sum of (Na+K) in the soil was statistically higher (mean 52 meq/L) than for high-pH no SCC sites (24 meq/L), NNpH SCC sites (2 meq/L) or for NNpH SCC sites with no SCC (1 meq/L)
- at NNpH SCC sites, there is a higher concentration of cations in the trapped electrolyte where no SCC is found, suggesting that CP has penetrated and prevented cracking
- penetration of CP can prevent NNpH SCC either because of increase in pH or because of polarization
- (Na+K) preferentially concentration under both disbonded tape and disbonded asphalt coating, but the concentration factor if ~50 times greater for asphalt coatings

Check if additional Comments made ☐

Ref. no.: 185	
Title: CEPA study on characterization of pipeline pressure fluctuations in terms relevant to stress corrosion cracking	
Authors: R. Sutherby, T. Jack, G. Van Boven, M. Wilmott	
Source: Proc. 3rd International Pipeline Conference (ASME, New York, NY), Vol. 2, pp. 989-996	*Year:* 2000
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth, high-pH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.: H174, H175, N336, N337, N338	
Comments:	

Second in a series of three papers aimed at characterizing SCADA pressure data in terms of individual cycles. Characterization in terms of R values, maximum stress, strain rates, numbers and frequency of cycles. Analysed SCADA data from NPS10 to NPS42 pipe, from both liquid and gas lines, and for storage facilities, transmission pipelines, and smaller feeder pipelines.

Key observations/conclusions:

- 90% of pressure cycles for gas transmission pipelines had an R value ≥0.90
- liquid pipelines exhibited more variable R values, with 10% of cycles characterized by an R value <0.7
- there is a wide variation in hoop strain rates between different facilities, with values from 10^{-11} to 10^{-6} s^{-1}, with most at 10^{-9} s^{-1} or lower

Check if additional Comments made ☐

Ref. no.: 186	
Title: Characterizing pressure fluctuations on buried pipelines in terms relevant to stress corrosion cracking	
Authors: G. Van Boven, R. Sutherby, F. King	
Source: Proc. 4th International Pipeline Conference (ASME, New York, NY), paper IPC2002-27149.	*Year:* 2002
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, crack growth, high-pH SCC susceptibility, initiation, crack growth	
Sub-phase/keywords: Rainflow counting SCADA data	
Results support R&D Guideline no.: H176, H177, H178, N339, N340, N341, N342, N343	
Comments: Third in a series of IPC papers characterizing pressure fluctuations to abstract parameters useful for SCC testing and prediction. Comparison of various methods for characterizing cycles in time-dependent data sets. Selected approach based on Rainflow counting. Characterized SCADA pressure fluctuations from various types of facility and compared behaviour. Applied analysed data to U Waterloo super-position model for NNpH SCC. Key observations/conclusions: • significant difference in the characteristics of pressure fluctuations for gas and liquid pipelines • smaller diameter liquid laterals have a higher frequency of more damaging pressure cycles • the most damaging cycles are located close to the discharge of the compressor or pump station • locations closer to the suction side have increased number of pressure cycles due to forward and backward propagating waves • although the frequency of pressure cycles is greater the R ratio and, of course, the maximum stress are lower	

Check if additional Comments made ☐

Ref. no.: 187	
Title: Report on model modules to assist assessing and controlling SCC	
Authors: H. Casteneda, B.N. Leis, S.E. Rose	
Source: Report prepared for US Department of Transportation PHMSA, Contract DTRS56-05-T-0003	*Year:* 2008
Relevant phase(s) in SCC Guidelines: High-pH SCC, NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: H179, H180, N344, N345, N346	

Comments:

Experimental studies and analyses of various aspects of high-pH and NNpH SCC.

Key observations/conclusions:

- High-pH and NNpH SCC environments are reversible and could occur in the same location
- Reversibility of the environments could be driven by seasonal variations, particularly temperature
- Hydrogen plays a significant role in NNpH SCC, but the mechanism has not been identified
- Need an understanding of the effects of cyclic loading and microstructure on cyclic softening on order to be able to interpret macroscopic crack growth data and models.
- Discuss NNpH mechanism involving H reduction from bicarbonate ions presented in ref. no. 039.
- Present crack depth/length data showing similar trends for high-pH and NNpH SCC in different parts of the World
- Aspect ratio tends to decrease with increasing depth for both high-pH and NNpH SCC for cracks away from the failure but show no clear trend with depth for cracks that lead to failure

Comments:

- large but seemingly unfocussed study
- emphasizes the confusing NNpH SCC mechanism of Colwell involving HCO_3^- as the source of H

Check if additional Comments made ☐

Ref. no.: 188	
Title: Stress corrosion cracking prediction model	
Authors: J.A. Beavers, W.V. Harper	
Source: Proc. CORROSION/2004, NACE International (Houston, TX), paper no. 04189	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N347	
Comments: Description of the development of a correlative type site-selection model for NNpH SCC for a single pipeline for a single company. Key conclusions: • three parameters were found to be key predictors of NNpH SCC: pipe manufacturer, coating type, and soil type • model predicts severity of cracking • >4 times more likely to find SCC in glaciofluvial soil than in lacustrine soil • >3 times more likely to find SCC under asphalt coating compared with other coatings (CTE, epoxy urethane, FBE, tape, wax) • >18 times more likely for pipe from manufacturer G to exhibit SCC than pipe from manufacturers A, B, or C	

Check if additional Comments made ☐

Ref. no.: 189	
Title: Cyclic stress-behavior and SCC susceptibility of line pipe steels	
Authors: B.N. Leis, J.A. Colwell, T.J. Kilinski, B. Hindin	
Source: Report prepared for the Materials Technical Committee, Pipeline Research Council International, Catalog No. L51838	*Year:* 2001
Relevant phase(s) in SCC Guidelines: High-pH susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: None	

Comments:

Description of an experimental study to examine the cyclic stress-strain properties of pipeline steels as a potential screening method for high-pH SCC susceptibility.

Key conclusions:

- the kinetics of film formation in the high-pH environment indicate cyclic periods on the order of hundreds of seconds or more are needed to stabilize the passivating film that forms in this environment,
- specimens subjected to short-term mechanical histories under either potentiostatic and galvanostatic control showed correlation between the evolution of plastic strain and electrochemical indicators of bare surface due to such straining,
- given that the long-term evolution of micro-plastic strain under nominally elastic stresses as occurs in pipelines controls their susceptibility to high-pH SCC, the data generated are consistent with discriminating susceptibility using the test protocol evaluated herein

Comments:

- essentially a description of a development project.

Check if additional Comments made ☐

Ref. no.: 190	
Title: Protocol to prioritize sites for high-pH stress-corrosion cracking on gas pipelines	
Authors: R.J. Eiber, B.N. Leis	
Source: Report prepared for the Pipeline Corrosion Supervisory Committee, Pipeline Research Council International, Catalo No. L51864.	*Year:* 1998
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: H181, H182	

Comments:

Description of a correlative ranking model for identifying high-pH SCC sites.

Key conclusions:

- High-pH SCC Protocol Likelihood Index developed(see table)
- Seven categories of factors were identified that contribute to high-pH SCC (with maximum % contribution for each category)
  - Coating, soil, moisture content (29%)
  - Maximum temperature (18%)
  - Surface preparation (4%)
  - Hoop stress (18%)
  - Stress fluctuation (18%)
  - CP level (7%)
  - Initial hydrotest pressure level (7%)
- Factors found to lead to a high probability of high-pH SCC
  - CTE/asphalt coating with alternate wet-dry moisture conditions
  - PE single or double-wrap coating
  - temperatures greater than 52°C (125°F)
  - hoop stress >67% SMYS
  - Pressure fluctuations with R <0.85
  - CP level more-positive than -850 mV_{CSE}
  - Initial hydrotest below 90% SMYS

Check if additional Comments made ☒

Comments (continued):

	1. Coating, Soil, Moisture	Index Value 40		3. Surface Coating Preparation	Index Value 5
1	**Fusion bonded epoxy/urethane/ extruded PE-all conditions** - all soil and moisture types	1	1	No surface prep. or knife and wire brushing of pipe	5
2	**Coal Tar/Asphalt-good condition-low to medium resistivity sand/gravel/rock soils-all** moisture conditions	5	2	Shot peen, grit blast, pickle	1
3	**Coal Tar/Asphalt-good condition-low to medium resistivity silt and clay soils**-dry moisture conditions	15	**4. Hoop Stress**		**25**
	Alternate wet/dry moisture conditions	30	1	>72 %SMYS	25
4	**Coal Tar/Asphalt-good condition**-very high resistivity soils		2	67 to 72 %SMYS	20
a	Alternate wet-dry, or continuous intermed. level of moisture from depressional area, bottom to side of slope and flat irrigated areas	20	3	60 to 66 %SMYS	10
b	Top of a slope regardless of the moisture level	10	4	<-60% SMYS	1
c	Continuous high level of moisture	5	**5. Stress Fluctuation (R, min/max Stress)**		**25**
d	Dry	5	1	>0.92	1
5	**Coal Tar/Asphalt-disbonded, cracked, sagging condition-low to high resistivity silt and clay soils**		2	0.91 to 0.86	8
a	Alternate wet-dry, or continuous intermed. level of moisture from depressional area, bottom to side of slope and flat irrigated areas	40	3	0.85 to 0.75	20
b	Top of a slope regardless of the moisture level	15	4	< 0.74	25
c	Continuous high level of moisture	20	**6. CP Level**		**10**
d	Dry	10	1	Generally below - 0.85v	1
6	**PE tape single or double wrap**- in sand, gravel, or rock-all moisture conditions except dry	15	2	Above and below level for corrosion, - 0.85 v.	10
7	**PE tape single or double wrap**- in clay/silty fine textured soils- all moisture conditions except dry	40		* Assumes pipe surface is pitted	
8	**PE tape single or double wrap**- in all soils - dry	5	**7. Initial Test Pressure Level**		**10**
	2. Max. Temperature	**25**	1	<90 % SMYS	10
1	>136F	25	2	>91 to 105 % SMYS	7
2	<135 F	20	3	>105% SMYS	2
3	<125F	10			
4	<115F	5			
5	<95F	1			

Ref. no.: 191	
Title: Cathodic protection conditions conducive to SCC	
Authors: J.A. Beavers, C.L. Durr	
Source: Report prepared for the Corrosion Supervisory Committee, Pipeline Research Council International, Catalo No. L51897	*Year:* 2000
Relevant phase(s) in SCC Guidelines: High-pH SCC susceptibility, near-neutral pH SCC suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: H183, H184	

Comments:

Study to determine under what conditions the 100 mV polarization criterion (commonly used for CP on older, poorly coated lines where it is difficult to achieve -850 mV_{CSE}) may render the pipe susceptible to either high-pH or near-neutral pH SCC.

Key observations/conclusions:

- CP is generally beneficial for NNpH SCC either because it polarizes the pipe surface or, more generally, because it leads to an increase in electrolyte pH
- the 100 mV criterion can be used for lines susceptible to high-pH SCC if any of the following conditions are met:
    - FBE coating
    - white or near-white surface preparation
    - MAOP <40% SMYS
    - operating temperature <35^{o}C
    - soil pore-water Na + K concentrations <10 meq/L
- If all of these criteria are not met, then the 100 mV polarization criterion should be avoided as it may lead to either development of the high-pH environment and/or result in the pipe surface potential being within the range for cracking

Check if additional Comments made ☐

Ref. no.: 192	
Title: Effect of dissolved oxygen on stress corrosion cracking of X70 pipeline steel in near-neutral pH solution	
Authors: Z.Y. Liu, X.G. Li, C.W. Du, L.X. Wang, Y.Z. Huang	
Source: Corrosion 66, 015006-1 to 015006-6	*Year:*
Relevant phase(s) in SCC Guidelines: NNpH SCC sucsptibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: N348	
Comments: Experimental study of the effect of O_2 on NNpH SCC using SSRT. Key observations/conclusions: • SCC susceptibility increases with decreasing O_2 concentration • suggested that at E_{CORR} "concentrated" dissolved O_2 combines with H to from a passive film that reduces hydrogen embrittlement Comments: • "SCC susceptibility" assessed from loss of ductility and reduction in tensile strength, despite pipe operating in macro eleastic region • second conclusion would seem to contradict the first	

Check if additional Comments made ☐

Ref. no.: 193	
Title: Localized dissolution of millscale-covered pipeline steel surfaces	
Authors: Z. Qin, B. Demko, J. Noël, D. Shoemsith, F. King, R. Worthingham, K. Keith	
Source: Corrosion 60, 906-914	*Year:* 2004
Relevant phase(s) in SCC Guidelines: NNpH SCC susceptibility, initiation	
Sub-phase/keywords:	
Results support R&D Guideline no.: N349, N350	

Comments:

Electrochemical study of the dissolution of millscale-covered C-steel electrodes in CO_2-containing dilute electrolytes.

Key observations/conclusions:

- millscale goes through various stages of dissolution when exposed to CO_2-containing environments
- millscale can galvanically couple to the underlying steel and, whilst the potential is controlled by reactions on the millscale, significantly anodically polarize the steel surface leading to rapid localized dissolution at the base of defects in the film
- this electrochemical activity can lead to the formation of "trenches" at the base of cracks in the millscale aligned axially along the pipe which will act as ideal crack initiation sites

Check if additional Comments made ☐

Ref. no.: 194	
Title: Predicting the growth of low- and high-pH SCC on gas transmission pipelines based on operating conditions	
Authors: F. King, G. Van Boven, T.R. Jack, R. Sutherby, L. Fenyvesi	
Source: In Proc. CORROSION/2003 Research Topical Symposium: Modeling and Prediction of Lifetimes for Corrodible Structures, J.R. Scully and D.W. Shoesmith (eds.), NACE International (Houston, TX), pp. 127-155	*Year:* 2003
Relevant phase(s) in SCC Guidelines: High-pH SCC crack growth, NNpH SCC crack growth	
Sub-phase/keywords:	
Results support R&D Guideline no.:	

Comments:

Theoretical assessment of the failure times due to high-pH or NNpH SCC based on suitable crack growth rate expressions coupled with analysis of pressure fluctuations and distance dependence of the gas temperature. Both models assume that permissive conditions exist at pipe surface.

Key observations/conclusions:

- Applied U Waterloo super-position model for NNpH SCC
- Developed high-pH SCC model based on slip dissolution mechanism and including:
  - effect of temperature on crack growth rate
  - effect of temperature on width of potential window for cracking
  - effect of strain rate on rupture of passive film at crack tip
- Predictions from model are consistent with observed failure frequency as a function of distance downstream of the compressor station
- Predicted crack growth rates are consistent with field-derived crack growth rates

Check if additional Comments made ☐

Ref. no.: 195	
Title: A permeable coating model for predicting the environment at the pipe surface under CP-compatible coatings	
Authors: F. King, T. Jack, M. Kolar, R. Worthingham	
Source: Proc. 5th International Pipeline Conference (ASME, New York, NY), paper IPC04-0368	*Year:* 2004a
Relevant phase(s) in SCC Guidelines: High-pH SCC suspcetible	
Sub-phase/keywords:	
Results support R&D Guideline no.: H185, H186, H187	
Comments: Description of a mathematical model for predicting the development of a high-pH SCC environment under a disbonded porous (permeable) coating Key observations/conclusions: • The development of a high-pH SCC environment is a balance between the rate of OH^- production and the rate of transport away from the pipe surface through the permeable coating • The permeable coating could become shielding if carbonate minerals precipitate in the pores of the coating • Model predicts lower permeability coatings (5% porosity or lower) are able to trap the high-pH electrolyte against the pipe surface	

Check if additional Comments made ☐

Ref. no.: 196	
Title: A permeable coating model for predicting the environment at the pipe surface under CP-compatible coatings	
Authors: F. King, T. Jack, M. Kolar, R. Worthingham	
Source: Proc. CORROSION/2004, NACE International (Houston, TX), paper no. 04158	*Year:* 2004
Relevant phase(s) in SCC Guidelines: High-pH SCC suscpetibility	
Sub-phase/keywords:	
Results support R&D Guideline no.: H185, H186, H187, H188	
Comments: Description of a mathematical model for predicting the development of a high-pH SCC environment under a disbonded porous (permeable) coating. Very similar content to ref. no. 195 Additional observation/conclusion: • The porosity of asphalt coating exposed in the field for 20 years is ~11%, with a bimodal distribution with 23% of the total porosity associated with pores from 6 to 100 μm in diameter and the majority of the porosity associated with pores 0.003 to 0.08 μm in diameter	

Check if additional Comments made ☐

Ref. no.: 197
Title: A modeling approach to high pH environmentally assisted cracking
Authors: J. Been, F. King, L. Fenyvesi, R. Sutherby

Source: Proc. 5th International Pipeline Conference (ASME, New York, NY), paper IPC04-0361.	*Year:* 2004

Relevant phase(s) in SCC Guidelines: High-pH SCC crack growth
Sub-phase/keywords:
Results support R&D Guideline no.: H189, H190, H191
Comments:

Probabilistic high-pH SCC model based on a super-position principle involving an SCC term described by a slip-dissolution model and a fatigue term for the mechanical growth of deep defects. Model predicts film rupture based on crack-tip strain rate for the slip-dissolution component. Probability distributions are used for certain input parameters, including: the crack aspect ratio, crack-tip radius, film rupture strain, pressure fluctuations.

Key observations/conclusions

- High-pH SCC crack growth can be divided into an environmentally assisted term and a mechanical fatigue component
- High-pH crack growth rates decrease significantly with distance downstream of the compressor station, primarily due to the decrease in temperature and partly by effects on the crack-tip strain rate
- High-pH SCC is primarily driven by environmental effects with only a small contribution from mechanically driven fatigue

Check if additional Comments made ☐

Ref. no.: 198	
Title: Development of guidelines for the identification of SCC sites and the prediction of re-inspection intervals for SCC DA	
Authors: F. King, M. Piazza	
Source: Proc. CORROSION/2009, NACE International (Houston, TX), paper no. 09111	*Year:* 2009
Relevant phase(s) in SCC Guidelines: High-pH SCC, NNpH SCC	
Sub-phase/keywords:	
Results support R&D Guideline no.: H192	
Comments: Overview of current project. Key observations/conclusions • Rate of soil-gas CO_2 generation is a function of soil moisture content and temperature and can be expected to vary seasonally	

Check if additional Comments made ☐

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APPENDIX B: R&D GUIDELINES

Appendix B contains two tables of R&D Guidelines, one each for high-pH SCC and near-neutral pH SCC. Each R&D Guideline comprises:

- a unique reference number denoted by HXXX or NXXX for high-pH and near-neutral pH SCC, respectively
- a summary of the R&D Guidelines, consisting of a brief description which is underlined, followed in most cases by supplementary information. In a few cases, a figure is also included
- the reference to the original source in Appendix A
- an indication of the associated SCC Guideline described in the main report and in Appendix D.

Table B.1: R&D Guidelines – High-pH SCC

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H001	Cold work increases the susceptibility to high-pH SCC. Based on SSRT data in dilute (0.01 mol/L $NaHCO_3$) solution at 50°C.	Yunovich et al. (1998)	
H002	Natural aeration increases susceptibility to high pH SCC. Based on SSRT data in dilute HCO_3^- solution at pH 8 and 10, possibly as the result of a shift of E_{CORR} into the cracking range.	Yunovich et al. (1998)	
H003	CP leads to an increase in susceptibility to high-pH SCC. Based on data in dilute HCO_3^- solutions, but may be due to a change in mechanism to HIC. Would seem to be contrary to H002.	Yunovich et al. (1998)	
H004	IGSCC can be obtained in the absence of CO_2 and carbonate species. IGSCC observed in pure sulphate solutions at pH 8	Szklarska-Smialowska et al. (1994)	
H005	IGSCC observed at (cathodic) potentials at which dissolution could not be involved. Contrary to suggestions of a dissolution mechanism for IG cracking	Szklarska-Smialowska et al. (1994)	
H006	Crack path seems dependent on pH with IGSCC prevalent at higher pH. Possible evidence for a transition in crack path from TG to IG with increasing pH.	Szklarska-Smialowska et al. (1994)	H-0-6
H007	Increasing temperature results in higher crack growth rates and a wider potential window for cracking. The activation energy for high-pH SCC cracks is of the order of 42 kJ/mol.	Parkins (1996)	H-0-2, H-I-1, H-IV-2
H008	Application of CP current density ca polarize a mill-scaled or rusted steel surface into the cracking range. In lab tests, a cathodic current density of 60 μA/cm^2 was sufficient to polarize the surface into the cracking range.	Parkins (1996)	H-I-4, H-I-15
H009	iR drop along the disbondment can shift the potential into the cracking range. Thus, the complete loss of CP may not be necessary to shift the potential into the cracking range. The required environment could be generated by CP elsewhere in the disbondment and diffuse to the location of permissible potential.	Parkins (1996)	H-I-4

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H010	Overprotection at potentials more negative than -1.1 V_{SCE} can result in H_2 bubbles that block CP and shift potential into cracking range. Another mechanism by which the effects of CP may be lost and the potential fall within the crcking window is because of the formation of gas bubbles at potentials less than or equal to -1.1 V_{SCE}.	Parkins (1996)	H-I-7
H011	Decreasing the amplitude of pressure fluctuations leads to an increase in threshold stress for crack initiation. Less cracking would, therefore, be expected on with fewer fluctuations (for a given stress level).	Parkins (1996)	H-II-1
H012	Evaporative concentration of $NaHCO_3$ solution can lead to the precipitation of a range of sodium carbonate solids. Nature of precipitate depends on (i) p_{CO2} and (ii) temperature. Solids predicted to form include natron, nahcolite, and trona.	Watson et al. (1996)	H-0-2, H-I-1, H-I-2
H013	In the field, high-pH SCC is possible under permanently aerobic dry conditions. Only two sites were investigated, which were both dry, permanently aerobic. Although high-pH SCC is possible under these conditions, it should not be inferred that these are the preferred conditions.	King et al. (2004b)	H-I-5
H014	Due to temporal transitions, high-pH SCC might not be continuous. The discontinuous nature of cracking should be accounted for in crack growth models.	King et al. (2004b)	H-I-12
H015	Development of high-pH SCC environment under permeable coating is a balance between the applied current density and the permeability of the coating. The applied cd generates OH^-, which is then balanced by complexation with CO_2, whereas the permeability of the coating determines the rate at which alkalinity can escape from the pipe surface.	Been et al. (2004)	H-I-3

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H016	A permissive potential for high-pH SCC requires either the loss of CP or application of a small current density. An excessive cd (>0.01 mA/cm^2 for the experimental set up and model coating permeability) causes the potential to be polarized outside the window for cracking	Been et al. (2004)	H-I-4
H017	Development of the high CO_3^{2-}/HCO_3^- concentration requires an efficient supply of CO_2. CP alone results in the generation of an alkaline NaOH solution, but not the concentrated CO_3^{2-}/HCO_3^- solution associated with high-pH SCC. Gas-phase transport through dry soil/coating, the presence of holidays, or the *in situ* generation of CO_2 in the disbondment are possible causes of CO_2.	Been et al. (2004)	H-I-5
H018	Occurrence of high-pH SCC consistent with specific site characteristics. High-pH SCC consistent with: inadequate CP, high K/Na to Ca/Mg ratio, high soil resistivity, wet/dry cycles, high temperature.	Van Boven et al. (2004)	H-I-8
H019	Ca/Mg in groundwater precipitate in regions of high-pH, leaving Na/K-rich solution. This chromatographic phenomenon results in the development of K/Na-rich trapped waters to support high-pH SCC without the requirement that the groundwater itself be necessarily rich in K/Na.	Jack et al. (2000)	H-I-6
H020	Development of high-pH environment requires a balance between CP, coating properties, and groundwater composition. If the coating is too permeable or the current density too low, a concentrated high-pH cannot be sustained at the pipe surface. Similarly, if the current density is too high, then the pH will be too high and a Na/K hydroxide solution will result. Implies that appropriate conditions for the development of high-pH SCC environment will not be that common.	Jack et al. (2000)	H-I-3
H021	CP must be lost in order for potential to be within cracking window. Unless there is a perfect balance between coating permeability and current density, the application of CP will cause the potential to be outside the window for cracking, even though the environment may be permissive. CP must then be lost for cracking to occur. Potential will relax faster than environment, resulting in a period of appropriate conditions for cracking. Implies possible cyclic behaviour of environment generation/cracking, etc. Further implies that conditions for cracking may not be that common.	Jack et al. (2000)	H-I-4

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H022	Critical range of CO_2 partial pressure for generation of high-pH environment by evaporation. Partial pressure of CO_2 must be between that in air and 5 vol.% for the pH of the resulting evaporate to be within the range for high-pH SCC.	Jack et al. (2000)	H-I-2
H023	Observation of wide, corroded cracks with a predominantly intergranular crack path. Observation of corroded intergranular crack path associated with deflection of cracks. Therefore, difficult to assess whether this is a case of high-pH to NNpH transition or a third type of cracking.	Sutherby and Chen (2004)	
H024	Intergranular crack path determined by through-thickness microstructure. Change in hardness leads to local plastic deformation in central softer core with shear stress then driving crack direction	Sutherby and Chen (2004)	
H025	At potential of maximum susceptibility to high-pH SCC, surface covered by Fe_3O_4 and often incorporates $FeCO_3$. Most likely film responsible for initial passivation near active-passive transition is Fe_3O_4, although some $FeCO_3$ possible. Question is what is the chemistry and potential inside crack and at crack tip?	Odziemkowski et al. (1994)	
H026	Reducing the gas outlet temperature is an effective method of mitigating high-pH SCC. Lower temperatures: (i) delay coating degradation, (ii) slows the generation of the high-pH environment, (iii) reduces the potential range of which cracking occurs, and (iv) reduces the rate of crack growth	Parkins (1994)	H-0-2, H-I-1
H027	Overprotection (more negative than -1.2 V_{CSE}) of the pipe should be avoided as the formation of H_2 bubbles can shift the potential into the cracking range. Potential drops down simulated disbondments have been correlated with the formation of H_2 bubbles, especially at the mouth of the disbondment. The value of -1.2 V_{CSE} (or -1.1 V_{SCE}) represents a thermodynamic/kinetic threshold for the generation of H_2 at a significant rate. Avoiding over-protection will also minimize the electrochemical formation of the high-pH environment.	Parkins (1994)	H-I-7
H028	Susceptibility of different steels is associated with the different cyclic stress-strain behaviour, rather than any difference in chemical composition. The rate of crack growth can be related to the cyclic stress-strain behaviour. High-pH SCC failures have been observed for steels with a wide range of chemical composition.	Parkins (1994)	H-I-13

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H029	Lifetime prediction requires a stochastic approach. Scatter observed in coating failure, crack initiation (which is associated with pitting), crack growth, resulting in a distribution of apparent crack growth rates, which must be treated statistically.	Parkins (1994)	H-0-7
H030	High-pH SCC is uncommon on liquid pipelines. Because of the lower temperature generally associated with liquid lines, although there have been vases in warm climates (Saudi Arabia), and the shipment of hot liquids could induce this form of cracking.	Parkins (1994)	H-I-19
H031	High-pH SCC cracks follow an intergranular path. This implies a fundamental weakness at grain boundaries, thought to be associated with the cyclic stress-strain behaviour.	Parkins (1994)	
H032	Field evidence for Fe_3O_4 with some $FeCO_3$ on fracture surfaces. These observations are consistent with lab findings (see H025)	Parkins (1994)	
H033	No evidence for role of stress raisers for high-pH SCC. Unlike NNpH SCC for which stress raisers are very important, there is no indication that stress raisers are necessary for high-pH SCC, although cracking has been observed in dents. Probably appropriate to state that stress raisers are not necessary for high-pH SCC but they do not preclude this form of cracking.	Parkins (1994)	H-I-18
H034	A constant supply of CO_2 is required to maintain the high-pH SCC environment. If the CO_2 supply is interrupted then the pH increases to >11 and lies outside the range for cracking (as the re-passivation rate will exceed the rate of film breakdown).	Parkins (1994)	H-I-5
H035	A CO_2 partial pressure of a few vol.% of an atmosphere is necessary to maintain a high-pH SCC environment. If the p_{CO2} is too low (say, <0.1 vol.%), then the pH will exceed pH 11, and if it is too high (>5 vol.%) the pH is too low (<pH 8) for cracking.	Parkins (1994)	H-I-5
H036	The high-pH SCC environment can be generated by evaporation of a neutral pH groundwater. Evaporation of a pH 6.5 solution results in the formation of a pH 9-10 $NaHCO_3/Na_2CO_3$ solution.	Parkins (1994)	H-I-2

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H037	Cracking occurs within a window of potentials, with that window being a function of temperature, pH, solution composition, and strain rate.	Parkins (1994)	H-IV-3
H038	A threshold strain rate exists below which cracking does not occur, because the rate of re-passivation exceeds the rate of film rupture	Parkins (1994)	
H039	The crack growth rate is a function of temperature, exhibiting a range of activation energies of 20-67 kJ/mol, with a best estimate of 42 kJ/mol	Parkins (1994)	H-0-2, H-I-1
H040	The upper threshold pH for cracking is ~pH 10.5, at which point the potential window for cracking decreases to zero	Parkins (1994)	
H041	Threshold stress for cracking depends on the severity of cyclic loading, with the threshold decreasing with decreasing R value, but is only weakly dependent on frequency	Parkins (1994)	H-II-1
H042	Threshold stress for cracking is independent of electrolyte composition and temperature, although all electrolytes tested were reasonably concentrated	Parkins (1994)	H-II-1
H043	Presence of chloride and sulphate in electrolyte have no apparent effect on SCC behaviour, implying that, within the normal limits in groundwater, the Cl^- and sulphate concentrations will not indicate the presence of SCC	Parkins (1994)	
H044	The native potential is more-positive than the cracking range, since pipeline steel is passive in high-pH electrolytes and the cracking range is slightly more positive than the active-passive transition	Parkins (1994)	
H045	Application of adequate CP will shift the potential more-negative than the cracking range, indicating that some source of iR drop is required for cracking on a protected pipe	Parkins (1994)	
H046	High-pH SCC can occur on a protected pipe. The potential will be within the cracking range if the pipe is inadequately protected or if there is some source of iR drop. The suggestion that CP must be lost for the potential to be within the range for cracking, and the implication of a seasonal effect, is not correct	Parkins (1994)	H-I-4
H047	Millscale will poise potential in cracking range on protected pipe. A CP current density of ~60 $\mu A/cm^2$ will control E in cracking range in 1N-1N at 75^oC	Parkins (1994)	H-I-15

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H048	Polished steel surfaces cannot be maintained in the cracking potential range under galvanostatic conditions. For this reason, lab studies are done under potentiostatic control. This is a moot point for field conditions, since pipes will have either a millscale or corroded surface. However, this is one more reason why shot blasting the pipe will prevent high-pH SCC	Parkins (1994)	H-I-15
H049	On protected pipe, there is an iR drop along length of disbondment, with the magnitude being time dependent, as well as dependent on the disbondment height and the conductivity of the electrolyte. Increasing disbondment gap causes the potential to move more quickly through the cracking range.	Parkins (1994)	H-I-4
H050	If CP is lost, potential drifts through cracking range to more-positive values, with the period within the cracking range possibly months in duration	Parkins (1994)	H-I-10
H051	Threshold stress or SIF for sustained crack growth, which are dependent on electrolyte composition, potential, and temperature and are of the order of K_{ISCC} ~21 MPa$\sqrt{m}$, σ_{th} ~305 MPa in 1N-1N, 75-90^{o}C, -0.65 V_{SCE}.	Parkins (1994)	H-IV-1
H052	Threshold stress and SIF for sustained crack growth represent a dormancy condition. Crack initiation and growth may occur below the threshold values but the CGR will decline with time and the cracks will become dormant.	Parkins (1994)	H-III-1
H053	Whether cracks grow is determined by the relative rates of film formation and film rupture. Consequence of slip dissolution model. Rate of film rupture determined by the crack-tip strain rate ($\dot{\varepsilon}_{CT}$).	Parkins (1994)	H-III-3
H054	Most important loading characteristic is the strain rate. Under cyclic loading conditions, the strain rate is more important than the stress or stress range. Under static loading the creep rate determines the effective strain rate	Parkins (1994)	H-III-2
H055	Cyclic loading promotes crack growth through the enhancement of low-temperature creep. Under static loading conditions, work hardening limits amount of creep strain, but this effect can be overcome by cyclic loading. For a given maximum stress, creep is more extensive under cyclic (under-)loading conditions than at constant load. Therefore, cracking will occur at a lower stress under cyclic loading compared with static loading.	Parkins (1994)	H-III-2

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H056	Increased stress promotes higher crack densities in shorter times, than lower stress. Therefore, crack initiation is favoured by higher stress	Parkins (1994)	H-II-3
H057	Rate of crack initiation would be expected to decrease with time due to shielding and work hardening effects, but the total number of cracks continues to increase with time. The continued initiation of cracks, albeit at an increasingly slower rate, is important for crack growth and re-activation of dormant cracks by coalescence	Parkins (1994)	H-II-4
H058	Periodic unloading/reloading events prevent crack dormancy. As for NNpH SCC.	Parkins (1994)	H-III-4
H059	Grit blasting increases the threshold stress for cracking, with the extent of increase determined by the duration and nature of blasting.	Parkins (1994)	H-II-5
H060	Under static load, the threshold stress is of the order of the actual yield stress. Indicates that plastic deformation is required fro crack initiation.	Parkins (1994)	H-II-2
H061	Under cyclic loading, the threshold stress for cracking is reduced by 60-80 MPa for each 0.1 decrease in R. Reduction in σ_{th} is a consequence of the effect of cyclic loading on the promotion of microplastic deformation	Parkins (1994)	H-II-1
H062	Increase resistance to high-pH SCC by improving cyclic stress-strain behaviour, but uncertain how to do this.	Parkins (1994)	H-I-13
H063	Rarely observe cracks under millscale, unless millscale itself is cracked. This has implications for the propensity of MnS inclusions to promote crack initiation since it suggests that is only possible if the inclusion coincides with a crack in the millscale.	Parkins (1994)	
H064	Alloying additions of Ti, Cr, Mo, and Ni reduce susceptibility to high-pH SCC, but of limited practical use as the amounts required would make the steel prohibitively expensive	Parkins (1994)	
H065	Cracking follows a slip dissolution mechanism. Important consideration for modelling and prediction.	Parkins (1994)	H-0-1
H066	Maximum crack growth rate determined by the Faradaic limit under film-free conditions. Estimated to be of the order of $5 \pm 2 \times 10^{-6}$ mm/s (160 ± 60 mm/yr)	Parkins (1994)	

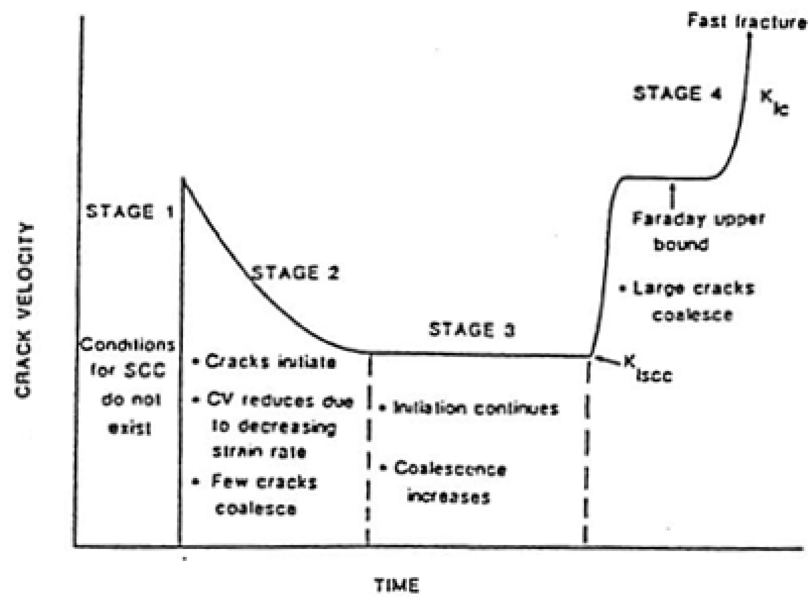
continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H067	Crack growth is discontinuous, with even large cracks becoming dormant for long periods until crack coalescence leads to re-activation.	Parkins (1994)	H-III-3, H-III-5
H068	Crack aspect ratio changes with depth, suggesting intermediate depth cracks (0.5 < c < 1.5 mm) are stress driven and deeper cracks (C > 1.5 mm) grow by coalescence with smaller cracks, hence cracks coalesce later in life	Parkins (1994)	
H069	Crack coalescence is of fundamental importance for crack growth. Later stage cracks grow by coalescence, with coalescence responsible for re-activating dormant cracks	Parkins (1994)	H-0-4, H-III-5, H-III-6
H070	Crack coalescence occurs for $y \leq 0.14(2a)$. The same rule was found for both lab and field high-pH SCC samples, and for NNpH SCC, the latter suggesting that coalescence is a mechanics-driven process.	Parkins (1994)	
H071	Battelle model for crack growth prediction involves (i) the material cyclic stress-strain behaviour, (ii) a crack growth rate expression for the slip dissolution model, and (iii) the above condition for coalescence. The model further considers a surface layer of reduced stiffness (restraint) that exhibits greater microplastic deformation than the bulk of the material. Cracks may become dormant at the surface layer/bulk material interface if the strain or strain rate in the bulk is insufficient to sustain crack growth. It is found that only cracks in sparse colonies can grow to a sufficient depth to be of concern.	Parkins (1994)	H-0-8
H072	Newcastle model for crack growth involves (i) cycle-dependent diminishing rate of crack growth and crack nucleation described by power laws and (ii) the above condition fro crack coalescence. Cracks initiate and grow at a diminishing rate and may become dormant, only to either extend or re-activate by coalescence. Model parameters are taken from experimental data, with assumed random initiation of cracks. Besides the selection of parameter values, there is relatively little inherent dependence on environment and is largely a mechanics-driven model.	Parkins (1994)	H-0-8
H073	Important to account for the stochastic nature of crack growth in lifetime predictions	Parkins (1994)	

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H073	High-pH SCC can be described by a four-stage process 	Parkins (1994)	H-0-5, H-0-7, H-0-8
H074	Lowering the temperature is beneficial as it (i) slows coating deterioration, (ii) inhibits evaporative concentration of the electrolyte, and (iii) reduces the crack growth rate	Parkins (1994)	H-0-2, H-I-1
H075	Avoiding over-protection, especially within 20 km of the C/S is recommended with an acceptable range of potentials being -0.9 to -1.2 V_{CSE}	Parkins (1994)	H-I-7
H076	Minimizing pressure fluctuations is beneficial with little probability of cracking at 72% SMYS for R > 0.90	Parkins (1994)	H-I-17
H077	Shot blasting the surface of new pipe is beneficial.	Parkins (1994)	H-I-15

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H078	SCCLPM model predictions indicate most effective mitigation strategies for high-pH SCC are to: (i) reduce the frequency and amplitude of pressure cycles and (ii) reduce gas discharge temperature	Leis (1997)	H-0-8
H079	Chemical composition of steel has little effect on crack growth rate. Based on comparison of K_{ISCC} and stage II CGR for six different X-52 steels, although CGR is a factor of 10-100 below the Faradaic rate proposed by Parkins (1994).	Danielson et al. (2000)	H-IV-5
H080	Modern steels exhibit lower K_{ISCC} than vintage X-52 steels. Possible reasons include: (i) absence of hard pearlite phase, (ii) unusual segregation (or lack of) of alloying impurities, (iii) enhanced cyclic softening	Danielson et al. (2001)	H-IV-5
H081	CGR decreases with time due to creep exhaustion. Observed decrease in CGR with time, but creep should have been promoted by cyclic loading.	Danielson et al. (2001)	
H082	Cyclic loading enhances crack growth by cyclic softening, which results in higher crack-tip strain rate. Confirms fact that crack tip strain is required for crack propagation.	Danielson et al. (2001)	H-III-2
H083	Primary coating factors affecting SCC susceptibility are resistance to disbondment and the ability to pass CP. On the other hand, grit blasting, as tested, did not consistently show benefit	Beavers (1992)	H-I-11
H084	FBE more-resistant to high–pH SCC than CTE, with PE being the least resistant. Ranking based on disbondment characteristics and CP permeability.	Beavers (1992)	H-I-11
H085	CTE on millscale-covered surface more resistant to disbondment than FBE. Implication is that field-applied CTE may be more-resistant to disbondment, and SCC, than FBE	Beavers (1992)	
H086	For shielding coatings, bare area adjacent to disbondment prevents any protection under disbondment. Thus, for PE ctg, a bare area will be preferentially polarised with no CP reaching disbondment. However, bare area has less effect of distribution of current for CTE which is generally permeable.	Beavers (1992)	
H087	Inadequate grit blasting can lead to no improvement in SCC resistance. Appear to require a white surface finish, rather than near-white, to ensure sufficient grit blasting to prevent SCC. Older FBE lines may have been inadequately blasted.	Beavers (1992)	H-I-15

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H088	Differences in SCC susceptibility due to different cyclic stress-strain behaviour of steels.	Leis and Parkins (1998)	H-I-13
H089	Between K_{ISCC} and K_Q the crack is growing at the Faradaic limiting CGR.	Leis and Parkins (1998)	
H090	Shallow cracks prefer to propagate along the surface, rather than in the depth direction as there is less constraint to deformation of the surface layer	Leis and Parkins (1998)	H-III-1
H091	Cracks may become dormant as they enter the stiffer bulk material if the strain rate is insufficient to sustain film rupture	Leis and Parkins (1998)	H-III-3
H092	Dense colonies are a result of widespread microplasticity at stresses above yield.	Leis and Parkins (1993)	H-II-3
H093	Sparse, banded collinear colonies are a result of localized plasticity at stresses just below or above yield.	Leis and Parkins (1993)	
H094	Surface microplasticity can be induced by normal pipeline operation.	Leis and Parkins (1993)	H-II-1
H095	As cracks grow in depth direction, growth becomes controlled by mechanical factors.	Leis and Parkins (1993)	
H096	Crack coalescence is a key factor in the crack growth process.	Leis and Parkins (1993)	H-0-4, H-III-6
H097	A crack with a surface length >6 mm will exceed K_{ISCC} and subsequent crack growth will be rapid. Implies that vast majority of pipe lifetime is spent in incubation, initiation, and early stage growth and that management of cracks in the range 0-6 mm is required.	Leis and Parkins (1993)	H-0-8, H-IV-1
H098	Uniform microstructures are more resistant to cracking than mixed microstructures. Pearlite-ferrite microstructures are more susceptible than bainitie-ferrite or ferrite microstructures. Implies modern TMCP steels are less susceptible than	Asahi et al. (1999)	H-I-14
H099	Coarser-grained material more susceptible to local plastic deformation than uniform microstructures. Would be consistent with Leis' suggestion that local microplasticity controls crack initiation and early-stage growth	Asahi et al. (1999)	H-I-14

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H100	Pickled (stripped) millscale surfaces have same susceptibility as millscaled surfaces. Implies effect of millscale is not due to millscale as such, but some related factor, such as surface roughness	Asahi et al. (1999)	
H101	Decarburized surface layers are particularly susceptible to high-pH SCC. Due to the softer material and larger grain size.	Asahi et al. (1999)	
H102	Grit blasting prevented cracking, most likely to the formation of a hard surface layer, with some possible influence due to introduction of compressive residual stress	Asahi et al. (1999)	H-I-15
H103	Increased surface roughness increases susceptibility to high-pH SCC.	Asahi et al. (1999)	H-I-15
H104	TTT showed modern European steels not susceptible whereas two vintage X-50 and X-60 steels were susceptible. Unknown test conditions, but likely to be 1N-1N at 75^{o}C. Unknown steel properties for modern materials, but of 1980's vintage.	Sloterdijk (1996)	H-I-14
H105	Applied Newcastle model to predict remaining lifetime. Based on material properties determined with actual steels in service and knowledge of operating conditions.	Sloterdijk (1996)	H-0-8
H106	Criterion for failure is time to reach surface length of 6 mm. Criterion used in Newcastle model to indicate the exceedance of K_{ISCC} and the onset of Stage II crack growth.	Sloterdijk (1996)	H-IV-1
H107	Cracks in dense crack patches tend to become dormant because of shielding by neighbouring cracks. Dense patches defined as those with a crack spacing of <20% of the wall thickness)	Leis and Colwell (1997)	H-III-3
H108	Cracks in sparse crack patches can continue to grow unhindered by shielding. A crack patch is not the same as a crack colony, the latter being more defined by the shape and size of the disbondment.	Leis and Colwell (1997)	H-III-4
H109	Complex 3-D interaction of stress within a crack patch with the crack-tip stress increasing, decreasing, or remaining constant with increasing depth under various circumstances.	Leis and Colwell (1997)	

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H110	High-pH and NNpH SCC cracks show similar characteristics in terms of crack size, spacing, and shape	Leis and Colwell (1997)	
H112	Increasing stress causes decreased crack spacing in general, although there can be local variation due to microscale differences in grain orientation, local stress-strain properties, local microplasticity	Leis and Colwell (1997)	H-II-3
H113	Development of high-pH environment is balance between rate of OH^- transport and loss of OH^- from disbonded region. Implies that there is a necessary balance between the CP current demand and the coating properties. If the CP is too high then pH increases above pH range for cracking. If coating is too permeable, then cannot retain solution adjacent to pipe surface.	Been et al. (2005)	H-I-3
H114	Supply of CO_2 is required to develop concentrated HCO_3^-/CO_3^{2-} solution. In the absence of CO_2, a NaOH solution forms and pH increases because of absence of buffering. Implicitly require a certain flux of CO_2 for a given combination of CP current demand and coating permeability.	Been et al. (2005)	H-I-5
H115	Field high-pH electrolytes are more dilute than 1N-1N. In terms of g/L of Na_2CO_3 and $NaHCO_3$, the standard solution is 53-83, whereas electrolytes found in the field are more dilute 12-37, 18-28, 23-20.	Beavers et al. (1998)	
H116	Simulated field electrolytes are less aggressive than 1N-1N. 1N-1N peak CGR are higher than simulated field electrolytes and potential window is slightly wider. However, peak potential for field electrolytes is more negative than that for 1N-1N and, therefore, closer to potential of a protected pipe.	Beavers et al. (1998)	H-IV-4
H117	Cracking range moves to more negative values with increasing temperature. Cracking range is within 120 mV of -850 mV at 40°C, but only 30 mV at 75°C resulting in more likely cracking on protected pipe at higher temperature.	Beavers et al. (1998)	H-IV-3
H118	Field electrolytes high in Na/K and low in Ca/Mg. As shown elsewhere, this is a requirement for generating a concentrated carbonate/bicarbonate solution due to the limited solubility of ca and Mg carbonates.	Beavers et al. (1998)	H-I-6
H119	Width of potential window increases with increasing temperature. Approximately 50 mV at 25°C and ~150 mV at 75°C. Width of window is ~30% larger for 1N-1N than for 12-37.	Beavers et al. (1998)	H-0-2, H-I-1, H-IV-2

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H120	Possible high-pH SCC mitigation strategies include: reduce coating disbondment/defects, inhibitor, reduce stress (uneconomic), more-resistant steel, effective CP, reduce temperature	Fessler et al. (1977)	
H121	Under mild cyclic loading, threshold stress decreases with decreasing frequency. Unlike crack growth, initiation becomes more likely with decreasing frequency. Very mild cyclic loading with R values of 0.90-0.97	Fessler (1976)	H-II-1
H122	Threshold stress decreases with increasing stress range (decreasing R).	Beavers et al. (1985)	H-II-1
H123	Crack growth rate decreases with time. From results of TTT but consistent with results from other techniques. Strong tendency for high-pH SCC cracks.	Beavers et al. (1985)	H-III-1
H124	Crack density increases with time.	Beavers et al. (1985)	H-II-4
H125	Weld metal is less susceptible than either base metal or HAZ. Some questions over experimental technique used.	Černý and Linhart (2004)	
H126	Ferrite more resistant than ferrite-pearlite microstructure. Some questions over experimental technique used, but consistent with evidence from other studies that uniform microstructures are more resistant.	Černý and Linhart (2004)	
H127	Cracking in high-pH environment at potentials below -800 mV_{SCE} is due to HE. Can also get H effects in high-pH solutions, but need to get H into material through passive film.	Wang and Atrens (1996)	
H128	Threshold stress for initiation of high-pH SCC is greater than YS and requires plastic deformation.	Wang and Atrens (1996)	H-II-1
H129	Steels become more susceptible to high-pH SCC initiation with increasing strength. Based on observation that ratio of $\sigma_{init}/\sigma_{YS}$ tends to 1 with increasing YS	Wang and Atrens (1996)	
H130	High-pH SCC cracks initiate at etched grain boundaries or at pits. GB initiation involves formation of oxide and cracking of that oxide at gb. Majority of pits do not initiate cracks.	Atrens et al. (1996)	

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H131	Probabilistic model for high-pH SCC based on slip dissolution mechanism and expression for crack-tip strain rate, and probability of coalescence.	Francis and Jandu (2006)	H-0-8
H132	Even deep cracks can become dormant due to stress shielding. Presumably the crack becomes deep in the first place because it is in a sparse patch, but continued nucleation then produces a dense patch.	Parkins (1996)	H-III-3
H133	Vast majority of a crack's life is spent below K_{ISCC}. Majority of lifetime is taken up with incubation, crack initiation, early-stage growth (Stages 1, 2, 3).	Parkins (1996)	H-0-5
H134	Carbon steels are susceptible to IGSCC, TGSCC, quasi-cleavage, or no cracking over a wide range of pH and potential. Interesting observation that means that both IGSCC and TGSCC could be observed under similar conditions.	Parkins and Zhou (1997a)	H-0-6
H135	At pH range associated with high-pH SCC, only IGSCC is observed. Thus, if the potential is slightly more-positive or more-negative than the cracking range, no SCC is observed.	Parkins and Zhou (1997a)	H-0-6
H136	At pH range associated with NNpH SCC, only quasi cleavage is observed (with transgranular fissuring possible at potentials 400 mV more positive). Thus, under NNpH conditions only ever likely to observe quasi cleavage,	Parkins and Zhou (1997a)	
H137	Quasi-cleavage only observed at potentials below HER equilibrium line. But, at least for the conditions of these tests, need to be ~100 mV more-negative than the H_2 equilibrium line (for 1 atm H_2). Does this indicate thatyou need a certain rate of H_2 evolution, or is it not significant?	Parkins and Zhou (1997a)	
H138	At intermediate pH (pH 7-9.5) could observe either IGSCC or transgranular fissuring, depending upon potential. Range of 200-300 mV over which would expect to see either IGSCC of TG fissures, but why is none reported from the field?	Parkins and Zhou (1997a)	H-0-6
H139	IGSCC is observed over a wide range of pH (pH 6.6-11). Why is high-pH SCC only reported in the range ~pH 9.5-11.5? Is the potential never in the right region?	Parkins and Zhou (1997a)	H-0-6
H140	Peak crack growth rate shifts to more-negative potentials with increasing T. On the assumption that more-negative potentials are more likely because of the effects of CP, then high-pH is more likely at higher T.	Parkins and Zhou (1997a)	H-IV-2

continued …..

Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H141	IGSCC cracking range shifts to more-negative potentials with increasing pH. Again, on the assumption that more-negative potentials are more likely on protected pipe, then cracking becomes more likely with increasing pH.	Parkins and Zhou (1997a)	H-IV-4
H142	Nature of gb attack differs for IGSCC and TGSCC conditions. IGSCC conditions result in etching of GB, TGSCC conditions to milder IGA	Parkins and Zhou (1997b)	
H143	IGSCC occurs over a wider range of potentials, pH, and solution composition than normally associated with high-pH SCC. IGSCC observed from pH 7-11, -200 to -700 mV_{SCE}, 0.1-2.0 mol/L carb/bicarb.	Parkins and Zhou (1997b)	H-0-6
H144	Crack growth rate increases with increasing bicarbonate concentration. Of the two species, bicarbonate seems to be more important than carbonate, possibly because of direct involvement in the dissolution process. The increase in CGR with $[HCO_3^-]$ implies that, within the pH range for cracking, the CGR increases with decreasing pH.	Parkins and Zhou (1997b)	H-IV-4
H145	Cracks with a circumferential spacing of <20% wall thickness will go dormant with very little growth in the depth direction	Leis (1997)	H-III-3
H146	Cracks with a circumferential spacing of >20% wall thickness will tend to continue to grow.	Leis (1997)	
H147	Initial crack spacing is determined by operating factors such as maximum stress, but subsequent spacing is affected by further initiation which depths on maximum stress and other factors	Leis (1997)	H-II-3
H148	Dense and sparse crack patches can be formed at similar stresses due to differences in micro-mechanical properties. Implies that a sparse patch can be converted into a dense patch.	Leis (1997)	
H149	Mechanics, rather than metallurgical or environmental factors, determine the SCC crack patterns observed, including the effect of coalescence. Implies no role for effects due to dissolution of inclusions, development of local chemistry, electrochemical effects of millscale, …	Leis (1997)	
H150	Once dormant, cracks in a dense patch will remain dormant. I.e., a dense crack patch cannot become a sparse dense patch!	Leis (1997)	H-III-3

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H151	Microstructure has effect on crack path. Cracks propagate according to microstructure, tending to prefer propagating along gb, especially in coarser-grained material.	Mitsui et al. (2008)	
H152	Weld metal is less susceptible to high-pH SCC than base metal. Thought to be due to finer grain structure of weld metal.	Mitsui et al. (2008)	H-I-14
H153	Cracks avoid pearlite or pearlite-dispersed regions. Consistent with suggestion elsewhere that cracks could arrest at pearlite grain boundaries.	Mitsui et al. (2008)	
H154	Mild cyclic loading (R = 0.9) enhances crack initiation by reducing threshold stress. Reported by others, but confirmed here for low stress range	Parkins and Singh (1990)	H-II-1
H155	Threshold stress lower on as-received (millscale) surface. Although the magnitude of the difference here was not great.	Parkins and Singh (1990)	H-II-5
H156	Density of cracks increases with increasing load. Implication is that more cracks likely with higher loads, but that the cracks will be denser (and, therefore, self shielding?).	Parkins and Singh (1990)	H-II-3
H157	Crack growth rate decreases with time, expressed on a per cycle basis - crack growth per cycle = $0.0065N^{-0.822}$ mm/cycle	Parkins and Singh (1990)	H-II-4, H-III-1
H158	Crack initiation continues at a decelerating rate, expressed on a per cycle basis – number of cracks per mm per cycle = $2.46N^{-0.803}$.	Parkins and Singh (1990)	H-II-4
H159	Condition for crack coalescence given by $y < 0.025 + 0.14(2a)$. In other publications, the initial 0.025 term is excluded.	Parkins and Singh (1990)	H-III-6
H160	Dormant cracks are reactivated by coalescence with new cracks. Crack nucleation is continuing, so slowing cracks can be reactivated by coalescing with a new crack.	Parkins and Singh (1990)	H-III-5
H161	Under static load, threshold stress is approximately equal to the yield stress. Since initiation needs some degree of plastic deformation. Implies should have little initiation on statically loaded pipeline operating at MAOP of 72-80% SMYS.	Parkins et al. (1993)	H-II-2

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H162	Cyclic loading causes cyclic softening of pipeline steels. Stress-strain curve obtained under cyclic loading lies under than for monotonic loading.	Parkins et al. (1993)	H-I-16
H163	Degree of cyclic softening increases with increasing stress range. Increasing $\Delta\sigma$ or decreasing R will create increasing cyclic softening, resulting in larger strains for a given stress.	Parkins et al. (1993)	H-I-16
H164	The stress at which the cyclic stress-strain behaviour departs from that for monotonic loading is approximately equal to the threshold stress. This equality strongly suggests that the reduction in threshold stress upon cyclic loading is a result of microplastic deformation.	Parkins et al. (1993)	
H165	Number of cracks nucleated increases with time and number of cycles, but is independent of frequency. Implies frequency is of less importance for high-pH SCC based on the mechanics of the system.	Parkins et al. (1993)	H-II-4
H166	Crack growth rate decreases with time and increasing number of cycles and is a function of stress level. Cracks decelerate because of strain aging and/or work hardening effects.	Parkins et al. (1993)	H-II-4
H167	Effect of coalescence is predominant in determining effective crack growth rates and service lifetimes. Based on observation that CGR decreases with time, conclusion is that coalescence and consequent re-activation of dormant cracks must be accounted for in any modelling approach for high-pH SCC.	Parkins et al. (1989)	H-0-4
H168	Threshold stress intensity factor K_{ISCC} = 25 MPa$\sqrt{m}$. For X-60 pipeline steel in 1N-1N at 75°C, -650 mV_{SCE}	Pilkey et al. (1995)	H-IV-1
H169	Stage II crack growth rate close to Faradaic limit. Reported CGR of 2.7×10^{-7} mm/s (8.5 mm/yr), which authors suggested was a factor of three lower than the Faradaic limit estimated from electrochemical data	Pilkey et al. (1995)	
H170	Implication is that pipeline spends very little time in Stage II. Based on data presented by Pilkey et al. this would be correct. Therefore, little point in measuring Stage II crack growth kinetics.	Pilkey et al. (1995)	H-0-5

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H171	The (Na+K)/(Ca+Mg) ratio in the soil is higher at high-pH sites. Ratio is higher at confirmed high-pH sites than at either suspected high-pH or confirmed or suspected NNpH SCC sites	Beavers and Worthingham (2002)	H-I-6
H172	The absolute amount of (Na+K) in the soil is higher at high-pH SCC sites. Ratio is higher at confirmed high-pH sites than at either suspected high-pH or confirmed or suspected NNpH SCC sites. Furthermore, the (Na+K) total is more discriminating than the soluble:insoluble cation ratio.	Beavers and Worthingham (2002)	H-I-6
H173	The (Na+K)/(Ca+Mg) ratio is higher under both disbonded tape and asphalt coatings compared with the soil, but the concentration effect is 50x greater for asphalt. This suggests that CP does penetrate below tape coating to some degree, but not to the same degree as for asphalt	Beavers and Worthingham (2002)	
H174	90% of pressure cycles for gas transmission pipelines had an R value $\geq$0.90.	Sutherby et al. (2000)	
H175	There is a wide variation in hoop strain rates between different facilities, with values from 10^{-11} to 10^{-6} s^{-1}, with most at 10^{-9} s^{-1} or lower.	Sutherby et al. (2000)	
H176	The most damaging cycles are located close to the discharge of the compressor station	Van Boven et al. (2002)	
H177	Locations closer to the suction side have increased number of pressure cycles due to forward and backward propagating waves.	Van Boven et al. (2002)	
H178	Although the frequency of pressure cycles is greater the R ratio and, of course, the maximum stress are lower.	Van Boven et al. (2002)	
H179	High-pH and NNpH SCC environments are reversible and could occur in the same location. Reversibility of the environments could be driven by seasonal variations, particularly temperature.	Castaneda et al. (2008)	
H180	Aspect ratio tends to decrease with increasing depth for both high-pH and NNpH SCC for cracks away from the failure but show no clear trend with depth for cracks that lead to failure.	Castaneda et al. (2008)	

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Table B.1: R&D Guidelines – High-pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H181	Site-selection model for high-pH SCC with seven categories of factors were identified that contribute to high-pH SCC (with maximum % contribution for each category) o Coating, soil, moisture content (29%) o Maximum temperature (18%) o Surface preparation (4%) o Hoop stress (18%) o Stress fluctuation (18%) o CP level (7%) o Initial hydrotest pressure level (7%)	Eiber and Leis (1998)	
H182	Factors found to lead to a high probability of high-pH SCC o CTE/asphalt coating with alternate wet-dry moisture conditions o PE single or double-wrap coating o temperatures greater than 52^{o}C (125^{o}F) o hoop stress >67% SMYS o Pressure fluctuations with R <0.85 o CP level more-positive than -850 mV_{CSE} o Initial hydrotest below 90% SMYS	Eiber and Leis (1998)	
H183	The 100 mV CP criterion can be used for lines susceptible to high-pH SCC if any of the following conditions are met: o FBE coating o white or near-white surface preparation o MAOP <40% SMYS o operating temperature <35^{o}C o soil pore-water Na + K concentrations <10 meq/L	Beavers and Durr (2000)	H-I-9
H184	If all of the criteria above are not met, then the 100 mV polarization criterion should be avoided as it may lead to either development of the high-pH environment and/or result in the pipe surface potential being within the range for cracking	Beavers and Durr (2000)	

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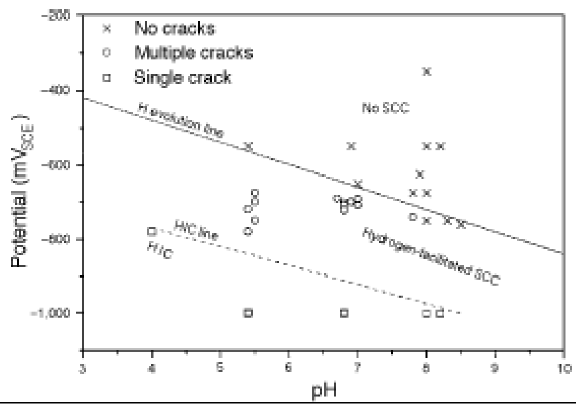
Table B.1: R&D Guidelines – High-pH SCC (concluded)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
H185	The development of a high-pH SCC environment is a balance between the rate of OH^- production and the rate of transport away from the pipe surface through the permeable coating.	King et al. (2004a)	H-I-3
H186	Permeable coatings could become shielding if carbonate minerals precipitate in the pores of the coating.	King et al. (2004a)	
H187	Permeable Coating Model predicts lower permeability coatings (5% porosity or lower) are able to trap the high-pH electrolyte against the pipe surface.	King et al. (2004a)	H-I-3
H188	The porosity of asphalt coating exposed in the field for 20 years is ~11%, with a bimodal distribution with 23% of the total porosity associated with pores from 6 to 100 μm in diameter and the majority of the porosity associated with pores 0.003 to 0.08 μm in diameter.	King et al. (2004b)	
H189	High-pH SCC crack growth can be divided into an environmentally assisted term and a mechanical fatigue component.	Been et al. (2004)	H-0-8
H190	High-pH crack growth rates decrease significantly with distance downstream of the compressor station, primarily due to the decrease in temperature and partly by effects on the crack-tip strain rate.	Been et al. (2004)	
H191	High-pH SCC is primarily driven by environmental effects with only a small contribution from mechanically driven fatigue	Been et al. (2004)	
H192	Rate of CO_2 generation depends on soil moisture content and temperature. Implies that, since CGR is dependent on HCO_3^- concentration, would expect higher crack growth rates closer to compressor station outlet.	King and Piazza (2009)	H-0-2, H-I-1, H-I-5
H193	Deterministic lifetime prediction model based on slip dissolution mechanism. Model accounts for effect of T on crack growth rate and width of potential window, and effect of strain rate on rupture of passive film. Predictions consistent with distance dependence of high-pH SCC failures and field CGR.	King et al. (2003)	H-0-8

Table B.2: R&D Guidelines – Near-neutral pH SCC

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N001	NNpH SCC is the result of a H-assisted local anodic dissolution mechanism. H accumulating at the crack tip is supposed to increase the rate of local dissolution, thus promoting crack growth.	Gu et al. (1999)	N-0-9
N002	The presence of bicarbonate ions (or CO_2, in general) increases the susceptibility to NNpH SCC at a given pH. The %RA in SSRT at E_{CORR} in NS-4 solution was lower at a given pH if CO_2 was used for pH adjustment, as opposed to using H_2SO_4. This implies that HCO_3^- ions play some role in the cracking process, possibly by buffering the pH in the cracking range or as a cathodic reagent.	Gu et al. (1999)	N-0-4
N003	Hydrogen pre-charging enhances NNpH SCC crack initiation. Conclusion based on increased number of brittle areas on fracture surface.	Gu et al. (1999)	
N004	Severity of SCC increases with increased H concentration at the crack tip. %RA in SSRT and crack growth rate of CT specimens decreases with decreasing pH, more negative potential, and increasing K (which causes H to concentrate at the crack tip).	Gu et al. (1999)	N-III-1
N005	NNpH SCC initiation is a function of E and pH. Crack initiation is bounded by H evolution line (E_{HER} = -0.241 – 0.0591pH V_{SCE}) and a lower potential limit for the initiation of HIC (E_{HIC} = -0.567 – 0.0514pH V_{SCE}). 	Gu et al. (1999)	N-0-7, N-I-1

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N006	There exists a threshold potential/pH for the HIC of pipelines steels. As noted in N005, HIC of pipeline steels occurs at potentials and pH values below a threshold line given by E_{HIC} = -0.567 – 0.0514pH V_{SCE}.	Gu et al. (1999)	N-0-7
N007	Over-protection of pipelines will lead to HIC. Implication based on evidence from N005.	Gu et al. (1999)	N-0-7
N008	It may be possible to anodically protect against NNpH SCC. Implication based on the evidence from N005.	Gu et al. (1999)	
N009	Crack growth rate increased by presence of dent. Dent presumed to result in a stress intensification which results in higher crack growth rates.	Been et al. (2006)	N-I-9, N-IV-1
N010	Unconstrained dents result in higher crack growth rates than constrained dents. Stress intensification higher in unconstrained dents based on surface stress analysis.	Been et al. (2006)	N-I-9, N-IV-1
N011	Enhanced crack growth due to dents more severe for liquid lines and for deeper cracks. Based on the assumption that the role of the dent is as a stress intensifier, more severe crack growth would be expected for liquid lines (which generally exhibit more lower R values than gas lines) and for deep (long) cracks (for which the mechanical driving force is larger).	Been et al. (2006)	N-I-10, N-IV-1, N-IV-2
N012	Enhancement of H at notch tip increases with decreasing pH and potential and increasing stress intensity. The enhancement with K in particular is noteworthy, with enhancement factors of 2, 5, and 9.5 over that for unloaded samples for stress intensities of 21 $MPa \cdot m^{1/2}$, 70 $MPa \cdot m^{1/2}$, and 87 $MPa \cdot m^{1/2}$, respectively. This implies that H-assisted cracking should accelerate as the crack deepens.	Qiao and Mao (1998) Qiao et al. (1997)	N-III-1
N013	Hydrogen-enhanced localized plasticity (HELP) may be involved in NNpH SCC crack growth. The fact that H is generated at the potentials associated with NNpH SCC and readily permeates in C-steel and can be concentrated by residual and applied stress is consistent with a role of H in NNpH SCC.	Parkins (1998)	N-0-9

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Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N014	Susceptibility to SCC increases in the presence of CO_2. %RA tends to decrease with increasing CO_2, although much scatter. At pH 5.8, %RA decreases monotonically with decreasing pH, but at pH 6.5 and pH 8 minimum ductility at around E_{CORR} with second loss of ductility at more-negative potentials (possibly associated with HIC). Proposed role of CO_2 is to lower pH to promote H evolution.	Parkins et al. (1994)	N-0-1
N015	No systematic effect of temperature. No systematic dependence of %RA on temperature between 5°C and 45°C.	Parkins et al. (1994)	N-0-2
N016	Evidence for role of H in NNpH SCC. Cracking occurs at potentials below H equilibrium line, presence of quasi-cleavage on fracture surface characteristic of HIC, propensity for cracks to initiate in bands (probability of crack initiation increased by presence of crack), absence of corrosion products at crack tip, maximum dissolution current too small to explain observed crack growth rates, significant loss of ductility even for samples with few or no initiated cracks	Parkins et al. (1994)	N-0-9
N017	Tendency for cracks to initiate from original surface. Pre-existing surface defects are supposed to act as local sites for the development of aggressive acidified chemistries which promote H evolution and crack initiation, rather than acting as stress concentrators.	Parkins et al. (1994)	N-II-5
N018	Tendency for cracks to initiate in groups. Unlike high-pH SCC for which crack initiation appears to be spatially random. Infers H mechanism for initiation (see N016). Has consequences for life prediction as "directed" initiation promotes crack coalescence.	Parkins et al. (1994)	
N019	Crack coalescence occurred early in life of crack. Unlike high-pH SCC, for which crack coalescence becomes more important with time, evidence that NNpH SCC cracks coalesce early and then grow as distinct cracks.	Parkins et al. (1994)	N-0-9
N020	CP can penetrate significant distances under disbonded shielding coating. Based on a measurements with an instrumented simulated shielded disbondment, 175 mV of polarization can be achieved at a depth of 25 cm for an applied potential of -1.2 V_{SCE}.	Chen et al. (2009)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N021	Pipeline steel may passivate in NNpH environments in thin electrolyte films. Based on thin-film studies using an SKP. "Passive" layer could inhibit H pickup, thus reducing the importance of H in the mechanism.	Fu et al. (2009)	
N022	Corrosion fatigue model for NNpH SCC. Based on cyclic load testing in dilute solution purged with 10% CO_2 with and without 1% H_2S under relatively aggressive conditions.	Eadie et al. (2005)	N-0-10, N-IV-4
N023	Presence of H_2S can increase the rate of CF crack growth in dilute electrolytes by a factor of 5-10. Based on studies with 1% H_2S purge.	Eadie et al. (2005)	N-IV-11
N024	Threshold ΔK for CF in dilute electrolytes purged with CO_2 of ~10 $MPA \cdot m^{1/2}$.	Eadie et al. (2005)	
N025	Dissolution rate of pipeline steel increases with applied tensile stress above 80%YS.	Tang and Cheng (2009)	
N026	Initiation of NNpH SCC is promoted by cathodic polarization. H thought to be involved in initiation process on polished samples, possibly by accumulation at voids around Al-containing inclusions.	Liu et al. (2009)	N-0-7
N027	Al-containing inclusions exhibit a greater propensity for crack initiation than Si-containing inclusions. Based on studies on polished samples in an acidic soil extract. Also a role of cathodic polarization (see N026)	Liu et al. (2009)	
N028	Cold work promotes cracking in near-neutral solutions. Similar test procedure and conclusion as for high-pH studies (cf. H001).	Rebak et al. (1996)	N-I-15
N029	Presence of CO_2 apparently not necessary for cracking. Based on results in sulphate solutions in absence of any form of carbonate. Contrary to others observations.	Rebak et al. (1996)	
N030	Crack orientation is a function of potential. Tendency for IG cracking at potentials more positive than E_{CORR} and transgranular at more-cathodic potentials.	Rebak et al. (1996)	N-0-8
N031	Hydrogen embrittlement mechanism for NNpH solutions. Based on enhanced cracking at cathodic potentials. But is this an artifact due to a change in mechanism with decreasing potential?	Rebak et al. (1996)	N-0-9

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N032	Upper potential limit for cracking in NNpH solutions. Apparent anodic threshold of -0.725 V_{SCE} above which cracking ceases(?)	Rebak et al. (1996)	
N033	Increasing CP penetration along disbondment with high (more-cathodic) applied potential. Apparently inconsistent with field observation of NNpH electrolytes, unless the latter are pH buffered by CO_2 permeating through coating.	Brousseau and Qian (1994)	
N034	MnS inclusions promote initiation of NNpH SCC. Inclusions considered to act as stress raisers, rather than by affecting the local chemistry, as Parkins suggests.	Asher and Singh (2009)	N-II-6
N035	Stress concentration required to initiate NNpH SCC cracks. Smooth samples did not initiate cracks at 85% YS, but samples with localized corrosion at inclusions initiated cracks as low as 30% YS. Dissolution of inclusions leads to stress raisers.	Asher and Singh (2009)	N-II-1
N036	Hydrogen is responsible for NNpH SCC crack initiation. Stress raiser required to accumulate sufficient H to initiate cracks.	Asher and Singh (2009)	N-0-9
N037	Correlation between fatigue models and SCC severity for liquid lines. Three types of fatigue model tested, involving ΔK only; ΔK and K_{MAX}, and ΔK; K_{MAX}, and f. All three models seem to apply equally well.	Been et al. (2006)	N-0-10, N-IV-2, N-IV-4
N038	No correlation between strain-rate based models and SCC on liquid lines. Three types of strain-rate model tested, with varying degrees of influence of maximum pressure.	Been et al. (2006)	
N039	Presence of CO_2 increasing susceptibility to SCC, but the actual concentration seems to be unimportant. Based on similar %RA with 5% CO_2 and 100% CO_2, despite lower pH in latter case.	Gu et al. (1999)	N-0-4
N040	NNpH SCC mechanism involves dissolution. Based on apparent decrease in ductility at potentials close to E_{CORR}	Gu et al. (1999)	
N041	HIC, rather than NNpH SCC, is the predominant process for cathodically polarized samples. Similar %RA at -1.0 V_{SCE} regardless of presence of CO_2 or not	Gu et al. (1999)	N-0-7

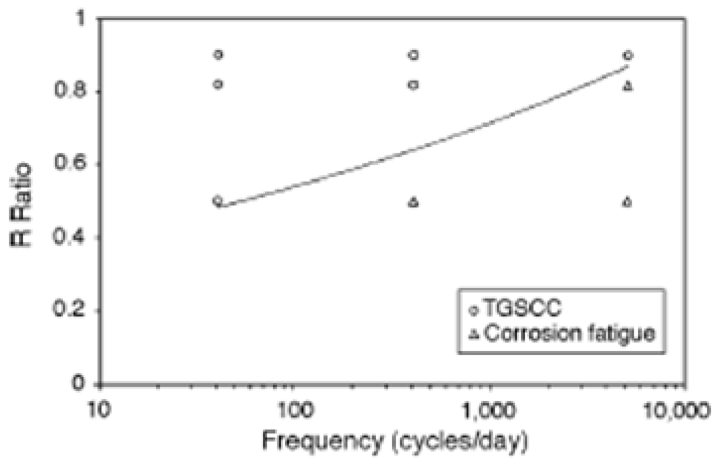
continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N042	Threshold S content of 0.01-0.02 wt.% for the susceptibility of reactor pressure vessel steels to corrosion fatigue. Similarities between this system and NNpH SCC of pipeline steels proposed by Gabetta (1997). Eadie et al. (2005) proposed important role of S in NNpH SCC environments. Question is whether a similar threshold value exists for NNpH SCC.	Van Der Sluys and Emanuelson (1990)	
N043	Hydrogen threshold for HSC/HIC is 10 ppb. If correct, then many of the NNpH SCC studies based on a correlation between H content may, in fact, be related to HSC rather than NNpH SCC.	Yamaguchi et al. (1998)	N-0-7
N044	There should exist a potential threshold between NNpH SCC and HSC/HIC. And that threshold, the source of which is a threshold H content, will depend on the nature of the environment (e.g., pH, presence of H-recombination poisons, etc.)	Yamaguchi et al. (1998)	N-0-7
N045	Corrosion fatigue mechanism under severe loading conditions. $da/dN = C(\Delta K)^m$, for $R = 0.5$ and 0.82 at 40 cycles/day and $R = 0.9$ at 5000 cycles/day	Ahmed et al. (1997)	N-IV-4
N046	SCC mechanism in NS4 solution under less-severe loading conditions. e.g., for lower frequencies and/or higher R values than for N045.	Ahmed et al. (1997)	N-III-5
N047	H-related mechanism for NNpH SCC with important role for MnS inclusions. MnS acts as both a source for H (due to acidification of solution) and as a trap site.	Ahmed et al. (1997)	N-0-9, N-II-6
N048	Superposition model to account for NNpH SCC. Proposed equation of the from $\left.\frac{da}{dN}\right\|_{total} = \left.\frac{da}{dN}\right\|_{fatigue} + \left.\frac{da}{dt}\right\|_{scc} \cdot \frac{1}{f}$	Zhang et al. (1999)	N-III-4, N-III-5, N-IV-4
N049	NNpH SCC crack growth occurs under static load. Crack growth occurs under static load in NS4 solution at K_{MAX} of 34-38 $MPa{\cdot}m^{1/2}$	Zhang et al. (1999)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N050	In NNpH environments CF and TGSCC occur under different conditions of cyclic loading frequency and R value. Proposed boundary between CF and TGSCC regimes as a function of R and f  **FIGURE 9.** *Fracture map summarizing cyclic loading conditions for TGSCC and corrosion fatigue.*	Zhang et al. (1999)	N-III-4, N-III-5, N-IV-4
N051	Superposition model with addition of crack shading and coalescence accounts for crack growth in colony.	Lambert et al. (2000a)	
N052	Frequency-dependent CF model accounts for NNpH SCC growth. Of the form $\left(\frac{da}{dn}\right)_{total} = b f^{d} \Delta K_{eff}^{(ef+g)}$. Might account for growth rate of short (shallow) cracks	Williams et al. (2004)	N-III-4
N053	Periodic underloads lead to acceleration of crack growth. Possibly due to compaction or expulsion of corrosion products in crack, flattening of crack-face asperities, or refreshment of crack solution, resulting in larger ΔK_{eff} than before underload..	Williams et al. (2004)	N-III-2, N-IV-6

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N054	MnS inclusions act as sites for crack initiation. Possible roles include sites for blistering due to excessive H trapping or locals of damage due to local microplasticity at matrix/inclusion interface	Puigalli et al. (2002)	N-II-6
N055	NNpH SCC initiation results from alternating CP levels. Varying CP levels, between underprotection, protection, and/or overprotection result in crack initiation due to enhanced H ingress	Puigalli et al. (2002)	
N056	Lower pH solution lead to higher crack growth rate via H-related mechanism. Although lower pH solutions lead to higher corrosion rates, crack tip appears to be sharper than for less-corrosive solutions, possibly because of crack growth by H	Chen et al. (2008)	N-0-9
N057	Importance of crack closure effects on dormancy. Crack closure effects may result from corrosion or mechanical overload/underload, work hardening at crack-tip	Been et al. (2008a)	
N058	Synergistic effect between mechanical and environmental factors in NNpH SCC growth. Superposition model generally does not account for crack growth rates on gas lines, propose a frequency-dependent CF approach instead	Been et al. (2008a)	N-0-10, N-IV-4
N059	In poorly buffered systems, could get transition from NNpH to high-pH SCC conditions. At low CO_2 partial pressures, there may be insufficient H_2CO_3/HCO_3^- to maintain NNpH conditions and could get transition from H-related TGSCC to dissolution-based IGSCC	Colwell et al. (2008)	N-0-8
N060	Continuum of cracking mechanisms, with NNpH SCC at and around E_{CORR} and HSC/HIC at more-negative potentials. Evidence is a "local" peak in susceptibility (as measured by a decrease in time for crack initiation and an increase in cgr) at potentials around E_{CORR}. Initiation time faster and cgr faster at more-negative potentials, but this is likely a different H-related mechanism.	Lu and Luo (2008)	N-0-7, N-II-5
N061	Millscale promotes the reduction of H_2O and the generation of H. Based on cathodic kinetics on polished and millscale-covered electrodes.	Been et al. (2008b)	N-I-18
N062	Millscale increases the crack growth rate and maintains a sharp crack tip. Galvanic coupling to a millscale-covered surface enhances crack growth	Been et al. (2008b)	N-I-18
N063	Millscale affects the pickup of H. The presence of millscale blocks the absorption and lowers the effective diffusivity of H, but by less than the factor of ten effect that it has on the rate of H_2O reduction.	Been et al. (2008b)	N-I-18

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N064	Faster kinetics and crack growth rates in H_2O, as opposed to D_2O, solutions indicates the importance of hydrogen in NNpH SCC. Based on a combination of observations from electrochemical studies, corrosion rate measurements, SSRT, and cyclic crack growth measurements.	Been et al. (2008b)	N-0-9
N065	No crack initiation in MnS-free pipeline steels. Primary role of MnS inclusions in initiation of both NNpH SCC at or around E_{CORR} (due to dissolution and pit formation) and HIC at more-negative potentials (mechanism uncertain)	Delafosse et al. (2008)	N-II-6
N066	Presence of martensite increases susceptibility in SSRT. Martensite produced by water quenching exhibits greater susceptibility during SSRT in 0.01 mol/L $NaHCO_3$	Gonzalez-Rodriguez et al. (2002)	N-II-7
N067	Uniform microstructures, such as bainitic-ferrite or bainite, are less susceptible than non-uniform ferrite-pearlite microstructures. Tests in NS4 solution under cathodic polarization, so unclear whether cracking was due to NNpH SCC or HSC/HIC	Kushida et al. (2001)	N-I-16
N068	TGSCC can be obtained in the absence of CO_2 and carbonate species. TGSCC observed in pure sulphate solutions at pH 6.2 and pH 8	Szklarska-Smialowska et al. (1994)	
N069	TGSCC observed at (anodic) potentials at which H could not be involved. Contrary to suggestions of a H mechanism for TG cracking	Szklarska-Smialowska et al. (1994)	
N070	Crack path seems dependent on pH with TGSCC prevalent at lower pH. Possible evidence for a transition in crack path from TG to IG with increasing pH.	Szklarska-Smialowska et al. (1994)	N-0-8
N071	Microstructure affects susceptibility to SCC in NS4 solution. Susceptibility of X-70 steel increased according to: quenched (most) > normalized > Q+T > annealed (least), based on SSRT %RA. Corrosion rate follows same sequence, with quenched material exhibiting the highest corrosion rate	Bulger and Luo (2000)	
N072	Threshold stress for NNpH SCC initiation is approximately the actual yield stress. Based on studies under cathodic polarization, which may compromise their validity to NNpH SCC conditions.	Gu et al. (1999b)	N-II-1

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N073	Martensitic structure introduced by quench and tempering is more susceptible to crack initiation than either as-received or annealed conditions. Based on tests under cathodic polarization, so relevance to NNpH SCC conditions uncertain.	Gu et al. (1999b)	N-II-7
N074	Corrosion potential of millscale-covered surface is about 200 mV more-positive than that of polished surface. This has implications for all SCC studies on polished samples since the OCP at which they are performed is not representative of the E_{CORR} in the field.	Touzet et al. (1998)	N-I-18
N075	Dissolution promotes crack initiation. Based on evidence that greatest ductility loss occurred when CP was only applied in plastic range, ie, after dissolution at E_{CORR} had initiated cracks	Touzet et al. (1998)	
N076	Greater susceptibility to crack initiation of non-polished surface. Authors suggest this is due to localization of H entry, but this is unlikely at the E_{CORR} of a non-polished surface (-0.58 V_{SCE}) where a large effect was observed	Touzet et al. (1998)	N-I-18, N-II-5
N077	Crack loading conditions, for example the crack-tip strain rate, are more important than environmental considerations for circumferential NNpH SCC. This would suggest that NNpH SCC is possible in a wide range of environments, but only under certain loading conditions.	Gabetta et al. (2000, 2001)	
N078	Lab crack growth rates exceed the mean rates derived from the field because cracks in the field only grow for part of the time. For this to be the case based on the results of this study, field cracks would only grow for 0.1-1% of the time. Focus of this work seems to be circumferential SCC, where this criterion could be met (eg, periodic landslides).	Gabetta et al. (2000, 2001)	N-0-5
N079	Circumferential crack growth rates are a factor of 100-1000x faster than axial crack growth rates. This is an implication of the conclusions from this study, rather than an experimental observation.	Gabetta et al. (2000, 2001)	
N080	Mechanism of TGSCC for asphalt enamel coatings may be different than for tape coatings. Cathodic polarization can produce a form of TG HSC that has similar characteristics to NNpH SCC, i.e., quasi cleavage, TG crack growth, although no dissolution	Le Friant et al. (2000)	N-0-7

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N081	Primary role of MnS inclusions in NNpH SCC crack initiation. Crack initiation was observed to occur for a vintage X-65 but not a modern MnS-inclusion-free modern steel. At E_{CORR}, crack initiation occurs at pits created by the dissolution of MnS inclusions. Under cathodic polarization, H is trapped at MnS inclusion-matrix interface, precipitates as H_2 as creates voids (initiation sites) due to over-pressurization.	Le Friant et al. (2000)	N-II-6
N082	Small surface defects are capable of initiating NNpH SCC by local concentration of H. Crack initiation was observed for a cyclically loaded MnS-free modern steel at notch-like defects as small as 50 μm, which acted as sites for H accumulation. The authors introduce the concept of a "critical surface defect." Small notches can induce cracking in relatively mild environments.	Le Friant et al. (2000)	
N083	At E_{CORR}, NNpH SCC initiates at pits produced by the dissolution of MnS inclusions. Iniation was observed for high-S vintage X-52, but not for a modern alloy with non MnS inclusions. Under cathodic polarization, MnS inclusions initiate cracks by trapping H and creating voids at MnS-matrix interface by precipitating H_2.	Le Friant et al. (2000)	N-II-6
N084	NNpH SCC is the result of a H mechanism, but anodic dissolution is important as the source of H. Evidence for H based on nature of fracture surface (quasi-cleavage, inconsistent with dissolution), primary role of MnS as H trap sites, and formation of internal defects ahead of crack tip. Role of anodic dissolution is to generate H. Implies any process that leads to more absorbed H will promote cracking at E_{CORR}.	Le Friant et al. (2000)	N-0-9
N085	Mild cathodic polarization results in less cracking. Although cathodic polarization increases the rate of H production, the simultaneous suppression of anodic dissolution results in an increase in pH (due to less hydrolysis of dissolved Fe(II)). The increase in pH more than offsets any effect of the cathodic polarization and less H is produced than at E_{CORR}.	Le Friant et al. (2000)	N-0-1
N086	The local, as opposed to the bulk, hydrogen concentration is the important factor for crack initiation and growth. Clearly, crack initiation and growth is the result of locally high concentrations of H. Thus, SCC susceptibility may not be related to bulk concentration as much as factors that concentrate H.	Le Friant et al. (2000)	N-0-9

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N087	The absence of MnS inclusions can prevent NNpH SCC crack initiation. Cracks did not initiate at E_{CORR} in an inclusion-free steel. However, there may be other causes of crack initiation.	Le Friant et al. (2000)	N-II-6
N088	Dynamic strain is important for crack propagation, rather than a given stress level. This implies an effect of crack tip strain rate.	Le Friant et al. (2000)	N-0-3, N-III-3
N089	The susceptibility of steel to NNpH SCC can be ranked using a dynamic loading test with a notched sample whilst cycling the potential between E_{CORR} and -1.2 V_{SCE}. This test might be useful for ranking steels, but could also be used for assessing the effect of strain rate and potential.	Le Friant et al. (2000)	
N090	Periodic or episodic over-protection of asphalt coated lines can lead to TGSCC. Cracking due to over-protection can appear to be NNpH SCC.	Le Friant et al. (2000)	N-0-7
N091	Need to develop lifetime predictions models based on extrapolation of lab crack growth rate data. The difficulty of distinguishing H effects from dissolution makes the development of a mechanistic model difficult. At E_{CORR}, H and dissolution effects are certainly difficult to separate, but are they synergistic as suggested by the authors?	Parkins and Beavers (2003)	
N092	At realistic strain rates, dissolution alone cannot account for field crack growth rates. Even though rapid straining or scratched electrodes give higher dissolution currents than non-strained electrodes, extrapolation to field strain rates results in anodic dissolution rates significantly less than field crack growth rates.	Parkins and Beavers (2003)	N-0-9
N093	Current transients at pH 6.5 and 8.3 show evidence for film formation. Film formation could have two effects: (i) support a slip dissolution model, or (ii) impede H pick up.	Parkins and Beavers (2003)	
N094	Require continuous exposure to electrolyte for crack growth. Pre-exposed specimens show ductility similar to air when tested in air. Implies that cracking is not possibly if electrolyte is not present, with implications for possible seasonal effects.	Parkins and Beavers (2003)	N-0-5, N-0-9

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N095	Crack growth rate decreases with increasing exposure time. This observation is inconsistent with a stress-based mechanism and K will be increasing with crack depth. May be due to (i) work hardening of crack-tip region, (ii) changes in the crack chemistry which promotes blunting, and (iii) for smooth samples, an increase in the number of cracks, resulting in a decrease in crack-tip strain rate.	Parkins and Beavers (2003)	N-III-8
N096	Cracks initiate from pits, but not all pits initiate cracks. This observation implies some particular role for pits. If the role was solely to create a permissive environment for crack initiation, then all pits would initiate cracks. This implies some stress-related role (as well?). Again, how do observations on polished surfaces relate to millscale-covered pipe?	Parkins and Beavers (2003)	N-II-1
N097	Crack growth rate decrease with decreasing crack-tip strain rate. Furthermore, extrapolation to field-relevant strain rates gives a crack growth rate of 0.03-0.3 mm/yr, which is not that dissimilar from field observation. However, this effect of strain rate is not related to an effect on dissolution as the dissolution rate at these strain rates is too low to account for field CGR.	Parkins and Beavers (2003)	N-0-3, N-III-3
N098	Sub-surface H content increases with increasing cathodic polarization and decreasing pH. Sub-surface or diffusible H results in H-related damage. Total H concentration includes trapped H, which is irrelevant to present discussion. Cathodic polarization may be irrelevant if pipe surface is always at OCP. Effect of pH could be important in acidified pores, and also implies increasing H concentration with increasing p_{CO2}. Question is whether, at OCP and moderate plastic strain, the susceptibility to cracking is affected by the H concentration.	Parkins and Beavers (2003)	N-0-9
N099	Sub-surface H concentration is independent of alloy type. This implies that all steels are equally susceptible, if the mechanism is H-related. This observation may only apply to ferrite-pearlite steels. Is there evidence for a similar lack of sensitivity for other steels?	Parkins and Beavers (2003)	N-I-17

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

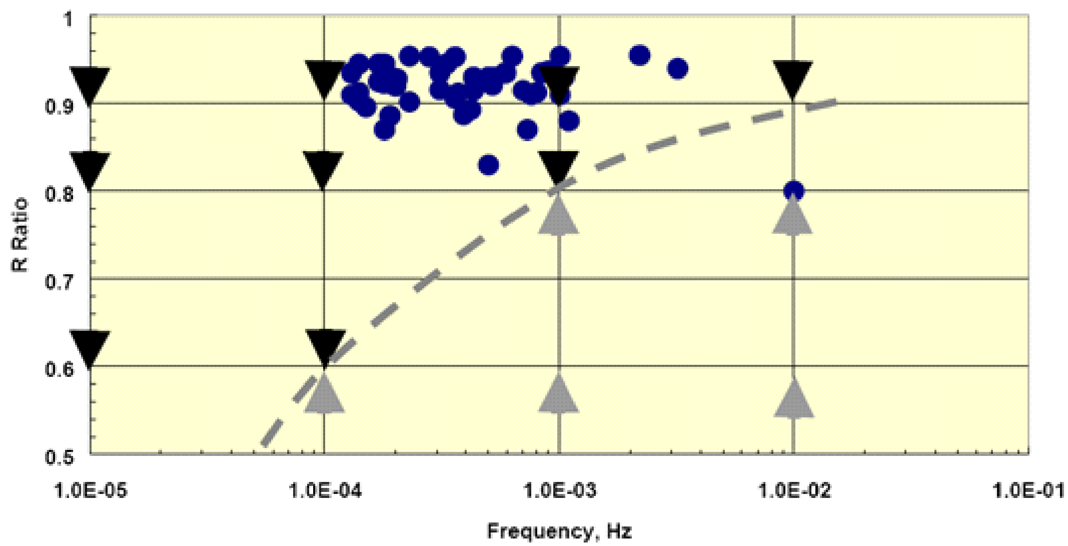
Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N100	Cracks decelerate at high R and/or low frequency Conditions for dormancy consistent with gas line loading  Figure 38. Summary of crack growth data, showing effects of R ratio and frequency on change in crack growth rate with time. Closed circles indicate operating conditions for gas transmission pipeline, taken from Figure 2.	Beavers and Jaske (2004)	N-III-8
N101	Threshold ΔK of ~10 $MPa \cdot m^{1/2}$ in NS4 solution. Provides comparison with field operating conditions to test whether dormancy would be expected.	Beavers and Jaske (2004)	

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Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N102	<u>Modified CF super-position model fits lab data</u>. Combination of corrosion fatigue and SCC can account for lab data with SCC rate of 0.1 mm/yr $\left.\frac{da}{dN}\right\|_{total} = \left.\frac{da}{dN}\right\|_{CF} + \left.\frac{da}{dt}\right\|_{SCC} \cdot \frac{1}{f}$ where $\left.\frac{da}{dN}\right\|_{CF} = 6.9 \times 10^{-8} (\Delta K)^{3.0}$	Beavers and Jaske (2004)	N-0-10, N-III-4, N-III-5, N-IV-4
N103	<u>Modified CF super-position model does not account for field observed rates</u>. When used in conjunction with cycles for gas transmission pipelines, modified super-position model underestimates field CGR. May indicate that short-crack growth is under-estimated by the modified super-position model which was developed nder conditions appropriate for long-crack growth.	Beavers and Jaske (2004)	N-0-10, N-III-4, N-III-5, N-IV-4
N104	<u>NS4 solution may be less aggressive than field electrolytes</u>. This is one explanation why lab-derived modified super-position model underestimates rates observed in field.	Beavers and Jaske (2004)	
N105	<u>For gas lines, specific events may be needed to avoid dormancy</u>. Such as: changes to electrolyte to sharpen tip, low R values or periodic underload/overload (to drive H to crack tip and induce cracking ahead of crack tip)	Beavers and Jaske (2004)	
N106	<u>On gas lines, majority of damage caused by a relatively few low-R cycles</u>. Vast majority of high-R cycles on gas lines do no damage (due to exponent on ΔK term).	Beavers and Jaske (2004)	N-0-10, N-IV-3
N107	<u>Relative contribution from CF will increase with decreasing R and increasing frequency</u>. Apparent from form of modified super-position model. Also apparent that CF more important for liquid lines.	Beavers and Jaske (2004)	N-0-10, N-IV-2, N-IV-4
N108	<u>(Mechanically) short cracks can grow at rates of up to 500x higher than long cracks due to an environmental enhancement</u>. Although this evidence comes from studies of the CF of HSS in 3% NaCl solution, it has implications for NNpH SCC of pipeline steels.	Gangloff (1985)	N-III-6
N109	<u>Short to long crack growth is characterized by a transition from IG to TG cracking</u>. In the case of HSS, a H mechanism has been proposed. Metallurgically, short cracks grow intergranularly, whereas long crack growth is characterized by brittle TG cracking.	Gangloff (1985)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N110	Environmental enhancement due to effects of cyclic loading on crack chemistry and promotion of H absorption for short cracks. Short cracks have high surface area:volume ratios. O_2 consumed on crack walls so that crack-tip pH is maintained low and promotes H^+ reduction and H absorption. In the case of HSS, acidification due to hydrolysis of Cr(III).	Gangloff (1985)	N-III-6
N112	Short cracks grow up to a factor of 10 faster than long cracks in sour environments. Results for X-65 pipeline steel and, although a sour environment, of some relevance to NNpH SCC. At a ΔK~9 MPa·m$^{1/2}$, transition from short to long cracks occurs at ~6 mm.	Holtam et al. (2010)	N-III-6
N113	Accelerated growth of short cracks likely due to environmental effect on H absorption at crack tip. Could be result of lower crack-tip pH for short cracks or, if bulk charging is most important, gradient of [H] across wall thickness.	Holtam et al. (2010)	N-III-6
N114	Crack initiation favoured on original pipe surface and at pits or regions of corrosion. Although original pipe surface was not compared with polished surface, more cracks initiated on external vs. internal surface. Cyclic load tests done under reasonable conditions of R, σ, and f.	Senigallia and Pontremoli (1999)	N-II-5
N115	NNpH SCC cracks can initiate under bonded tape coating. In one of three tests cracks initiated even though coating was still in place. Therefore, do not need exposure to large volume of solution	Senigallia and Pontremoli (1999)	N-II-8
N116	Crack initiation favoured at higher frequency. During cyclic loading, observed greater tendency for crack initiation at 10^{-4} Hz compared with 10^{-5} Hz. However, this could be a result of the higher number of cycles at the higher frequency (approx 1000 vs. 50 cycles).	Senigallia and Pontremoli (1999)	N-0-3, N-II-2
N117	Plastic strain required to accumulate H to cause NNpH SCC. The implication is that some form of localized plastic strain is required to cause crack growth to failure.	Fang et al. (2006)	N-III-1
N118	Higher crack growth rates with variable amplitude loading. Compared with constant R, higher CGR observed if range of R values used. Attributed to crack-tip film rupture during low-R cycles. Would, therefore, expect to see more cracking on a variable P line than on, say, a mainline or bullet line	Williams et al. (2003)	N-0-3, N-IV-5

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N119	Accumulation of corrosion product can reduce crack-tip opening displacement. Based on observation of crack growth rate lower than in air.	Williams et al. (2003)	N-III-8
N120	Dissolution of elongated MnS inclusions creates site for SCC initiation. Trench-like defect ideal for crack initiation sites	Kuniya et al. (1992)	N-II-6
N121	Probability of initiation depends on probability of MnS inclusion existing at surface. Which, in turn, is related to S content	Kuniya et al. (1992)	N-II-6
N122	Length of inclusions increases with increasing S content. With increasing S (0.016%S) content, tend to observe elongated inclusions, whereas low-S (0.004 %S) exhibits spherical inclusions.	Kuniya et al. (1992)	N-II-6
N123	Threshold ΔK of 10 MPa·m$^{1/2}$ for CF of pipeline steel in H_2S environments. Testing under severe conditions by injecting 100 ppm H_2S into crack. May be different CF mechanism than for NNpH SCC (ie., may involve slip dissolution and sulphidation)	Van Der Sluys et al. (1998)	
N124	Presence of sulphide accelerates NNpH SCC crack growth. Evidence suggests that presence of sulphide in crack or produced by SRB in the environment can accelerate crack growth in NNpH environments.	Van Der Sluys et al. (1998)	N-III-10, N-IV-11
N125	NNpH SCC growth observed at high R at very low frequency. Based on surface crack extension, crack growth reported at R of 0.95 with 1 cycle/week (2×10^{-6} Hz).	Van Der Sluys et al. (1998)	N-0-3
N126	Under high-frequency cyclic loading, cracks observed to initiate at inclusions. Because of high Frequency (1 Hz) and large amplitude (R = 0.4) of cyclic loading, question is whether this is a mechanical or chemical effect?	King et al. (2001)	N-II-6
N127	Aligned defects promote crack initiation. A line of aligned pits formed in the base of polishing lines on prepared surfaces lead to crack initiation (caused by apparent dissolution, even with ~100 mV cathodic polarization). Suggests these are high energy sites	King et al. (2001)	
N128	Cracks initiate at pre-existing defects on pipe surface. Pre-existing defects on pipe surface (often under millscale) observed to initiate pits, acting either as a stress raiser or to locally modify chemistry	King et al. (2001)	N-II-5
N129	Cyclic loading produces persistent slip bands which act as crack initiation sites. Under constant load, crack initiation observed on samples cyclically loaded to simulate 20 yrs service on gas line, but not on non-pretreated samples.	King et al. (2001)	N-0-3, N-II-2

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N130	Cracks initiate adjacent to, but still under, disbonded coating. Cracks are aligned along edge of disbonded coating, implying that disbondments aligned axially will result in cracks similarly aligned axially. Therefore, alignment of tape overlaps may be important.	King et al. (2001)	N-II-8
N131	Mechanically short cracks grow below K_{ISCC}. Evidence is that % of cracks growing in colony and surface extension rate are independent of maximum load.	Willmott and Sutherby (1998)	N-III-6
N132	K_{ISCC} for NNpH SCC is of the order of 9 $MPa \cdot m^{1/2}$. Based on estimated K_I for short cracks in field samples and observation of growth of 38% of cracks.	Willmott and Sutherby (1998)	
N133	For short cracks, there is no effect of load on the crack growth rate. Based on evidence of similar distribution of surface extension rates for field cracks at loads of 40, 70, and 100% SMYS.	Willmott and Sutherby (1998)	N-III-6
N134	Growth of short cracks is not due to a dissolution process. Based on observation that corrosion rate of solution was not related to CGR and cracks did not widen during tests.	Willmott and Sutherby (1998)	N-III-6
N135	Cracks in a colony grow at different rates due to effects of interactions. Based on observation that not all cracks in a given field colony grew during exposure to soil solution.	Willmott and Sutherby (1998)	
N136	Early-stage crack growth occurs primarily (64%) around periphery of colony. However, no difference in growth rates in centre and periphery of colony. Has implications for time dependence of disbondment. If disbondment continues to grow then cracks may stop growing in favour of new cracks around periphery.	Willmott et al. (1996)	
N137	Environmental conditions affect fraction of early-stage cracks that grow. Fraction of short cracks that grow increase with increasing bicarbonate and decreasing sulphate concentrations, but is independent of the Cl^- concentration and the potential (within a narrow range of E_{CORR} values). Bicarbonate may be important for pH buffering and inverse relationship with sulphate may indicate role of SRB and sulphide.	Willmott et al. (1996)	N-III-6, N-III-10

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N138	Early-stage crack growth is promoted by increasing bicarbonate concentration. As noted in N137, fraction of cracks growing increases with increasing [HCO_3^-], but average surface extension rate does not correlate. Could be related to pH buffering.	Willmott et al. (1996)	N-III-6
N139	Early-stage crack growth is promoted by presence of sulphide. Inferred from the inverse relationship of fraction of cracks growing with sulphate concentration and positive correlation with SRB MPN. However, no correlation between environmental parameters and mean surface extension rate.	Willmott et al. (1996)	N-III-6, N-III-10
N140	A large fraction of early-stage cracks could be re-started by exposure to simulated field conditions. In this study and in Willmott and Sutherby (1998), 16% and 38% of cracks could be induced to grow under relatively constant load. This is a much higher fraction than apparently continue to grow on pipelines.	Willmott et al. (1996)	
N141	Observed surface extension rate is of the same order as corrosion rate implying that a dissolution mechanism is possible.	Willmott et al. (1996)	
N142	Model organic compounds generally inhibit H permeation and lead to lower crack growth. However, also appear to lead to increased loss of ductility during SSRT, so effects are not entirely consistent.	Been et al. (2003)	N-0-9, N-III-11, N-IV-12
N143	pH is the primary factor determining C_H^0 and loss of ductility. pH of the solution is more important than p_{CO2} or other factors	Been et al. (2003)	N-0-4, N-III-1
N144	Sulphide increases absorbed H concentration and leads to loss of ductility. Question is whether loss of ductility in SSRT can be related to NNpH SCC	Been et al. (2003)	N-III-10
N145	Oxygen can lead to increased absorbed H and increased loss of ductility. Unclear as to the role of O_2	Been et al. (2003)	N-IV-11
N146	Rate of H permeation increases with elastic stresses above 80% SMYS. Increase in H permeation is due to increase in absorbed H concentration rather than increased diffusivity.	King et al. (2000)	N-0-9, N-III-1

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N147	Scratches or linear defects aligned perpendicular to loading direction increases probability of crack initiation. Based on %RA from SSRT.	He et al. (2000)	
N148	Stress concentration due to shape of weld crown is the major contributing factor to long seam weld NNpH SCC. SCF of 2.1-2.8 found for various DSAW welds (interestingly, only ERW weld studied had lower SCF of 1.2). Stress concentration under operating conditions more than overcomes compressive residual stress in weld toe to create net tensile stress greater than yield.	Eadie et al. (2002)	N-I-9
N149	Shot peening is an effective way to impact sufficient compressive stress to overcome stress concentrating effect of shape of weld crown.	Eadie et al. (2002)	
N150	Stress raisers can promote short crack growth. However, stress concentration factor lost quickly with growth of crack and, for weld crown and pit, little enhancement for cracks deeper than 1 mm	Been et al. (2004)	N-I-9
N151	Stress raisers more important for crack initiation than early stage crack growth. Conclusion based on relatively high SCF for surface stresses, but rapid decrease in stress intensification with crack depth.	Been et al. (2004)	N-I-9, N-II-1
N152	Threshold ΔK for dormancy/crack growth in range 12-15 $MPa \cdot m^{1/2}$. Based on data from strain rates of 10^{-4} to 0.005 Hz.	Been et al. (2006)	N-0-3
N153	20 mV cathodic polarization (to simulate effect of millscale) results in 2-5x higher CGR. Although the cathodic polarization was done ostensibly to simulate the apparent effect of millscale, could simulate any source of cathodic polarization, e.g., partial CP penetration.	Been et al. (2006)	N-I-18
N154	Dormant cracks can be reactivated by resumption of more-aggressive cyclic loading. Apparent that dormant cracks are just that, they are dormant rather than dead. Apparently relatively easy to reactivate cracks after as long as 4 days without growth.	Been et al. (2006)	N-III-9
N155	Crack growth is strongly dependent on strain rate. da/dN decreases but da/dt increases with increasing frequency.	Been et al. (2006)	N-0-3

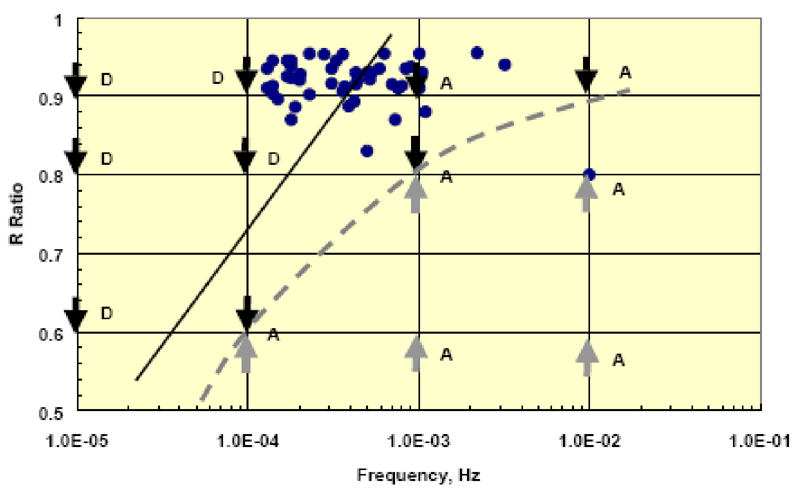
continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N156	NNpH SCC crack growth controlling process changes as crack grows. Three-regime "map' developed, with strain-rate control under mild loading conditions, CF model at intermediate loading conditions, and rapid cracking at high K_{MAX}	Been et al. (2006)	N-III-3, N-III-5
N157	Under mild loading conditions, a crack-tip strain rate model is appropriate. Based on poor fit of CF model to field data at low $K_{MAX}/\Delta K$, strain rate model deemed to be more appropriate, especially given observation of strain rate dependence of da/dt (da/dt = 0.0085·$\dot{\varepsilon}_{CT}$[illegible])	Been et al. (2006)	N-III-3, N-III-5
N158	CF model appropriate at intermediate K/ΔK. Transition from strain-rate to CF model at K_{MAX}-dependent ΔK. Above threshold $da/dN = 3.27 \times 10^{-8} \cdot \Delta K^{2.88} \cdot K_{MAX}^{0.42}$.	Been et al. (2006)	N-0-10, N-IV-4
N159	Rapid crack growth at high K_{MAX}. For deep cracks ($K_{MAX} > 82$ MPa·m$^{1/2}$), rapid crack growth independent of ΔK, given by $da/dN = 2.57 \times 10^{-4} \cdot K_{MAX}^{0.6}$	Been et al. (2006)	
N160	Dormant crack can be defined as one with a CGR of <0.06 mm/yr (2×10^{-9} mm/s). Based on either a rate predicted not to cause failure in a 50-year service life or a rate equal to the rate of general corrosion.	Beavers (2004)	
N161	CGR is correlated with crack-tip strain rate. However, because of variability in models used to predict $\dot{\varepsilon}_{CT}$, cannot use this correlation to predict CGR's on pipelines.	Beavers (2004)	N-III-3
N162	Use frequency and R ratio to rank tendency for cracks to become dormant. Can be done based on correlation in guideline N100, but this figure may be specific to crack geometry and the environment. See also N166	Beavers (2004)	N-III-8, N-III-9
N163	Unload-reload transients can increase the CGR and re-initiate dormant cracks. Occurred in majority of lab cases.	Beavers (2004)	N-III-2, N-III-9
N164	Overloads had no consistent effect on CGR or dormant cracks. Neither the occurrence nor the magnitude of overloads had a clear effect in the lab.	Beavers (2004)	
N165	Simulated hydrotests did not affect dormant cracks but slowed active cracks. Hydrotesting does not re-activate dormant cracks, but does slow actively growing cracks (due to introduction of compressive zone ahead of crack).	Beavers (2004)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N166	A critical crack-tip strain rate exists below which cracks go dormant. The value of the critical crack-tip strain rate is uncertain because of variability in models to predict $\dot{\varepsilon}_{CT}$, but it should correspond to the boundary established below between accelerating and decelerating cracks.  Figure 23. Figure 13 superimposed with the active/dormancy (A/D) predictions based strain rate calculated from Equation 11 and a critical crack tip strain rate of 9.6 × 10^{-6} sec^{-1}. Equation 11 is a $\dot{\varepsilon}_{CT}$ due to Scott and Truswell	Beavers (2004)	N-III-8, N-III-9
N167	Increasing p_{CO2} can re-activate dormant cracks. Mechanism not explained, but possibly due to decrease in pH and consequent increase in absorbed H concentration.	Beavers (2004)	N-III-9, N-III-10

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N168	No clear effect of O_2 on re-activation of dormant cracks. In tests, both addition of O_2 and reduction in p_{O2} lead to re-activation of dormant cracks.	Beavers (2004)	
N169	Results of SSRT and H permeation tests in soil extracts correlate with Marr soils model prediction. Implication is that Marr soils model has some basis in terms of the aggressive of the soil pore-water chemistry.	Jack et al. (1999)	
N170	During SSRT, crack initiation/growth occurs at loads/strains beyond yield point. Implies plastic deformation needed for crack initiation/growth.	Zheng et al. (1995)	N-II-1
N171	Modelling suggests that the crack-tip pH is one unit lower than that of the trapped electrolyte. Based on a reactive-transport model. Consistent with fact that, under NNpH SCC conditions, dissolved Fe will be in the Fe(II) state and there are no other strongly hydrolysable cations in the system.	Watson et al. (1996)	N-0-9
N172	Presence of specific species in crack can accelerate cracking. Addition of sulphide or $MgSO_4$ to crack accelerates cracking by up to 20x the rate in air. Effects could be associated with greater H absorption. Need effective transport mechanism into crack, but pK HS^-/H_2S is 7, so little HS^- present at pH 5. Therefore concentration of MnS inclusions may be important as increases probability of crack encountering inclusion.	Psaila-Dombrowski et al. (1997)	N-IV-11
N173	Organic component of organic/sand soil can inhibit aggressiveness of sand component. Extract from organic soil inhibits H permeation and results in greater SSRT ductility.	King et al. (2004a)	
N174	There is no single soil extract parameter that correlates with SCC susceptibility. Conclusion is that there is unlikely to be a single parameter that can be used to rank SCC sites.	King et al. (2004a)	N-I-2
N175	More-negative E_{CORR} (native potential) and redox potential is an indicator of higher susceptibility (as measured by SSRT and H-perm). Suggestion is that native potentials could be used as a measure of susceptibility. Consistent with observation of more-negative redox potentials at field SCC sites.	King et al. (2004a)	N-I-1

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N176	Modern, microalloyed, un-used steels were less susceptible than older, ferrite-pearlite steels from service. Cause of greater loss of ductility and higher C_H^0 for vintage steels is uncertain, but does correlate with more-negative E_{CORR} values. Possible causes: difference in microstructure, effect of microalloying constituents on E_{CORR}, absence of cyclic softening in un-used steels.	King et al. (2004a)	N-I-16
N177	Organics both promote and inhibit SCC and the net effect is determined by the depth of organics. Organics promote SCC by creating anaerobic conditions and negative native potentials, but one or more organic components act as inhibitors. If the pipe is fully surrounded by organics then the inhibiting effect dominates, but if the pipe is in sand or clay overlain by organics then SCC is possible because of the anaerobic conditions that this promotes.	King et al. (2004a)	N-I-1
N178	Site selection is best done based on an overall scenario, rather than based on a single parameter. This is consistent with the multivariate nature of the issue, as well as the fact that we cannot measure pipe surface conditions.	King et al. (2004a)	N-I-3
N179	In the field, NNpH SCC is associated with permanently anaerobic or cyclic aerobic/anaerobic conditions. For tape lines observe both permanently anaerobic and cyclic sites, whereas for asphalt-coated lines only cyclic sites. The latter could be associated with cyclic aerobic/anaerobic conditions or shielding.	King et al. (2004b)	N-0-5, N-0-7, N-I-1
N180	Temporal and spatial transitions seem to be important for NNpH SCC. Pipe-depth conditions shown to vary seasonal and around circumference of pipe.	King et al. (2004b)	N-0-5
N181	Due to temporal transitions, NNpH SCC might not be continuous. The discontinuous nature of cracking should be accounted for in crack growth models.	King et al. (2004b)	N-0-5
N182	Permeability of shielding coating to CO_2 could help maintain near-neutral pH conditions within the disbondment. CO_2 can diffuse through PE. This conclusion arises from modelling studies, the purpose of which was to explain the experimental observation that the application of CP leads to an increase in pH under shielding coatings. The problem is that, taken to its limit, this mechanism would end up generating a high-pH environment under a shielding coating.	Been et al. (2004)	
N183	Precipitation at the mouth of the disbondment can prevent CP penetration. $CaCO_3$ build up at the mouth of a disbondment can block CP penetration and maintain near-neutral pH conditions.	Been et al. (2004)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N184	Pre-exposure to microbially active soil increases the number of initiated cracks. Pre-exposure to nitrate- or sulphate-reducing conditions leads to ~3-fold increase in the number of secondary cracks compared with an abiotic control. Microbes may enhance initiation by preferentially colonizing surface scratches (thus creating linear defects suitable for initiation) or inclusions.	Jack et al. (2004)	
N185	Threshold soil resistivity for NNpH SCC. No ILI SCC indications for soils with soil resistivity >14,000 ohm cm. May be linked to availability of water to support electrochemical dissolution and H generation.	Van Boven et al. (2004)	N-I-4
N186	Threshold redox potential for NNpH SCC. No NNpH SCC ILI indications observed in soils with ORP of -0.32 to -0.68 V_{CSE}. These redox potentials represent the maximum value of the corrosion potential E_{CORR}. These redox potentials lie above (more positive) than the H_2 evolution equilibrium line.	Van Boven et al. (2004)	N-I-1
N187	NNpH SCC associated with a suite of soil properties and terrain characteristics. Higher probability of finding NNpH SCC: with level to gently sloping terrain, low soil resistivity, low redox potential, poor CP, poor drainage, organic over lacustrine soils (could be region-dependent)	Van Boven et al. (2004)	N-I-3
N188	Organics inhibit NNpH SCC crack growth. Based on results of cyclic crack growth studies, natural and model organics inhibit crack growth.	Been et al. (2004)	N-IV-12
N189	NNpH SCC trapped water exhibit lower sulphate concentration than in groundwater. Implies that SRB may have reduced sulphate to sulphide within disbondment.	Jack et al. (2000)	N-I-5
N190	NNpH SCC trapped water exhibit lower bicarbonate concentration than in groundwater. Consistent with microbial activity in disbonded region generating CO_2.	Jack et al. (2000)	N-I-5
N191	Little effect of heat treatment on susceptibility to NNpH SCC. Based on SSRT with X-70 in AR, Q, Q+T, and water-sprayed conditions.	Torres-Islas et al. (2008)	N-I-17

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N192	Cyclic loading at maximum stress >110% YS increases number and depth of micro-crack initiation events. The results of this study do not necessarily mean that cyclic loading enhances crack initiation, but if it does then it does so only at high maximum stress requiring the presence of a significant stress raiser (>1.5-2.0)	Chen et al. (2003)	N-II-1, N-II-2
N193	Cyclic loading promotes crack initiation by producing areas of local deformation. Emergent persistent slip bands create local deformation and promote crack initiation, possible due to localised plasticity or local stress concentration. Similar effect observed with polishing lines in this and other studies. No quantitative relationship between cyclic loading and crack initiation established	Wang et al. (2002)	N-II-2
N194	Slight cathodic polarization promotes crack initiation. Could be an artifact of the use of polished specimens in a relatively corrosive environment and the consequent need to prevent dissolution from removing local areas of deformation	Wang et al. (2002)	
N195	Crack initiation promoted by tensile residual stress. Cracks initiate in micropits that form in areas of tensile, but not compressive, residual stress. Optimum tensile residual stress range of 150-200 MPa for crack initiation.	Van Boven et al. (2007a)	N-II-3
N196	Evidence for crack blunting by dissolution and creep deformation at a specific depth at which rate of crack growth has slowed below dissolution rate because of decrease in residual stress. Speaks to competition between crack propagation and dissolution as opposing driving forces.	Van Boven et al. (2007a)	N-III-8, N-III-12
N197	Crack growth rate increases with level of tensile residual stress. Evidence from long-term cyclic load tests.	Van Boven et al. (2007a)	N-III-12
N198	Evidence for threshold residual stress of 150 MPa for crack growth. Evidence from short-term cyclic loading studies.	Van Boven et al. (2007a)	N-III-12
N199	High tensile stress gradient promotes crack initiation and prevents dormancy. High stress gradients provide large driving force for crack initiation and growth and stops crack slowing to the point that dissolution or creep can cause blunting.	Van Boven et al. (2007b)	N-III-8

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N200	Cyclic loading affects the magnitude and distribution of residual stress. Cyclic loading promotes room-temperature creep that can cause a reduction in both the magnitude and gradient of residual stress.	Van Boven et al. (2007b)	N-II-2, N-III-12
N201	Crack entering a zone of low tensile or compressive residual stress may become dormant. Residual stress can be re-distributed as crack grows causing reduction in tensile residual stress at crack tip	Van Boven et al. (2007b)	N-III-8
N202	High tensile residual stress gradient prevents crack dormancy. Large tensile stress gradient provides continuing mechanical driving force fro crack growth as crack deepens.	Van Boven et al. (2007b)	N-III-12
N203	Trapped water solution can be more acidic than the bulk solution in the presence of CP. Based on experimental observation using simulated disbondment and application of CP with and without CO_2 purge.	Fang et al. (2008)	
N204	Gradation of corrosion damage along disbondment due to potential gradient. Less corrosion near mouth, pitting at intermediate locations, and general corrosion furthest from mouth. Penetration of CP will depend on various factors, including: disbondment height, current density, conductivity of solution, physical/spatial restrictions.	Fang et al. (2008)	
N205	Under cyclic loading, pits in disbonded region nucleate cracks. Cracks initiate some distance away from disbondment mouth at location where pits nucleate. Initial surface condition of steel plate unknown.	Fang et al. (2008)	N-II-2
N206	Cyclic loading can induce a burst of room-temperature creep of pipeline steels. Creep burst could have significance for crack initiation and growth for both high-pH and NNpH SCC.	Chen et al. (2009)	N-0-3, N-I-20, N-II-2
N207	Aggressive soils exhibit a narrow range of pH as a function of CO_2 partial pressure. May indicate that highly buffered solutions are more aggressive. However, in this study aggressiveness was determined by TTF of SSRT, so question of what is being measured.	Chen et al. (2002)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N208	Maximum soil aggressiveness at pH 7.5. Based on comparison of behaviour of different soil extracts using TTF in SSRT as a measure of SCC susceptibility. Could be useful for assessing aggressiveness of different soils.	Chen et al. (2002)	
N209	Crack growth can occur during hydrotesting in solution but not if exposed to air. Helps explain pressure reversals during hydrotesting. Must be rapid crack growth for measurable crack extension to be observed in such a short period.	Chen and Sutherby (2006)	
N210	C2 solution causes more crack growth than NOVA trapped water. The C2 solution appears to be very aggressive and maintains a sharper crack than the NOVA trapped water.	Chen and Sutherby (2006)	N-I-7
N211	Diffusible H concentration is a factor of 3-10x lower than threshold for blistering of X-70 pipeline steel. Some question about whether the diffusible H concentration reported is in fc the total H concentration.	Chen et al. (2000)	
N212	More corrosive solution causes greater crack growth at low ΔK. HC4/C2 solution is more corrosive, but produces sharper crack tip with less corrosion. Possible role of H in maintaining sharp crack tip.	Chen and Sutherby (2004)	N-III-1
N213	Room temperature creep blunts crack tip. RT creep resulting in strains of up to several % will blunt NNpH SCC crack tip.	Chen and Sutherby (2004)	N-III-8
N214	Slower the CGR, greater the opportunity for crack-tip blunting by RT creep and dormancy. The longer the material is plastically deformed at the crack tip, the more opportunity there is for RT creep to blunt crack. Implies slower growing cracks will blunt and become dormant more readily.	Chen and Sutherby (2004)	N-III-8
N215	Less corrosive solutions increase probability of dormancy through crack-tip blunting. Crack tip may blunt either because slower crack allows more time for RT creep or less-corrosive solution produces less H to maintain sharp crack tip.	Chen and Sutherby (2004)	N-I-20
N216	Competition between blunting and sharpening at crack tip determines whether cracks with become dormant or continue to grow. Factors that promote blunting include RT creep and dissolution. Factors that promote sharpening include H-assisted dislocation movement and high diffusible H concentration.	Chen et al. (2009)	N-III-8
N217	Near-static loading promotes dormancy. Under these conditions, plenty of time for RT creep and absence of enhanced dislocation movement to sharpen crack.	Chen et al. (2009)	N-III-8

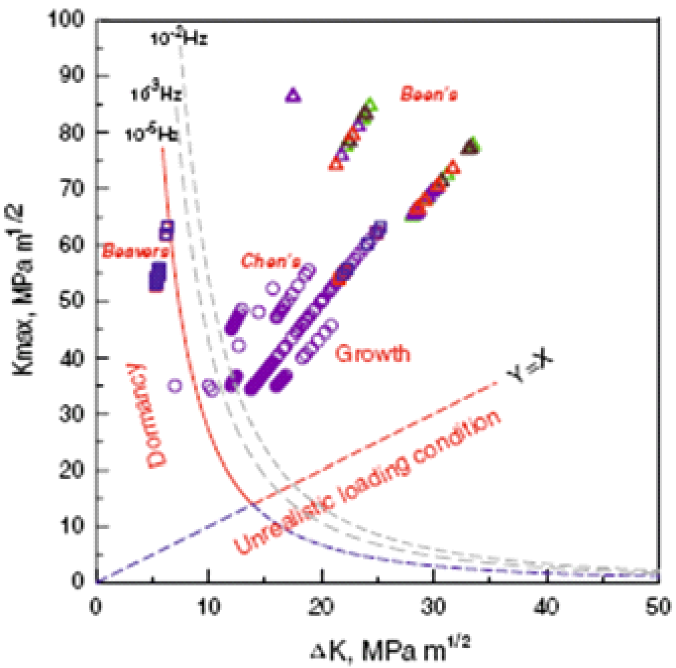
continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N218	Crack growth on gas lines occurs by repeated dormancy, crack growth cycles. As gas lines operate under nearly static loading conditions, cracks have a high tendency to become dormant, implying that crack growth is discontinuous.	Chen et al. (2009)	N-III-13
N219	Discontinuous nature of NNpH SCC crack growth implies CGR is much higher than time-averaged rate. If cracking only occurs 10% of the time, say, CGR during cracking must be 10x higher than field-observed time-averaged CGR.	Chen et al. (2009)	
N220	Hydrogen produced outside the crack is more important than internally produced H. H produced by general corrosion and CP is more important than H absorbed in crack, but argument presented does not consider various factors	Chen et al. (2009)	N-0-9
N221	Development of crack colony requires high residual stress. Residual stress purported to be important for short-crack growth.	Chen et al. (2009)	N-I-11, N-II-13, N-III-12
N222	Cracks initiate from pits. Cracks appeared to be wide, implying dissolution mechanism for initiation	Fang et al. (2009)	
N223	Probability of pit initiation increases with increasing pit depth:width. Due, presumably, to increasing stress concentration factor (SCF).	Fang et al. (2009)	
N224	Probability of pit initiation increases with increasing peak stress. Up to 106% SMYS, with concentrating effect of pit.	Fang et al. (2009)	
N225	Probability of pit initiation increases with decreasing R value.	Fang et al. (2009)	N-II-2
N226	Probability of pit initiation increases with increasing inclusion density. Presence of inclusions lead to more and deeper pits.	Fang et al. (2009)	N-II-6
N227	Probability of pit initiation decreased with increasing corrosivity of the solution. Corrosive environments removed pre-formed pits by general corrosion.	Fang et al. (2009)	
N228	NNpH SCC follows a corrosion fatigue mechanism. Correlation developed that involves K_{MAX}, ΔK, and f ($da/dN = f(\Delta K^2 K_{MAX}/f^{0.1})$).	Chen and Sutherby (2007)	N-0-10
N229	Crack growth rate decreases with increasing pH. Consistent with both a H and dissolution mechanism.	Chen and Sutherby (2007)	N-III-1

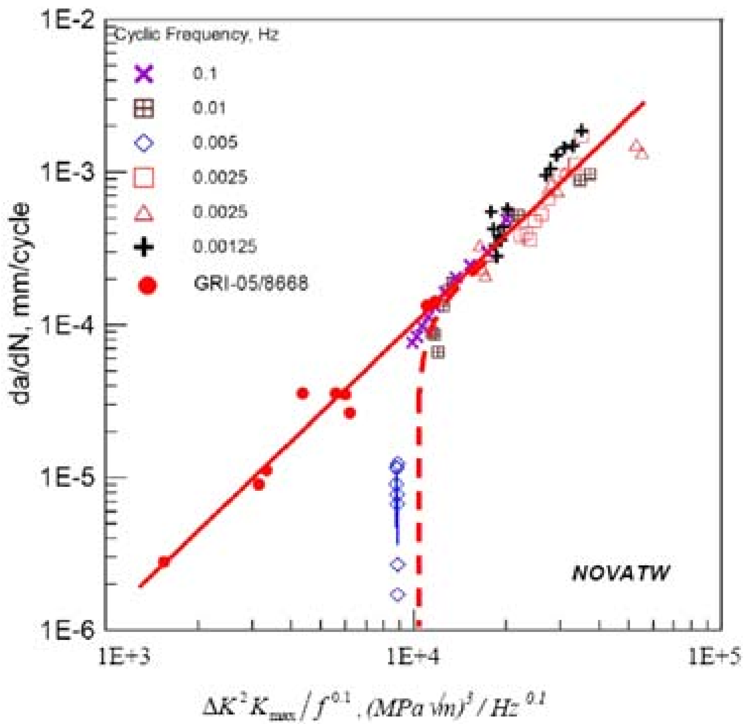
continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N230	Frequency-dependent envelope for crack dormancy. 	Chen and Sutherby (2007)	N-III-8
N231	Threshold $\Delta K^2 K_{MAX}/f^{0.1}$ value of 8500 $(MPa\cdot\sqrt{m})^3/Hz^{0.1}$. Threshold value may be environment and material dependent. May also only apply to CT specimens, as cracks on full-scale pipe continue to grow below threshold (see N232).	Chen and Sutherby (2007)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N232	<u>Short cracks on full-scale pipe grow below threshold for CT specimens</u>.  Implication is that short cracks on full-scale pipes are subject to a different (and more realistic) type of loading than CT specimens. There may be no threshold for cracks on pipe.	Chen et al. (2008)	
N233	<u>H has the effect of maintaining a sharp crack</u>. Transport of H to crack tip creates locally high [H] and induces HIC which continuously creates a sharp crack at the crack tip.	Chen et al. (2009)	N-0-9

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N234	Most important source of H is the external surface. H from corrosion of surface or CP is more important than H produced in the crack.	Chen et al. (2009)	N-0-9
N235	Crack sharpening by H from corrosive solution overcomes crack blunting effect of dissolution. Implies that CGR should increase with corrosivity of solution, not because crack growth is due to dissolution but because of increased H.	Chen et al. (2009)	N-III-8
N236	Crack dormancy can result from the crack tip "outrunning" the source of H. If the external surface is the most important source of H, then as the crack deepens the crack can become dormant because the flux of H decreases.	Chen et al. (2009)	N-III-8
N237	Dormant cracks can be re-activated by an increase in H flux. This would imply that increased CP would re-activate crack. Also an increase in corrosivity, perhaps due to seasonally increase in CO_2 production, would re-activate crack.	Chen et al. (2009)	N-III-9
N238	Crack initiation enhanced by cyclic loading.	Wang et al. (2000)	N-II-2
N239	Rocks in dents can shield CP. Possible increased probability of NNpH SCC due to dents, rather than high-pH SCC	Brongers and Beavers (2005)	N-I-12
N240	Dent acts as a stress concentrator and a source of residual stress.	Brongers and Beavers (2005)	N-I-12
N241	NNpH crack growth rate increases with increasing CO_2. Cyclic crack growth rate increases with p_{CO2}, as does E_{CORR}, i_{CORR}, and rate of H permeation, although data may only indicate that presence of CO_2 is necessary to increase CGR	Johnson et al. (2000)	N-0-4
N242	No effect of O_2 partial pressure on CGR. No apparent effect of O_2. Therefore, any increased susceptibility at cyclic sites is not due to periodic increase in p_{O2}.	Johnson et al. (2000)	
N243	Crack growth rate decreases with increasing R value. Result from early cyclic loading studies with CT specimens.	Beavers et al. (1998)	
N244	Crack growth rate increases with decreasing solution corrosivity. Cyclic CGR observed to increase with decreasing i_{CORR} and E_{CORR}. Implies less-corrosive soils maintain sharp crack.	Beavers et al. (2001)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N245	No correlation between soils model ranking and crack growth rate. The lack of correlation is perhaps not surprising since site selection encompasses many aspects of overall cracking process.	Beavers et al. (2001)	
N246	No correlation between microbial population and H perm or crack growth. This does not necessarily mean absence of microbial effects since microbial population is known not to correlate with corrosion. It is microbial activity that is important.	Beavers et al. (2001)	
N247	Presence of soil in soil electrolyte reproducibly creates peak in H permeation curve. The peak in H permeation curves is due to damage to steel by microcracking or blistering under severe H loading conditions. Fact that this only occurs in presence of soil "teabag" may indicate a role of bacteria (SRB).	Beavers et al. (2001)	N-I-5
N248	Organics over clay soil solution gave by far the highest CGR. There is no explanation for this observation, but it is consistent with observations from SSRT.	Beavers et al. (2001)	
N249	Effect of environment on late-stage crack growth. Testing was done at K_{MAX} for a near-critical flaw at MAOP, i.e., for a very deep crack. Nevertheless, the observed CGR varied by a factor of ~10 over the 8 soils tested, with one soil exhibiting no crack growth.	Beavers et al. (2001)	
N250	Strong correlation between SCC colonies and increasing residual stress. Surface residual stress near zero, and increases with depth up to 2 mm (no measurements at deeper depths)	Beavers et al. (2000)	N-I-11, N-III-12
N251	No evidence for decrease in residual stress at depths up to 2 mm. This observation is not consistent with suggestion that cracks become dormant because of decrease in residual stress.	Beavers et al. (2000)	N-III-12
N252	SCC colonies associated with mean maximum sub-surface (0-2 mm) residual stress of 220 MPa. Maximum residual stress corresponds to plateau value observed at depths between ~1-2 mm.	Beavers et al. (2000)	N-I-11, N-III-12
N253	No SCC colonies associated with mean maximum sub-surface (0-2 mm) residual stress of 100 MPa. Maximum residual stress corresponds to plateau value observed at depths between ~1-2 mm.	Beavers et al. (2000)	N-I-11

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N254	Increased microhardness levels show weak correlation with SCC colonies. Evidence for some correlation between increasing microhardness and SCC colonies, but correlation is weak.	Beavers et al. (2000)	
N255	Rougher surfaces associated with SCC colonies. Increased probability of finding SCC colonies in rougher areas. Roughness may lead to stress concentration.	Beavers et al. (2000)	
N256	No correlation between number, area, or type of inclusions and SCC colonies. This field evidence is in contrast to that from R&D studies on polished surfaces which show an overwhelming influence of inclusions on crack initiation. This difference may be due to importance of millscale on real pipe.	Beavers et al. (2000)	N-I-17, N-II-6
N257	No correlation between cyclic stress-strain behaviour and location of SCC colonies. It has been suggested that cyclic creep may induce crack initiation, but this study shows no evidence in support.	Beavers et al. (2000)	N-I-17
N258	No correlation between steel composition and SCC colonies. Detailed statistical analysis not performed, but no obvious dependence of occurrence of SCC colonies and steel composition	Beavers et al. (2000)	N-I-17
N259	No correlation between local galvanic activity and SCC colonies. No evidence for location of SCC colonies in local anodic or cathodic areas.	Beavers et al. (2000)	N-I-17
N260	Overloads inhibit subsequent crack growth. Compressive residual stress induced in plastic zone slows subsequent crack growth, as in hydrostest.	Beavers and Jaske (1998)	N-IV-8
N261	Underload/reload leads to increase in crack growth rate. This may be significant for gas pipelines that tend to operate at constant load, with occasional underloads.	Beavers and Jaske (1998)	N-0-3, N-I-13, N-IV-7
N262	Crack growth occurs during the loading part of the cycle. May have consequences for rate of unload/reload. For example, since CGR increases with strain rate and since cracking occurs on loading part of cycle, fast loading is worse than slow loading (see N263).	Beavers and Jaske (1998)	N-0-3, N-I-13, N-IV-9
N263	Fast loading/slow unloading cycle creates more damage than slow loading/fast unloading. It is not just the frequency of the cycle that is important, but more specifically the rate of loading (see N262).	Beavers and Jaske (1998)	N-0-3, N-I-13, N-IV-9

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N264	ERW welds exhibit high crack growth rates and poor fracture resistance. Susceptibility of ERW not only due to low fracture toughness.	Harle et al. (1995)	N-I-19
N265	Coarse-grained HAZ exhibits higher crack growth rates than base metal. May be associated with preferential microstructure comprising ferrite outlining large prior austenite grains.	Harle et al. (1995)	
N266	Magnitude of pressure fluctuations required to support cracking decreases with increasing stress. Pressure fluctuations are required to cause cracking at stress levels close to nominal operating stress, but only minor fluctuations are necessary at loads close to yield stress	Zheng et al. (2000)	N-0-3
N267	At loads close to yield stress, low-temperature creep may provide sufficient plastic strain to support cracking. In this case, creep is detrimental and supports crack growth, compared with the beneficial effect proposed by others to account fro crack-tip blunting.	Zheng et al. (2000)	N-I-20
N268	Net total stress can exceed nominal operating stress due to residual stress and stress raisers. Thus, pipe operating at, say, 80% SMYS could be close to yield due to residual stress and stress concentrator.	Zheng et al. (2000)	N-I-14
N269	No crack growth under constant or near-constant load. No crack growth observed on full-scale pipe for R = 1.0 or 0.97 at load equivalent to 80% YS (ie, 97% SMYS)	Zheng et al. (1997)	N-0-3
N270	Multiple initiation sites for NNpH SCC including surface geometrical discontinuities (pits) and features introduced by cyclic loading. Pits often associated with dislocations and are favoured initiation sites. Cracks associated with non-geometrical features initiate later.	Wang et al. (1998)	N-II-2
N271	Cracks of a given size exhibit a wide range of growth rates. Crack growth rates fit a Weibull distribution.	Wang et al. (1998)	N-0-11
N272	Stress range is more important than maximum stress for crack initiation. Low R cycles more detrimental than high stress.	Wang et al. (1998)	N-II-2
N273	Cyclic loading can promote crack initiation by slip dissolution mechanism. Basic mechanism for role of cyclic loading in crack initiation.	Wang et al. (1998)	N-II-2

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N274	Cracks can be arrested by 100 mV cathodic polarization. All cracks were arrested by 100 mV polarization, but a number of cracks were re-activated at 200 mV cathodic polarisation. Could this represent a "sweet spot" of cathodic protection? No clear explanation for effect of mild CP provided.	Zheng et al. (1996)	
N275	Direct admittance of CO_2 increases crack growth rate. Evidence that CO_2 near crack mouth can accelerate cracking. Mechanism unclear.	Zheng et al. (1996)	N-0-4
N276	Dormancy induced by mid-wall hard pearlite. Microstructural cause of dormancy, lower strain in harder mid-wall pearlite. Would suggest that banded structure should be less susceptible.	Zheng et al. (1996)	N-III-8
N277	Evidence for K_{ISCC} of ~37 MPa√m at R = 0.6 in soil box.	Zheng et al. (1996)	
N278	Original pipe surface more susceptible to initiation than polished surface. On original surface, cracks tended to initiate in depressed areas or valleys	Wang et al. (1999)	N-II-5
N279	Optimum conditions for early-stage growth is low R and corrosive environment. Early-stage crack growth is a balance between the mechanical loading conditions and corrosion. Under aggressive loading cracks can benefit from enhanced growth in corrosive environment (be it from H or dissolution) without being removed by general corrosion.	Wang et al. (1999)	N-III-1
N280	Dormancy or elimination of early-stage cracks occurs at high R. Under mild loading conditions, cracks may become dormant and even be removed by dissolution.	Wang et al. (1999)	N-III-8
N281	Mild CP (100 mV) accelerates growth of large cracks. Must be due to effect of H as dissolution rate would be suppressed. Deep cracks more under influence of cyclic loading, so greater concentration of H at crack tip	Wang et al. (1999)	
N282	Mild CP (100 mV) decelerates small cracks compared with rate at OCP. Small cracks would not be mechanically driven, so lower CGR under mild CP suggests a dissolution mechanism.	Wang et al. (1999)	
N283	Earliest stage growth is dissolution controlled, with switch to H mechanism as crack deepens/lengthens. Based on evidence from N281, N282 above. Switch from dissolution to H mechanism corresponds to point at which individual cracks coalesce.	Wang et al. (1999)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N284	Dynamic crack-tip strain required for crack growth. Based on results from full-scale testing with NPS20 pipe in soil box.	Zheng et al. (1996)	N-0-3
N285	Evidence for K_{ISCC} of ~27 MPa√m at R = 0.5 in soil box.	Zheng et al. (1996)	
N286	Cathodic polarization slows crack growth except in susceptible ERW weld. This seems to be in contradiction of N274 by the same authors	Zheng et al. (1998)	N-I-19
N287	Anodic polarization inhibits crack growth in ERW. Mild polarization by 100 mV slows crack growth, presumably due to lower [H]. Possible option to anodically protect from NNpH SCC.	Zheng et al. (1998)	
N288	Primary role of CO_2 is to maintain pH in cracking range. Tests performed with or without CO_2.	Zheng et al. (1998)	N-0-4
N289	Crack growth observed for R values of 0.9 or lower. This could possibly serve as a threshold for crack growth and a target for pipeline operators.	Zheng et al. (1998)	N-0-3
N290	Crack growth rate related to $K\cdot\Delta K/\Delta t$. Relationship between log (da/dt) and log ($K\cdot\Delta K/\Delta t$), where $\Delta K/\Delta t$ is rate of increase in K during loading part of cycle. same amount of crack growth for slow P fluctuation ($\Delta K/\Delta t$) at high load (K) as a fast P fluctuation at low load.	Zheng et al. (1998)	
N291	Trapped H plays no role in loss of ductility. H pre-charged specimens tested in air showed same ductility as non-pre-charged specimens. Therefore, trap density cannot be used to rank susceptibility of steels, even though it varies from steel-to-steel and is a measure of dislocation density.	Parkins and Delanty (1999)	N-0-9
N292	H pre-charged or H-non-pre-charged specimens show loss of ductility when strained in solution. Implies that active charging is required for loss of ductility. Since diffusivity of H in steel is high, may imply that diffusible H is responsible for loss of ductility. Would be consistent with behaviour of other materials.	Parkins and Delanty (1999)	
N293	Hydrogen entry is enhanced by CO_2. H concentration increases with increasing CO_2 partial pressure, but not necessarily related to crack growth rate	Parkins and Delanty (1999)	N-0-4

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N294	No evidence for H enhanced plasticity. Suggests that mechanism does not involve H enhanced localised plasticity (HELP)	Parkins and Delanty (1999)	N-0-9
N295	Increasing sub-surface H concentration leads to increasing loss of ductility. As determined by SSRT – may simply indicate the effect of H on the ductility under plastic deformation, which is of limited relevance to the behaviour of pipeline steels under realistic loading conditions.	Parkins and Delanty (1999)	N-0-9
N296	NNpH SCC mechanism involves a synergistic effect of H and dissolution. Parkins unable to identify mechanism since both H and dissolution are involved at E_{CORR}. Seems, in this work at least, to have excluded HELP mechanism, although mentions this mechanism elsewhere.	Parkins and Delanty (1999)	
N297	Many small cracks initiate from pits but then grow laterally and transform into pits. This represents a stage even before the initiation of identifiable crack-like features, of which most will then become dormant.	Parkins and Delanty (1996)	
N298	Because of stochastic nature of pitting and crack growth, NNpH SCC lifetime prediction should be treated stochastically. Implication is that a definitive CGR is neither achievable nor an appropriate description of the system.	Parkins and Delanty (1996)	N-0-11
N299	Small cracks can become dormant at interface of pearlite bands. Harder pearlite will not exhibit same degree of strain as softer ferrite grains, thus promoting dormancy of small cracks. Implies that heavily banded steels should be less susceptible.	Parkins and Delanty (1996)	N-III-8
N300	Variability of operating pressure fluctuations more damaging than regular fluctuations. Pressure fluctuations on operating pipelines comprise an apparently random series of random magnitude (within limits) fluctuations of random (within limits) strain rates. This randomness may result in greater damage as crack-closure events will be prevented by removal of corrosion product, etc.	Parkins and Delanty (1996)	N-0-3
N301	pH associated with NNpH SCC in field is inconsistent with significant CP reaching the pipe. This is a crucial observation and interpretation of field observations. Means that cracking involves freely corroding conditions, which immediately rules out an HIC mechanism.	Parkins (1992)	N-I-6

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N302	Presence of CO_2 reduces SSRT failure times. Early evidence of important role of CO_2 in mechanism.	Parkins (1992)	N-0-4
N303	SSRT %RA is not temperature dependent between 5 and 45°C. Precludes effect of T accounting for distance dependence from C/S	Parkins (1992)	N-0-2
N304	Cracks form in bands, presumably inducing initiation of subsequent cracks. Presence of cracks in bands implies that existing cracks influence where crack initation occurs. Growth of crack into newly initiated crack then drives coalescence and surface crack extension.	Parkins (1992)	N-II-4
N305	Cracks coalesce early in life. Important consideration, but contrary to evidence from other studies, since it implies that surface crack length is established early on in lifetime of crack.	Parkins (1992)	
N306	Growth during late-stage cracking is mainly in depth direction. Important implications for predicting crack growth. Implies aspect ratio (length/depth) decreases with time.	Parkins (1992)	
N307	Considerable scatter in both lab data and field observations. Any prediction of NNpH SCC behaviour should, therefore, be done statistically	Parkins (1992)	N-0-11
N308	Coalescence rule for cracks $y < 0.14 \cdot (2a)$. Applies to both field cracks and smaller cracks observed in lab. Similarly also to rules for high-pH SCC (check). Universality implies this is a mechanics-based rule.	Parkins (1992)	N-III-15
N309	Modern FBE, urethane, and liquid epoxy coatings appear to significantly lower, if not eliminate, probability of NNpH SCC. Based on field observations more than lab studies	Parkins (1999)	N-I-8
N310	Improved performance of modern coatings related to surface preparation procedures. Refers to removal of millscale and surface roughness and imposition of compressive surface residual stress by shot blasting pipe surface prior to coating.	Parkins (1999)	N-I-8

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N311	Uncertain whether new multilayer coatings will support NNpH SCC. Such coatings may exhibit apparently beneficial effects of FBE and/or the surface prep required to apply FBE or the detrimental effects of tape coating	Parkins (1999)	
N312	Do Cl^- and SO_4^{2-} play an active role in NNpH SCC? Cracking can be obtained in pure water purged with CO_2, yet all trapped waters contain Cl^- and sulphate.	Parkins (1999)	
N313	Crack initiation is not random, but is directed. Cracks often initiate just ahead of existing crack tips, or around periphery of un-corroded area with pit in centre, or adjacent to tape coating.	Parkins (1999)	N-II-4
N314	Dormant cracks can be reactivated if they coalesce with growing crack.	Parkins (1999)	N-III-9
N315	Static load near yield stress is insufficient to initiate cracks. Pipelines operating near constant load should not experience crack initation	Parkins (1999)	N-0-3, N-II-2
N316	Cyclic load necessary for NNpH SCC crack initiation. Initiation increases with decreasing R value.	Parkins (1999)	N-II-2
N317	Crack grows during hydrotest, but is subsequently slowed due to compressive residual stress. Overall, hydrotests are beneficial as additional crack growth during test is more than offset by subsequent reduction in CGR following return to service.	Parkins (1999)	
N318	HAZ of ERW is particularly susceptible to NNpH SCC.	Parkins (1999)	N-I-19
N319	Role of H probably involves decohesion but some evidence for HELP. H-assisted RT creep may enhance crack growth.	Parkins (1999)	N-0-9
N320	Based on SSRT data, no evidence that SRB are necessary for, or enhance, NNpH SCC. Preliminary study, careful about over-interpreting.	Davis and Parkins (1992)	
N321	Bending stress more important for crack on shoulder on an unconstrained dent than the hoop stress. Implies cracks associated with dents will grow in non-axial orientations	Brongers et al. (2009)	N-I-12
N322	Hydrotest procedure will not necessarily slow the subsequent growth of cracks in a dent. Based on CTOD observations of effect of simulation hydrotest on growth in air of crack on shoulder of unconstrained dent.	Brongers et al. (2009)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N323	Primary coating factors affecting SCC susceptibility are resistance to disbondment and the ability to pass CP. On the other hand, grit blasting, as tested, did not consistently show benefit	Beavers (1992)	N-I-8
N324	FBE more-resistant to high-pH SCC than CTE, with PE being the least resistant. Ranking based on disbondment characteristics and CP permeability.	Beavers (1992)	
N325	CTE on millscale-covered surface more resistant to disbondment than FBE. Implication is that field-applied CTE may be more-resistant to disbondment, and SCC, than FBE	Beavers (1992)	
N326	For shielding coatings, bare area adjacent to disbondment prevents any protection under disbondment. Thus, for PE ctg, a bare area will be preferentially polarised with no CP reaching disbondment. However, bare area has less effect of distribution of current for CTE which is generally permeable.	Beavers (1992)	
N327	Inadequate grit blasting can lead to no improvement in SCC resistance. Appear to require a white surface finish, rather than near-white, to ensure sufficient grit blasting to prevent SCC. Older FBE lines may have been inadequately blasted.	Beavers (1992)	N-I-8
N328	Cracks in dense crack patches tend to become dormant because of shielding by neighbouring cracks. Dense patches defined as those with a crack spacing of <20% of the wall thickness)	Leis and Colwell (1997)	N-III-8
N329	Cracks in sparse crack patches can continue to grow unhindered by shielding. A crack patch is not the same as a crack colony, the latter being more defined by the shape and size of the disbondment.	Leis and Colwell (1997)	N-III-14, N-IV-10
N330	Complex 3-D interaction of stress within a crack patch with the crack-tip stress increasing, decreasing, or remaining constant with increasing depth under various circumstances.	Leis and Colwell (1997)	
N331	High-pH and NNpH SCC cracks show similar characteristics in terms of crack size, spacing, and shape	Leis and Colwell (1997)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (continued)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N332	CP does not penetrate under simulated PE tape disbondment. One of the few studies in which there is limited penetration of CP into simulated tape disbondment. Expt performed in soil box, so possibly pressure of soil collapsed disbondment or the observed $CaCO_3$ precipitate at the mouth of the disbondment blocked the entry of CP	Been et al. (2005)	N-I-6
N333	TECTRAN simulations suggest that CO_2 permeation through PE coating is required to maintain a near-neutral pH environment. Question is why you do not then end up with a concentration HCO_3^- electrolyte? However, CO_2 permeability of coating could be a selection criterion for NNpH SCC	Been et al. (2005)	
N334	Trapped electrolyte is more concentrated where no NNpH SCC is found compared with sites where cracking is observed. Implies that CP penetrates and protects the pipe from cracking.	Beavers and Worthingham (2002)	N-I-6
N335	Trapped electrolyte pH at NNpH SCC sites is higher where no cracking is found. Implies that CP has penetrated and prevented cracking either because of increase in pH or by polarization of the pipe.	Beavers and Worthingham (2002)	N-I-6
N336	90% of pressure cycles for gas transmission pipelines had an R value ≥0.90.	Sutherby et al. (2000)	
N337	Liquid pipelines exhibited more variable R values, with 10% of cycles characterized by an R value <0.7.	Sutherby et al. (2000)	
N338	There is a wide variation in hoop strain rates between different facilities, with values from 10^{-11} to 10^{-6} s^{-1}, with most at 10^{-9} s^{-1} or lower.	Sutherby et al. (2000)	
N339	Smaller diameter liquid laterals have a higher frequency of more damaging pressure cycles.	Van Boven et al. (2002)	
N340	The most damaging cycles are located close to the discharge of the compressor or pump station	Van Boven et al. (2002)	
N341	Locations closer to the suction side have increased number of pressure cycles due to forward and backward propagating waves.	Van Boven et al. (2002)	
N342	Although the frequency of pressure cycles is greater the R ratio and, of course, the maximum stress are lower.	Van Boven et al. (2002)	

continued ….

Table B.2: R&D Guidelines – Near-neutral pH SCC (concluded)

Ref no.	R&D Guideline	Reference	Associated SCC Guideline
N343	There are significant difference in the characteristics of pressure fluctuations for gas and liquid pipelines.	Van Boven et al. (2002)	
N344	High-pH and NNpH SCC environments are reversible and could occur in the same location. Reversibility of the environments could be driven by seasonal variations, particularly temperature.	Castaneda et al. (2008)	N-0-8
N345	Aspect ratio tends to decrease with increasing depth for both high-pH and NNpH SCC for cracks away from the failure but show no clear trend with depth for cracks that lead to failure.	Castaneda et al. (2008)	
N346	Hydrogen plays a significant role in NNpH SCC, but the mechanism has not been identified.	Castaneda et al. (2008)	N-0-9
N347	In a correlative site-selection model for a single pipeline, three parameters were found to be key predictors of NNpH SCC: pipe manufacturer, coating type, and soil type. • >4 times more likely to find SCC in glaciofluvial soil than in lacustrine soil • >3 times more likely to find SCC under asphalt coating compared with other coatings (CTE, epoxy urethane, FBE, tape, wax) • >18 times more likely for pipe from manufacturer G to exhibit SCC than pipe from manufacturers A, B, or C	Beavers and Harper (2004)	
N348	Susceptibility to NNpH SCC increases with decreasing O_2 concentration.	Liu et al. (2010)	
N349	Dissolution of millscale can lead to axially aligned corrosion pits or trenches which act as ideal crack initiation sites	Qin et al. (2004)	N-II-5
N350	Millscale is electrochemically active and participates in the crack initiation and growth process. Although there is no evidence in support or contrary, millscale may exhibit varying electrochemical activity resulting in varying susceptibility.	Qin et al. (2004)	N-II-5

APPENDIX C: FIELD DATA AND ANALYSES

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Page

C.1 INTRODUCTION

A component of the current study is the validation of the SCC guidelines derived from the R&D literature against field data from operating pipeline systems. This validation exercise is necessary in order to test the ability of the guidelines to predict where, when, and how fast SCC may occur on operating pipelines and, hence, to provide confidence in their use.

Different types of field data are required for the validation process. In some cases, data from various operators can be combined into a large dataset that represents, for example, a large number of SCC failures or many miles of pipeline. These "rolled-up" datasets are most useful for validating SCC Guidelines that themselves are the result of combining a number of individual R&D Guidelines into a single testable SCC Guideline. For example, a number of individual R&D Guidelines would result in a decrease in occurrence or severity of SCC with increasing distance downstream of the compressor or pump station. For validation purposes, these R&D Guidelines are combined into a single testable SCC Guideline. In other cases, individual data sets are required to validate specific guidelines. An example of an individual data set would be a set of SCADA pressure data representing the time dependence of the pipeline operating pressure. Because the majority of R&D studies are focussed on one particular aspect of the overall SCC process, many of the guidelines developed from the R&D literature are best tested using these individual data sets.

Stress corrosion cracking is commonly considered to be the result of an aggressive environment acting on a susceptible material in the presence of a tensile stress. It is not surprising, therefore, that the data needed to validate the guidelines can also be divided into these three categories. Examples of the types of environmental data that are required include:

- temperature
- CP level
- trapped water composition (pH, concentrations of various ionic species)
- coating type
- soil type and moisture content

Examples of the types of material-related data that are required include:

- grade of steel
- manufacturer

Examples of useful stress-related information include:

- maximum allowable operating pressure
- time-dependent SCADA pressure data

There are, of course, other types of information that would be useful for validating certain guidelines, but which are unlikely to be available, e.g., level of residual stress, inclusion shape and density, etc.

These environmental, material, and stress-related parameters need to be correlated with some measure of the severity or occurrence of SCC, such as:

- crack growth rate, based on ILI or fracture surfaces from repeat hydrostatic tests
- number of crack colonies per unit length or area
- location of SCC failures with respect to the upstream compressor or pump station

Various sources have been used to collect field data. First, as described in more detail in Section C.2.1, pipeline operators in the U.S., Canada, and overseas were sent a questionnaire requesting information about the conditions under which SCC has been found as a result of in-service and hydrostatic test failures, ILI, or SCC DA. Second, existing industry databases, such as the Canadian Energy Pipeline Association (CEPA) database and the report from a recent joint-industry project, were used as sources of "rolled-up" data from a number of operating companies (Section C.2.2). Third, there are a number of reports of field SCC investigations in the open literature, often associated with failure investigations.

C.2 SOURCES OF DATA

C.2.1 PIPELINE OPERATORS

As part of a joint effort involving a number of PRCI- and DOT-funded SCC-related projects, a questionnaire was developed and sent to all PRCI-member companies. The aim of the joint effort was to collect data in a single effort and develop a significant SCC database to be shared by a number of related projects.

A Microsoft Excel-based spreadsheet format was used for the questionnaire. The data collection file comprised six individual spreadsheets: a sheet to capture information about the company's entire system (Table C-1), one each for in-service (Table C-2) and hydrostatic test (Table C-3) failures, one each for SCC found by ILI (Table C-4) or excavation (Table C-5), and one for additional comments (Table C-6).

Information regarding the company's entire pipeline system (Table C-1) was primarily designed for use in a separate project aimed at identifying operating conditions under which no SCC is found. In order to enable statistical analysis of these locations, the “no-SCC” spreadsheet required companies to define the length of pipe broken down by Class Location (1, 2, or 3), Year of Construction (categorized by decades), and Coating Type. The data were to be provided in terms of the length of different coating types of different ages, to permit normalization of the information per mile of installed pipe.

The spreadsheets for the in-service and hydrostatic test failures and for the ILI and excavation features (Tables C-2 to C-4) contained many of the same entries, including:

- Company/contact person information
- Pipeline designation
- Type of product (gas, single liquid, batched liquid)
- Grade
- Diameter
- Wall thickness
- Manufacturer
- Seam weld type
- Installation date
- Coating type
- Surface preparation method
- Coating location (field or mill)
- Maximum allowable operating pressure
- Type of CP system
- CP criterion
- Maximum historical temperature
- Environment information (slope, drainage, soil type, land use)
- Date of failure*
- Rupture or leak*
- Failure pressure*
- Distance downstream of pump or compressor station
- High-pH or near-neutral pH SCC
- Location of cracking on pipe
- Crack orientation (axial, circumferential)
- Additional information for SCC in dents (o'clock position, location of cracks in dent, association with mechanical damage, association with corrosion, unique features)

Table C-1: Spreadsheet A from Data Collection Survey Sent to Pipeline Companies Requesting Information on Entire Pipeline System.

Draft form for data to establish base for SCC-2-4

Company: Date:

Liquid or gas?

Contact person, name:

Phone:

e-mail:

(miles or km)

Number of miles (or km) [To be filled in]

		Mill-applied Coating									Over-the-ditch Coating											
Location Class	Year of Construction	FBE	Coal tar	Asphalt	3-layer PE	Yellow Jacket	other (specify)	other (specify)	other (specify)	other (specify)	Coal tar		Asphalt	PE tape	Liquid epoxy	Wax	other (specify)	other (specify)	other (specify)	other (specify)	other (specify)	
1																						
	2000-present																					
	1990-1999																					
	1980-1989																					
	1970-1979																					
	1960-1969																					
	1950-1959																					
	1940-1949																					
2																						
	2000-present																					
	1990-1999																					
	1980-1989																					
	1970-1979																					
	1960-1969																					
	1950-1959																					
	1940-1949																					
3																						
	2000-present																					
	1990-1999																					
	1980-1989																					
	1970-1979																					
	1960-1969																					
	1950-1959																					
	1940-1949																					

Table C-2: Spreadsheet B from Data Collection Survey Sent to Pipeline Companies Requesting Information on In-service SCC Failures.

In-service Failures Due to SCC

Company Name:
Company Address:
Contact Person:
Telephone:
Fax:
E-mail:

																													For Cracks in Deformations				
Pipeline Designation	Type of Product	Grade	Diameter (in or mm)	Wall Thickness (in or mm)	Manufacturer	Seam Weld	Installation Date	Most Recent Hydrotest Conducted before Failure Provide date	Coating Type	Surface Prep	Coating Location	MAOP, %SMYS	Type of CP System	CP Criterion	Maximum historical discharge temp. (F or C)	Slope (Looking downstream)	Drainage	Soil Type	Land Use	Date of Failure (MM/DD/YY)	Rupture or Leak	Failure Pressure (psig or kPA)	High-pH or NN-pH	ph of Trapped Water	Distance downstream from comp. or pump station (miles or km)	Crack Orientation	Location of origin	Comments	O'clock Position	Location of Cracks in Dent	Associated with Mechanical Damage?	Associated with Corrosion?	Any Unique Features of the Dents? Describe
	gas					DSAW			Bare	Grit blast	Mill		Impressed	-850 mV off		Level	Boggy	Sand	Arable							Axial	Body			Shoulder	Yes	Yes	
	single liquid					ERW			PE	Wire brush	Field		current	-850 mV on		Undulating	Poor	Clay	Forest							Circumferential	Toe of seam weld			Apex	No	No	
	batched liquids					Flash			PE tape (single)	Knives				100 mV shift		<15 degree downward slope	Intermediate	Organic	Grassland								Girth weld			Other			
						SSAW			PE tape (double)	Unknown			Galvanic	Other		15-30 degree downward slope	Good	Till	Wetland/bog								Hard spot						
						Lap			PVC				anodes			>30 degree downward slope	Very good	Organic/sand	Other								Dent						
						Seamless			Shrink sleeves							<15 degree upward slope	Varies seasonally	Transitional									Wrinkle						
									Somastic							15-30 degree upward slope		Other															
									Enamel							>30 degree upward slope																	
									Urethane																								
									Urethane epoxy																								
									CTE																								
									Asphalt																								
									FBE																								
									YJ1																								
									YJ2																								
									Two-layer																								
									Three-layer																								
									Wax																								

Table C-3: Spreadsheet C from Data Collection Survey Sent to Pipeline Companies Requesting Information on Hydrostatic Test SCC Failures.

Hydrostatic-Test Failures Due to SCC

Company Name:
Company Address:
Contact Person:
Telephone:
Fax:
E-mail:

																													For Cracks in Deformations				
Pipeline Designation	Type of Product	Grade	Diameter	Wall Thickness	Manufacturer	Seam Weld	Installation Date	Date of Most Recent Prior Hydrotest	Coating Type	Surface Prep	Coating Location	MAOP, %SMYS	Type of CP System	CP Criterion	Maximum historical discharge temp.	Slope	Drainage	Soil Type	Land Use	Date of Failure	Rupture or Leak	Failure Pressure, psig	High-pH or NN-pH	pH of Trapped Water	Distance downstream from comp. or pump station	Crack Orientation	Location of origin	Comments	O'clock Position	Location of Cracks in Dent	Associated with Mechanical Damage?	Associated with Corrosion?	Any Unique Features of the Dents? Describe
			(in or mm)	(in or mm)											(F or C)	(Looking downstream)				(MM/DD/YY)		(psig or kPA)			(miles or km)								
	gas					DSAW			Bare	Grit blast	Mill		Impressed	-850 mV off		Level	Boggy	Sand	Arable							Axial	Body			Shoulder	Yes	Yes	
	single liquid					ERW			PE	Wire brush	Field		current	-850 mV on		Undulating	Poor	Clay	Forest							Circumferential	Toe of seam weld			Apex	No	No	
	batched liquids					Flash			PE tape (single)	Knives				100 mV shift		<15 degree downward slope	Intermediate	Organic	Grassland								Girth weld			Other			
						SSAW			PE tape (double)	Unknown			Galvanic	Other		15-30 degree downward slope	Good	Till	Wetland/bog								Hard spot						
						Lap			PVC				anodes			>30 degree downward slope	Very good	Organic/sand	Other								Dent						
						Seamless			Shrink sleeves							<15 degree upward slope	Varies seasona	Transitional									Wrinkle						
									Somastic							15-30 degree upward slope		Other															
									Enamel							>30 degree upward slope																	
									Urethane																								
									Urethane epoxy																								
									CTE																								
									Asphalt																								
									FBE																								
									YJ1																								
									YJ2																								
									Two-layer																								
									Three-layer																								
									Wax																								

Table C-4: Spreadsheet D from Data Collection Survey Sent to Pipeline Companies Requesting Information on SCC Detected by ILI.

ILI Indications of SCC

Make one entry for each valve section that was assessed

Company Name:

Company Address:

Contact Person:

Telephone:

Fax:

E-mail:

Pipeline Designation	Type of Product	Grade	Diameter	Wall Thickness	Manufacturer	Seam Weld	Installation Date	Coating Type	Surface Prep	Coating Location	MAOP, %SMYS	Type of CP System	CP Criterion	Maximum historical discharge temp.	Slope
			(in or mm)	(in or mm)										(F or C)	(looking downstream)
	gas					DSAW		Bare	Grit blast	Mill		Impressed	-850 mV off		Level
	single liquid					ERW		PE	Wire brush	Field		current	-850 mV on		Undulating
	batched liquids					Flash		PE tape (single)	Knives				100 mV shift		<15 degree downward slope
						SSAW		PE tape (double)	Unknown			Galvanic	Other		15-30 degree downward slope
						Lap		PVC				anodes			>30 degree downward slope
						Seamless		Shrink sleeves							<15 degree upward slope
								Somastic							15-30 degree upward slope
								Enamel							>30 degree upward slope
								Urethane							
								Urethane epoxy							
								CTE							
								Asphalt							
								FBE							
								YJ1							
								YJ2							
								Two-layer							
								Three-layer							
								Wax							

Pipeline Designation	Drainage	Soil Type	Land Use	Date of ILI	Length of Tested Segment	Distance from Comp. or Pump Station to Upstream End of Segment	High-pH or NN-pH or Unknown	pH of Trapped Water	Crack Orientation	Location of cracks	Attach description of crack severity. How do you categorize the severity? How many indications of clusters of each severity category?	What ILI Tool?	O'clock Position	Location of Cracks in Dent	Associated with Mechanical Damage?	Associated with Corrosion?	Any Unique Features of the Dents? Describe
												For Cracks in Deformations					
				(MM/DD/YY)	(miles or km)	(miles or km)											
	Boggy	Sand	Arable						Axial	Body				Shoulder	Yes	Yes	
	Poor	Clay	Forest						Circumferential	Toe of seam weld				Apex	No	No	
	Intermediate	Organic	Grassland							Girth weld				Other			
	Good	Till	Wetland/bog							Hard spot							
	Very good	Organic/sand	Other							Dent							
	Varies seasonal	Transitional								Wrinkle							
		Other															

Table C-5: Spreadsheet E from Data Collection Survey Sent to Pipeline Companies Requesting Information on SCC Found by SCC DA.

SCC Found with Excavation

Make one entry for each valve section that was assessed

Company Name:
Company Address:
Contact Person:
Telephone:
Fax:
E-mail:

																											For Cracks in Deformations				
Pipeline Designation	Type of Product	Grade	Diameter	Wall Thickness	Manufacturer	Seam Weld	Installation Date	Coating Type	Surface Prep	Coating Location	MAOP, %SMYS	Type of CP System	CP Criterion	Maximum historical temp.	Slope	Drainage	Soil Type	Land Use	Date of Inspection	Length of Segment Inspected	Distance from Comp. or Pump Station to Upstream End of Segment	High-pH or NN-pH or Unknown	pH of Trapped Water	Crack Orientation	Location of cracks	Attach description of crack severity. How do you categorize the severity? How many indications of clusters of each severity category?	O'clock Position	Location of Cracks in Dent	Associated with Mechanical Damage?	Associated with Corrosion?	Any Unique Features of the Dents? Describe
			(in or mm)	(in or mm)										(F or C)					(MM/DD/YY)	(miles or km)	(miles or km)										
	gas					DSAW		Bare	Grit blast	Mill		Impressed	-850 mV off		Level	Boggy	Sand	Arable						Axial	Body			Shoulder	Yes	Yes	
	single liquid					ERW		PE	Wire brush	Field		current	-850 mV on		Undulating	Poor	Clay	Forest						Circumferential	Toe of seam weld			Apex	No	No	
	batched liquids					Flash		PE tape (single)	Knives				100 mV shift		<15 degree downward slope	Intermediate	Organic	Grassland							Girth weld			Other			
						SSAW		PE tape (double)	Unknown			Galvanic	Other		15-30 degree downward slope	Good	Till	Wetland/bog							Hard spot						
						Lap		PVC				anodes			>30 degree downward slope	Very good	Organic/sand	Other							Dent						
						Seamless		Shrink sleeves							<15 degree upward slope	Varies season	Transitional								Wrinkle						
								Somastic							15-30 degree upward slope		Other														
								Enamel							>30 degree upward slope																
								Urethane																							
								Urethane epoxy																							
								CTE																							
								Asphalt																							
								FBE																							
								YJ1																							
								YJ2																							
								Two-layer																							
								Three-layer																							
								Wax																							

Table C-6: Spreadsheet F from Data Collection Survey Sent to Pipeline Companies Requesting Additional Information and Comments.

Additional Comments	
Company Name:	

Many companies, both those who have and those who have not observed SCC, will have developed in-house theories for their company's SCC experiences. We would like to capture this "SCC folklore."

In the following textbox, please summarize your SCC folklore. For example, you may have identical lines running through similar terrain. One has SCC, the other does not. What is your explanation for this? Are there other instances where you would have expected to see SCC and have not, or conversely where you would not have expected SCC but do? If you have experienced SCC, does it tend to occur under certain conditions, or at a particular time of year? What about coating type?

In addition, has your company developed any particular strategies for managing or avoiding SCC? For instance, do you control temperature, pressure fluctuations, a certain level of CP, etc?

All of this information will be very useful for our SCC database.

For the ILI features (Table C-4) and for features found by excavation (Table C-5), one entry was to be made for each valve section inspected or excavated. In addition, the entries marked * in the list above were replaced by

- Date of inspection (or excavation)
- Length of segment inspected
- Description of the severity of cracking found
- Type of ILI tool used

The sixth and final worksheet in the data collection file was intended to capture company's in-house "SCC folklore" (Table C-6). Many companies, whether they have experienced SCC or not, have developed rationales for their experience, sometimes based on anecdotal evidence from the field. Because of each operators' intimate knowledge of their own systems, this information can be incisive and could be useful in the current project. Therefore, operators were asked to provide descriptions of such internal knowledge. For example, companies might have identical lines running through similar terrain, with one line experiencing SCC and another not. What is the explanation for this? Are there other instances where companies would have expected to see SCC and have not, or conversely where they would not have expected SCC but do? If companies have experienced SCC, does it tend to occur under certain conditions, or at a particular time of year? What about coating type? In addition, have companies developed any particular strategies for managing or avoiding SCC? For instance, do they control temperature, pressure fluctuations, a certain level of CP, etc?

The following data sets were collected from pipeline companies as a result of the direct request for data:

- Full or partial responses from 9 companies (3 liquid, 6 gas)
- Full coating information provided by four companies, comprising 18,700 miles
- Of the nine companies, six reported no SCC
- A total of 76 failures (17 in-service, 59 hydrostatic test) reported
- In addition to the 59 hydrostatic test SCC failures, a further 16 hydrostatic tests were reported in which no SCC failure occurred
- Of the 76 failures, 21 were (or were likely) due to high-pH SCC and 55 due to near-neutral pH SCC
- A total of 460 dig reports and/or reports of digs
- Log from a 140-km SCC ILI tool run

C.2.2 EXISTING INDUSTRY COMPILATIONS

A large body of data from a recent joint industry project (JIP) has been made available to the project (ASME 2008). These data come from a JIP involving five major natural gas transmission companies in North America (two other companies, whilst not formally part of the JIP, also supplied data). The companies involved in the JIP represent most of the SCC experience on gas pipelines in N. America over the past 40 years. The data set includes reports of both high-pH and near-neutral pH SCC.

The JIP data include (ASME 2008):

- Pipelines attributes: age, diameter and wall thickness, grade, coating type, operating pressure
- How and where SCC was discovered: date and means of discovery, location
- Extent and nature of SCC: type of SCC; size, depth, and number of crack colonies and of individual cracks

Data not collected as part of the JIP included environmental (terrain, soil texture/type), CP, coating condition, and operating temperature. The latter was excluded from the survey, despite the known correlation of temperature with coating damage and the growth of high-pH SCC, because of the change in operating temperatures that occurred in the 1980's when companies installed coolers and the difficulties associated in obtaining the more-relevant temperature records prior to this change.

Notwithstanding these limitations, the JIP data set represents a large number of SCC occurrences, including:

- 61 in-service high-pH SCC leaks and ruptures
- 19 in-service near-neutral pH SCC leaks and ruptures
- 308 hydrostatic test high-pH SCC leaks and ruptures (out of 675 hydrostatic tests)
- 52 hydrostatic test near-neutral pH SCC leaks and ruptures (out of 383 hydrostatic tests)
- 583 occurrences of high-pH SCC from a total of 4485 excavations
- 757 occurrences of near-neutral pH SCC from a total of 8894 excavations
- 6500 high-pH SCC defects with defect depths >10% WT found by ILI
- 800 near-neutral pH SCC defects with defect depths >10% WT found by ILI

Other industry sources of data include:

- CEPA Stress Corrosion Cracking Recommended Practices (CEPA 2007)

- CEPA Stress Corrosion Cracking Database first and second trending reports (CEPA 1998, 2000)
- The "Baker" study performed by Michael Baker Jr., Inc. for the DOT OPS (Baker 2005)
- Canadian National Energy Board (NEB) SCC inquiry report (NEB 1996)
- Transport Safety Board of Canada commodity pipeline occurrence reports (available from http://www.tsb.gc.ca/eng/rapports-reports/pipeline/index.asp)

C.2.3 DATA FROM THE OPEN LITERATURE

A number of papers published in the open literature contain data useful for validating the SCC Guidelines. The content of these studies are discussed in more detail in Sections C.3.1.3 and C.3.2.2.

C.3 DATA FOR VALIDATION OF SCC GUIDELINES

C.3.1 NEAR-NEUTRAL pH SCC

C.3.1.1 Pipeline Operator Experience Based on Current Survey and JIP Data

For the purposes of the current analysis, the failure data obtained from the questionnaire sent out for this project and the data from the JIP have been combined (R.R. Fessler, private communication, 2010). The combined dataset for near-neutral pH SCC comprises:

- 20 in-service and 64 hydrostatic test failures on gas pipelines reported by a total of four companies
- seven in-service and 12 hydrostatic test failures on liquid lines reported by two companies

Tables C-7 and C-8 summarize the distribution of in-service and hydrostatic test failures for gas and liquid lines, respectively, categorized by coating type and year-of-construction. The two sets of data show similar trends for both gas and liquid lines. The vast majority of failures have occurred on lines constructed from 1950-1980, with only one in-service failure on a line built in 1981 and no failures on line constructed since then. None of the data have been normalized against the total number of miles constructed in each of the decades, so caution should be exercised in drawing conclusions regarding the susceptibility of different vintages of pipelines.

Gas pipelines coated "over-the-ditch" using asphalt enamel accounted for ~60% of all in-service and hydrostatic test failures. Interestingly, tape coating, which is generally thought of as being shielding, accounted for only 25% of failures. Although there are fewer data, a similar

Table C-7: Summary of Near-neutral pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines by Coating Type and Year-of-Construction. All MAOP >60% SMYS with field-applied coating.

Year of Con-struction	In-Service Failures (Ruptures and Leaks)					Hydrostatic Test Failures				
	Coal Tar	As-phalt	PE Tape	Wax	**Total**	Coal Tar	As-phalt	PE Tape	Wax	**Total**
2000-2010	0	0	0	0	**0**	0	0	0	0	**0**
1990-1999	0	0	0	0	**0**	0	0	0	0	**0**
1980-1989	0	0	1	0	**1**	0	0	0	0	**0**
1970-1979	0	4	6	0	**10**	0	4	11	0	**15**
1960-1969	0	6	0	0	**6**	0	11	3	10	**24**
1950-1959	0	2	0	1	**3**	1	24	0	0	**25**
1940-1049	0	0	0	0	**0**	0	0	0	0	**0**
TOTAL	**0**	**12**	**7**	**1**	**20**	**1**	**39**	**14**	**10**	**64**

Table C-8: Summary of Near-neutral pH SCC In-service and Hydrostatic Test Failures on Liquid Pipelines by Coating Type and Year-of-Construction. All MAOP >60% SMYS with field-applied coating.

Year of Con-struction	In-Service Failures (Ruptures and Leaks)					Hydrostatic Test Failures				
	Coal Tar	As-phalt	PE Tape	Un-known	**Total**	Coal Tar	As-phalt	PE Tape	Un-known	**Total**
2000-2010	0	0	0	0	**0**	0	0	0	0	**0**
1990-1999	0	0	0	0	**0**	0	0	0	0	**0**
1980-1989	0	0	0	0	**0**	0	0	0	0	**0**
1970-1979	1	1	0	1	**3**	1	1	0	0	**2**
1960-1969	0	2	0	1	**3**	0	2	0	0	**2**
1950-1959	0	0	0	1	**1**	0	0	0	8	**8**
1940-1049	0	0	0	0	**0**	0	0	0	0	**0**
TOTAL	**1**	**3**	**0**	**3**	**7**	**1**	**3**	**0**	**8**	**12**

trend is displayed by the failure data for liquid lines. Again, these data have not been normalized for the miles of pipeline in service coated with each type of coating. However, the apparent prevalence of failures on asphalt-coated lines is interesting. There have been no reported failures on pipelines with mill-applied coatings, including FBE.

There have been no reported near-neutral pH SCC in-service or hydrostatic test failures on gas or liquid operated at <60% MAOP.

Figure C-1 shows the distribution of reported in-service and hydrostatic test failures on gas pipelines as a function of distance downstream of the compressor station reported by companies participating in the JIP study (ASME 2008). Failures on tape-coated lines are more common closer to the compressor station, but this trend is not followed by those on asphalt-coated lines. Since the latter form by far the largest group of failures, the distribution of all failures shows no significant dependence on distance downstream of the compressor station. However, data from other sources clearly show a tendency for a higher failure frequency (both in-service and hydrostatic test failures) closer to the compressor station (Figure C-2, King et al. 2003).

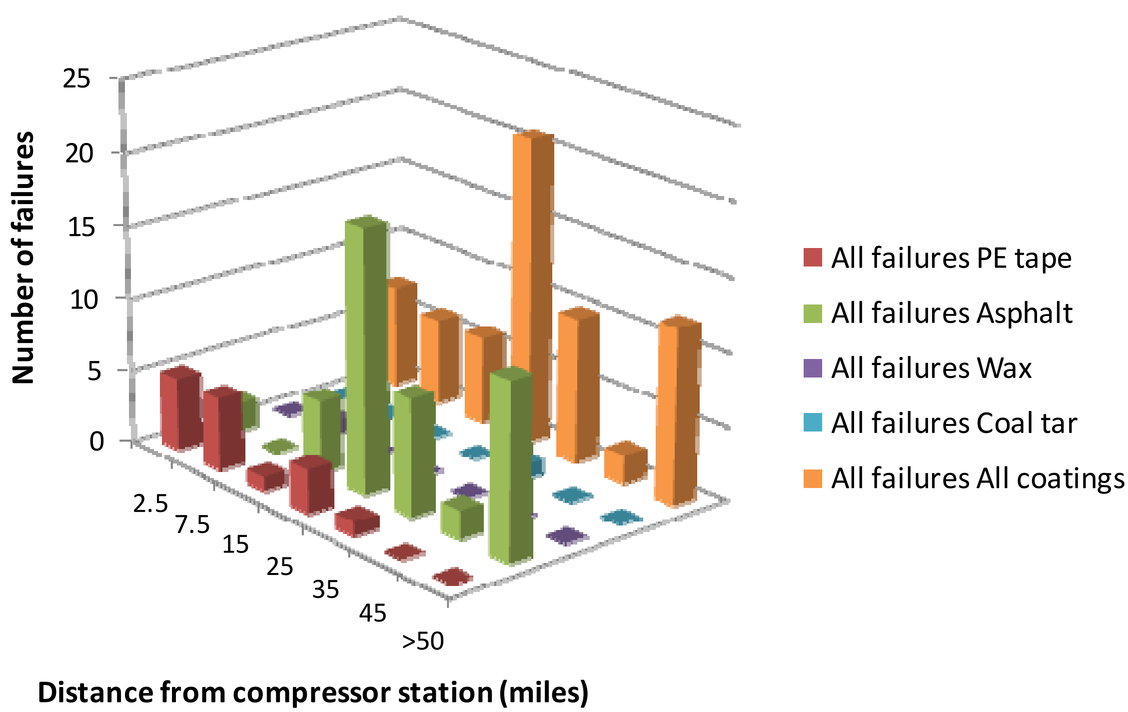


Figure C-1: Distribution of Near-neutral pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines as a Function of Distance Downstream of the Compressor Station Based on Results of a Joint Industry Project (ASME 2008).

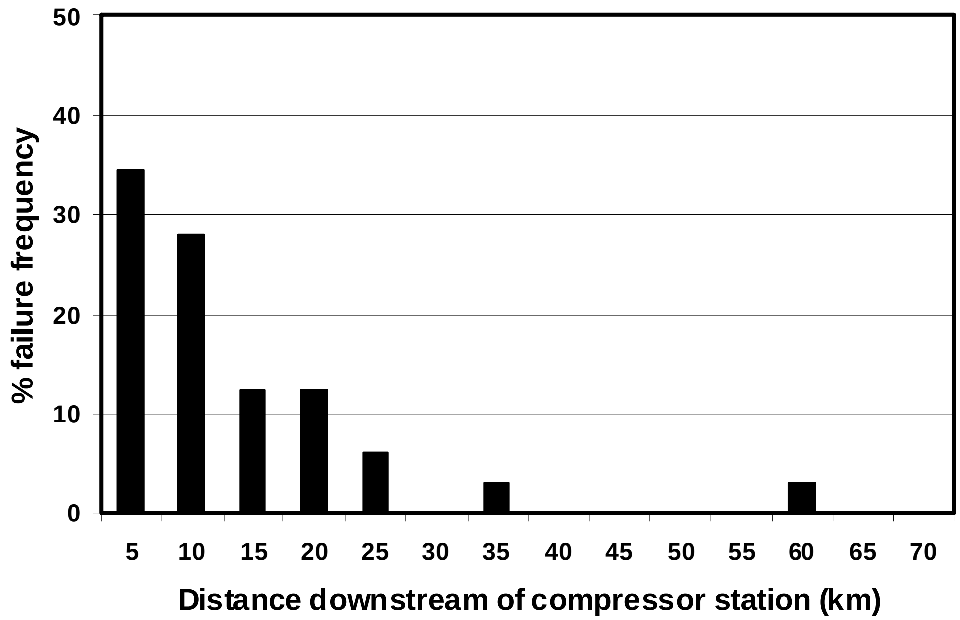


Figure C-2: Distribution of Near-neutral pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines as a Function of Distance Downstream of the Compressor Station (King et al. 2003).

The conclusions regarding near-neutral pH SCC from the JIP study were (ASME 2008):

- "Ten of the in-service ruptures and leaks due to axially oriented SCC have been on asphalt-coated pipe, with seven on tape-wrapped pipe and one on wax-coated pipe.
- In-service failures on tape-wrapped pipes have mostly been within 20 miles downstream of compressor discharges, whereas those on asphalt-coated pipe have been distributed along the entire pipeline length.
- Hydrostatic test failures on tape-wrapped pipes have mostly been within 30 miles downstream of compressor discharges, whereas those on asphalt-coated pipe have been distributed along the entire pipeline length.
- All the in-service failures and all the hydrostatic test failures have been on lines designed to operate at above 70% SMYS.
- In-service failures first occurred in 1985 and have continued at an average rate of one per year since the early 1990s.
- For tape-wrapped pipes, the first in-service failures occurred 12 years after installation, whereas, for asphalt-coated pipes, the first failures occurred after 22 years (excepting a failure at mechanical damage after 13 years).
- In targeted excavation programs, between 5% and 80% of the excavations have revealed SCC.
- Excavations have revealed only limited cracking in pipes operated below 60% SMYS.

- Where SCC has been found on tape-wrapped pipe, excavations have revealed anything from a few colonies to 100 or more; each colony could be up to 15 inches or more in both axial and circumferential directions and could contain a large number of closely-spaced individual cracks.
- Where SCC has been found on asphalt-coated pipe, excavations have revealed typically around 10-30 colonies, while on coal tar coated pipe less than 5 colonies have generally been found.
- Around 10% of the colonies and cracks found by excavation were sufficiently deep (>10%) and long (>2 inches) to be classified as Noteworthy. This is consistent with the findings of the CEPA Trending Study."

C.3.1.2 Canadian Energy Pipeline Association (CEPA) Database

CEPA have performed two trending studies based on data collected from their members on their experiences with near-neutral pH SCC. Although a number of CEPA members were also involved in the JIP and operator survey described above, the CEPA database focussed more on the results of excavations than failures.

The conclusions from the first trending study were (CEPA 1998):

- "SCC is more prevalent and serve (sic) on polyethylene tape coated pipe than asphalt/coal tar coated pipe.
- There is no obvious or apparent correlation between the presence or severity of SCC and pipe manufacture or manufacturing process.
- SCC is more prevalent and severe on natural gas pipeline systems than on liquid hydrocarbon pipeline systems.
- There is no obvious or apparent absolute threshold design stress for either SCC initiation or propagation.
- There is no obvious or apparent correlation between the presence or severity of SCC and pipe grade.
- For polyethylene tape coated pipe, the prevalence and severity of SCC generally increases as the soil drainage becomes more impeded (i.e., imperfect to very poorly drained).
- For asphalt/coal tar coated pipe the prevalence and severity of SCC generally increases as the soil drainage becomes more aerated (i.e., imperfect to well drained).
- The pH of the undercoating electrolyte associated with significant SCC on CEPA members pipeline systems is between 6 and 6.5."

The results from the second trending study (CEPA 2000) generally supported those from the first study, except:

- "…… For gas pipelines, there appears to be a trend of increasing SCC detection or presence with increasing pipeline diameter for both tape and asphalt-coated pipelines. This trend is not clear for liquid service lines. The reason behind such a trend is uncertain; it may be an artifact of bias in the data or a reflection of some susceptibility of large diameter pipes to SCC initiation. …….
- The second observation relates to the relative susceptibility of tape in gas and liquid service. Based on the correlation by age of tape-coated pipelines, the frequency of SCC detection for liquid service pipelines constructed prior to 1970 exceeds the detection frequency for those lines constructed after 1970. This increased frequency of detection and possibly SCC presence runs counter to the First Trending Report and broad operational experience. ….."

C.3.1.3 Open Literature

There are a number of useful studies in the open literature which provide insight into the field conditions in which near-neutral pH has been observed. Synopses of these studies are given below.

Zhigletsova et al. (2008)

This paper describes Russian experience with developing a “soils model” based on field observations at SCC failure sites. A total of 40 excavations were carried out at SCC failure sites at various locations in Russia. All failures occurred on tape-coated NPS48-56 gas transmission pipelines. Different levels of relative aggressiveness were ascribed to the different regions based on the historical incidence of SCC failures. Various analyses were made on the groundwater, soil extracts, and directly on the soil itself. After some preliminary technique development, the authors chose the following analyses for their study:

- field measurements of the pH of the groundwater (if any) and the redox potential (Eh) of the soil in the side of the excavation,
- laboratory measurements of the soil moisture content and of the concentration of sulphide,
- laboratory measurements on water extracts of the soil for pH, electrical conductivity, carbonate/bicarbonate, sulphate, nitrate, and chloride ions, and
- laboratory measurements on acid extracts of the soil for reduced and total iron ions.

The authors presented data from ten sites, nine corresponding to SCC failures and one site with no SCC. Visually, all sites exhibited gleying of the soil (as also reported in North America) and the greatest circumferential extent of gleyed soil was observed in that geographical region deemed to be the most aggressive. This gleying also seemed to be correlated with the ratio of Fe(II) to total Fe in the soil. Other conclusions included:

- There was a marginal correlation between redox potential and sulphide concentrations with SCC, with susceptible sites apparently more reducing than less-susceptible sites.
- There was no correlation between SCC and the other parameters, including: water content, Cl^-, NO_3^-, electrical conductivity, or absolute amount of Fe(II) (as opposed to the Fe(II):Fe_{TOT} ratio).

Wilmott and Diakow (1998)

Wilmott and Diakow (1998) report a study of the environmental conditions and their relationship with SCC along a 1.1-km section of NPS8 pipe in Northern Alberta. Various environmental measurements were made before and during excavation, during which SCC colonies were identified using magnetic particle inspection. Environmental factors that were found to correlate with SCC locations included:

- soil resistivity in the range 1000-2500 Ω cm
- anaerobic redox potentials more-negative than -450 mV_{CSE}
- high SRB population
- presence of swelling smectite clay
- presence of anaerobic corrosion products, including sulphides
- presence of CO_2
- possible saturation of the trapped electrolyte with Fe(II)
- low levels of aggressive ions, such as Cl^-

Penner et al. (2003)

A geological, geotechnical, and hydrogeological study was conducted of a near-neutral pH SCC rupture site in SW Manitoba, Canada. The conclusions from the study included:

- On a regional scale, the rupture site is near the boundary between an extensive till plain to the west and an extensive glaciodeltaic plain to the east. This geological boundary also represents a hydrogeological boundary between low-permeability till sediments to the west and a 60-m-deep aquifer to the east.
- The rupture site experiences annual water table fluctuations in the range 0.2-0.5 m, with water table depths around the rupture site of between 0.60 and 3.08 m below ground level.
- Because of this fluctuation in water table, the rupture site would experience fluctuating aerobic and anaerobic conditions.
- Cracking initiated at a location on the pipe that would correspond to the long-term interface between fully saturated and partially saturated soil.

- The failure occurred after the onset of the rising water table conditions during spring recharge in April 2002.
- The failure location is characterized by a decrease in soil conductivity from west to east.
- The groundwater chemistry is uniform across the study area.
- The study area exhibited a high level of microbial activity (aerobes, anaerobes), with high local CO_2 levels.
- SRB were identified along with aerobes, suggestive of juxtaposed aerobic and anaerobic microbial activity.

Leeson and Spitzmacher (2006)

This paper describes a study of an NPS16 liquid pipeline that was carried out following a rupture due to near-neutral pH SCC that occurred in Northern Alberta, Canada in August 2004. An ILI program was undertaken to identify possible crack-like, metal-loss, and geometrical features, of which a total of 339 crack- and notch-like features were excavated and inspected. The pipeline was constructed in 1966-67 using predominantly ERW pipe (X-35, X-52, and X-65) and was used to transport liquids in a batched mode. The NPS16 pipe contained varying wall thickness sections, ranging from 5.16 mm to 12.7 mm, with the heavier wall thickness sections immediately downstream of the main pump station and at river crossings. The external coating was (field-applied?) coal tar/asphalt wrapped with fibre-reinforced paper. The MAOP varied in different sections with a maximum value of 80% SMYS. No SCC failures were experienced during a 1997 hydrostatic test at pressures up to 127% SMYS

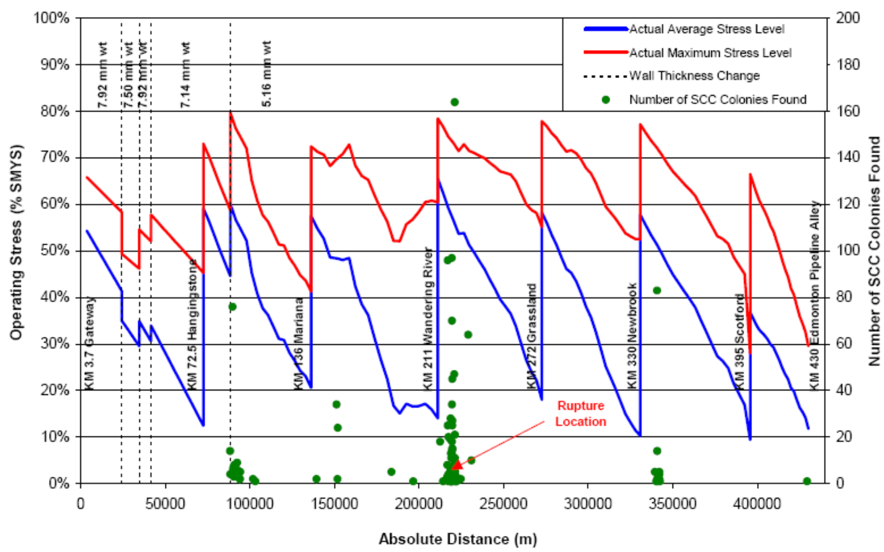


Figure C-3: Dependence of the Number of Near-neutral pH SCC Colonies on Operating Stress for an NPS16 Liquid Pipeline (Leeson and Spitzmacher 2006).

Approximately 97% of the SCC colonies were found between 0 and 20 km downstream of pump stations (Figure C-3). Although not shown in the figure, the more severe cracks were also observed closer to the pump stations.

A detailed site investigation program was conducted during the subsequent excavations and the following trends were observed:

- most SCC occurred in moderately-well to rapidly-drained soil with high resistivity
- very little or no SCC was observed in low-resistivity poorly drained soils, such as lacustrine clays or organics
- SCC occurred under disbonded coating only and only in areas where there were corrosion products and electrolyte
- the electrolyte was typically present as a thin film of solution on the pipe surface with a near-neutral pH
- the predominant corrosion products were iron oxides/hydroxides and $FeCO_3$
- in all cases SCC was associated with metal loss, albeit insignificant in depth (<10% WT)
- there were very few cracks in areas of severe corrosion
- 97% of SCC occurred within 20 km downstream of a pump station
- the occurrence and severity decreased with increasing distance away from the pump stations
- no SCC was observed on heavy-wall pipe sections, and was typically observed immediately after the transition from heavy-wall to light-wall pipe
- post-rupture metallurgical analysis suggests a mean crack growth rate of 0.7 mm/yr at the rupture location
- cracking was transgranular in nature

<u>Youzwishen et al. (2004)</u>

Youzwishen et al. (2004) developed a statistical correlation between environmental (soil conditions, drainage, local geography) and operational data (pipe geometry, metal loss features, CIS, operating pressure) and locations where SCC was found, or not found, during an SCC DA direct examination.

Key observations included:

- of the ten "high-probability" verification sites, seven exhibited SCC
- SCC was not found at the one "low-probability" site
- overall success rate 73% (8 of 11)
- predictors showing best correlation with SCC were:
    - CP on-potential

- o iR drop
- o presence of ground depression
- o bend angle of pipe
- o direction of bend (side or over/under bend)
- o proximity to metal loss and whether metal loss was near girth weld
- o metal loss severity

King et al. (2004)

King et al. (2004) reported the results of an extensive field 2-3-yr monitoring program of seven known near-neutral pH SCC sites. Parameters monitored or recorded included: pipe-depth NOVAProbe measurements (soil resistivity, redox potential, temperature, pH), corrosion coupons (CP conditions and native potential), miscellaneous data (pipe information; soil, groundwater, coating, and corrosion product samples; topography and land use; precipitation data; soil gas samples; SCADA pressure data; corrosion and SCC ILI information; CIS data; gas temperature (for high-pH SCC sites); and information about the nature of the SCC).

The major observations and conclusions regarding near-neutral pH SCC included:

- o cracking was associated with both permanently anaerobic and cyclic aerobic/anaerobic conditions on tape lines
- o cracking was associated only with cyclic aerobic/anaerobic conditions on asphalt lines
- o the sites were transitional nature
    - ▪ temporal transitions involving seasonal changes in the pipe-depth environment (resistivity, redox potential, soil-gas CO_2)
    - ▪ spatial transitions involving variation around the pipe and along the length of the pipe or variations in the height of the water table

Van Boven et al. (2004)

Van Boven et al. (2004) attempted to correlate pipe-depth soil data (resistivity, temperature, redox potential, pH, PSP) and terrain properties (drainage, soil type,) with ILI indications.

The authors concluded that:

- Of a total of 59 near-neutral pH SCC sites over a 90-km-long section, no SCC was observed at sites with soil resistivity greater than 14,000 ohm cm. No other single soil or site parameter correlated with SCC; however, there was a higher probability of finding near-neutral pH SCC under the following conditions:

- level to gently sloping terrain
- low soil resistivity
- low redox potential
- poor CP
- poor drainage
- shallow peat deposits over glacial-lacustrine sediments susceptible to ponding

- No near-neutral pH SCC was found at sites with redox potentials of -0.32 to -0.68 V_{CSE}

Beavers et al. (2000)

Beavers et al. (2000) correlated the presence of initiated cracks on pipe with various metallurgical parameters, including: residual stress, surface roughness, cyclic stress-strain behaviour, inclusions (number, area, composition), microhardness, steel chemical composition, and local galvanic behaviour. Fourteen pipe samples ranging from NPS8 to NPS 42, X-52 to X-70 and of 1950's-1970's vintage were examined.

The major findings of the study were:

- there was a strong correlation between residual stress and the presence of near-neutral pH SCC colonies
  - o residual stress increased with increasing depth, being near zero or negative at the surface in some cases
  - o no evidence for decrease in residual stress at depths <2 mm
  - o residual stress decreased with increasing distance from SCC colonies
  - o mean residual stress for SCC colonies was 220 MPa, without SCC colonies 100 MPa
- microhardness is also higher in SCC colonies than in control areas
- possible correlation of SCC to surface roughness
  - o rougher surface correlates to SCC
- no statistically significant correlation between occurrence of SCC colonies and:
  - o steel composition
  - o cyclic stress-strain behaviour

- o inclusion properties (S contents ranged from 0.003 to 0.021 ppm)
- o local galvanic behaviour

Beavers and Worthingham (2002)

Beavers and Worthingham (2002) studied the compositions of ground and trapped water from several hundred known high-pH and near-neutral pH SCC sites on the TransCanada system, with a focus on the composition of the groundwater, in particular the concentration of cations.

The main observations and conclusions were:

- historically, there has been no consistent groundwater or other soil indicator for either high-pH or near-neutral pH SCC
- the meq/L cation ratio (Na+K)/(Ca+Mg) in the soil for high-pH SCC sites was statistically higher (mean 0.46) for sites where SCC was found than for sites at which no SCC was found (mean 0.40), or for near-neutral pH SCC sites (0.33), and for near-neutral pH SCC sites with no SCC (0.25)
- the meq/L sum of (Na+K) in the soil was statistically higher (mean 52 meq/L) for confirmed high-pH SCC sites than for high-pH no SCC sites (24 meq/L), near-neutral pH SCC sites (2 meq/L) or for near-neutral pH SCC sites with no SCC (1 meq/L)
- at near-neutral pH SCC sites, there is a higher concentration of cations in the trapped electrolyte where no SCC is found, suggesting that CP has penetrated and prevented cracking
- penetration of CP can prevent near-neutral pH SCC either because of increase in pH or because of polarization

Beavers and Harper (2004)

Beavers and Harper (2004) developed a correlative type site-selection model for near-neutral pH SCC for a single pipeline for a single company.

The main conclusions from the correlation were:

- three parameters were found to be key predictors of near-neutral pH SCC, namely; pipe manufacturer, coating type, and soil type
- model was capable of predicting the severity of cracking
- >4 times more likely to find SCC in glaciofluvial soil than in lacustrine soil

- >3 times more likely to find SCC under asphalt coating compared with other coatings (CTE, epoxy urethane, FBE, tape, wax)
- >18 times more likely for pipe from manufacturer G to exhibit SCC than pipe from manufacturers A, B, or C

C.3.2 HIGH-pH SCC

C.3.2.1 Pipeline Operator Experience Based on Current Survey and JIP Data

For the purposes of the current analysis, the failure data obtained from the questionnaire sent out for this project and the data from the JIP have been combined (R.R. Fessler, private communication, 2010). The combined dataset for high-pH SCC comprises:

- 64 in-service and 325 hydrostatic test failures on gas pipelines reported by a total of ten companies

Tables C-9 to C-11 summarize the reported high-pH in-service and hydrostatic test failures on gas pipelines for various MAOP levels categorized by year-of-construction and coating types. As for near-neutral pH SCC failures there have been no failures reported by these ten companies on lines constructed in the past 30-40 years. Furthermore, failures have been most frequent for pipelines constructed in the 1940's-1960's.

Table C-9: Summary of High-pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines by Coating Type and Year-of-Construction. All MAOP >60% SMYS with field-applied coating.

Year of Con-struction	In-Service Failures (Ruptures and Leaks)				Hydrostatic Test Failures			
	Coal Tar	As-phalt	PE Tape	Total	Coal Tar	As-phalt	PE Tape	**Total**
2000-2010	0	0	0	**0**	0	0	0	**0**
1990-1999	0	0	0	**0**	0	0	0	**0**
1980-1989	0	0	0	**0**	0	0	1	**0**
1970-1979	0	0	0	**0**	0	0	0	**0**
1960-1969	1	0	3	**4**	0	0	0	**0**
1950-1959	17	1	11	**29**	109	0	51	**160**
1940-1049	21	0	1	**22**	152	0	0	**152**
TOTAL	**39**	**1**	**15**	**55**	**261**	**0**	**52**	**313**

Table C-10: Summary of High-pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines by Coating Type and Year-of-Construction. All 50% SMYS <MAOP ≤60% SMYS with field-applied coating.

Year of Con-struction	In-Service Failures * (All Leaks but One)				Hydrostatic Test Failures			
	Coal Tar	As-phalt	PE Tape	**Total**	Coal Tar	As-phalt	PE Tape	**Total**
2000-2010	0	0	0	**0**	0	0	0	**0**
1990-1999	0	0	0	**0**	0	0	0	**0**
1980-1989	0	0	0	**0**	0	0	0	**0**
1970-1979	0	0	0	**0**	0	0	0	**0**
1960-1969	1	0	0	**1**	0	0	0	**0**
1950-1959	1	0	0	**1**	1	0	0	**1**
1940-1949	2	0	0	**2**	0	0	0	**0**
TOTAL	**4**	**0**	**0**	**4**	**1**	**0**	**0**	**1**

Table C-11: Summary of High-pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines by Coating Type and Year-of-Construction. All MAOP ≤50% SMYS with field-applied coating.

Year of Con-struction	In-Service Failures * (All Leaks)				Hydrostatic Test Failures			
	Coal Tar	As-phalt	PE Tape	**Total**	Coal Tar	As-phalt	PE Tape	**Total**
2000-2010	0	0	0	**0**	0	0	0	**0**
1990-1999	0	0	0	**0**	0	0	0	**0**
1980-1989	0	0	0	**0**	0	0	0	**0**
1970-1979	0	0	0	**0**	0	0	0	**0**
1960-1969	0	0	0	**0**	0	0	0	**0**
1950-1959	4	0	0	**4**	11	0	0	**11**
1940-1949	1	0	0	**1**	0	0	0	**0**
TOTAL	**5**	**0**	**0**	**5**	**11**	**0**	**0**	**11**

Interestingly, failures were reported primarily on coal-tar coated (83% of all reported failures) or tape-coated (17% of failures), with a single failure on an asphalt-coated line and no failures associated with FBE.

The majority (95%) of high-pH SCC failures occurred on lines operated at an MAOP of >60% SMYS. However, a number of failures occurred on lines at lower MAOP, with five failures (1%) for MAOP between 50% and 60% SMYS and 16 failures (4%) for MAOP of less than 50% SMYS.

Figure C-4 shows the distribution of high-pH in-service and hydrostatic test failures as a function of distance downstream of the compressor station based on coating type. Overall, there is a clear tendency for a decrease in the frequency of failures with increasing distance away from the compressor station. This overall trend is determined largely by the trend for coal-tar coated pipelines and is not exhibited by the trend for tape-coated lines.

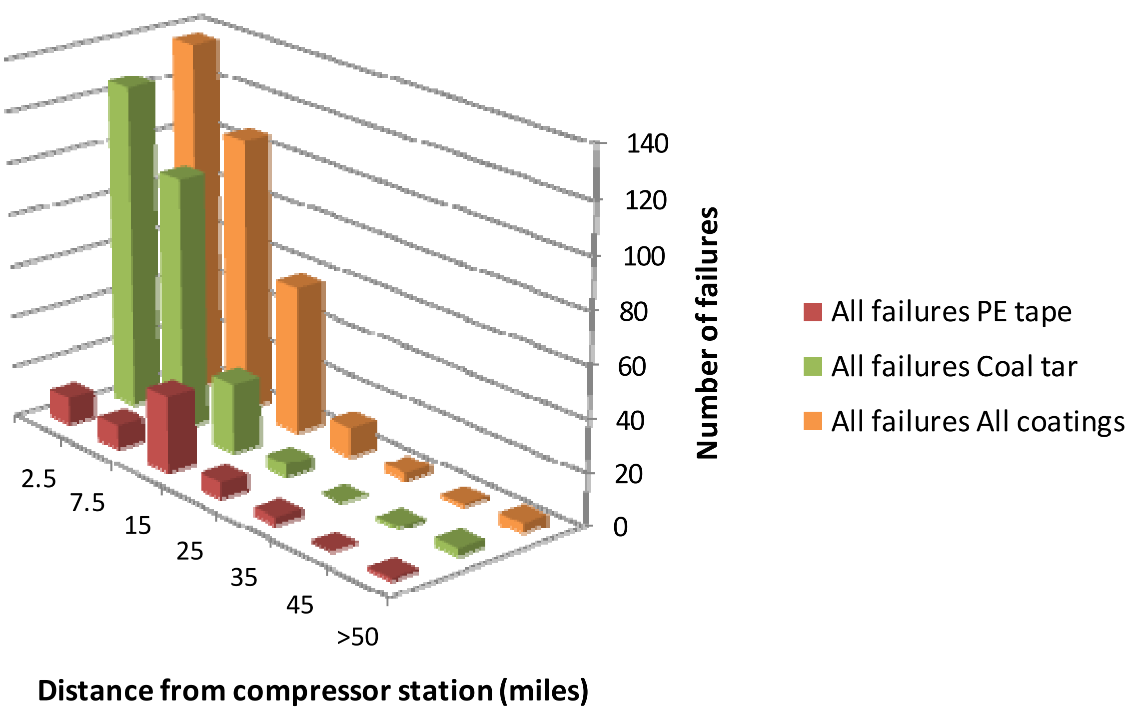


Figure C-4: Distribution of High-pH SCC In-service and Hydrostatic Test Failures on Gas Pipelines as Function of Distance Downstream of the Compressor Station Based on Results of a Joint Industry Project (ASME 2008).

The conclusions regarding high-pH SCC from the JIP study were (ASME 2008):

- "Around 90% of the in-service ruptures and leaks due to axially oriented SCC are within 20 miles of compressors, but the spread has increased a little since the analysis by Eiber and Leis.
- Around 95% of hydrostatic test failures are also within 20 miles downstream of compressors. The total is biased due to the high proportion of tests on first valve sections.
- Over 85% of in-service failures and over 95% of hydrostatic test failures have been in pipe designed to operate above 60% SMYS. Most of the exceptions are pipes less than 12 inches in diameter.
- In-service failures have continued to occur at a steady rate over the last 40 years, as pipeline age increases. Only two in-service failures, and no hydrostatic test failures, have been in pipes less than 10 years old. In more than 90% of the affected pipelines, SCC did not start to occur until after 20-30 years service.
- Over 70% of the in-service failures have been on coal tar coated pipe, with the remainder being on tape-wrapped pipe. Elsewhere there have occasionally been reported instances on asphalt coated, and wax coated pipe.
- Where SCC has been found on coal tar coated pipe, excavations have revealed anything from a few colonies to 200 or more. Colonies ranged from a few inches to 10 inches or more in axial and circumferential directions. Each colony contained from a few to 100 or more closely spaced individual cracks.
- In a dataset of ‘opportunistic’ excavations, less than 5% of the excavations revealed SCC, and estimates suggested that more than half of the colonies were less than 20% deep. In one developmental ILI run on a line with a history of high pH SCC, around half the pipe joints contained cracks 15-30% deep but only one tenth of the cracks found were more than 30% deep."

C.3.2.2 Open Literature

King et al. (2004)

King et al. (2004) reported the results of an extensive field monitoring program of two high-pH SCC sites in Canada over a period of 2-3 years. Parameters monitored included pipe-depth soil resistivity, redox potential, temperature, and pH. In addition, miscellaneous data (pipe information; soil, groundwater, and coating samples; topography and land use; precipitation data; soil gas samples; SCADA pressure data; CP data; and information about the nature of the SCC) were also collected at one or both sites.

Key observations on the high-pH SCC sites included:

- both sites were permanently aerobic, dry
- the sites were transitional in nature

- temporal transitions involving seasonal changes in pipe-depth environment (resistivity, redox potential, soil-gas CO_2)
- spatial transitions involving variation around pipe

Beavers and Worthingham (2002)

Beavers and Worthingham (2002) studied the compositions of ground and trapped water from several hundred known high-pH and near-neutral pH SCC sites on the TransCanada system, with a focus on the composition of the groundwater, in particular the concentration of cations.

Key observations/conclusions included:

- historically, there has been no consistent groundwater or other soil indicator for either high-pH or near-neutral pH SCC
- the meq/L cation ratio (Na+K)/(Ca+Mg) in the soil for high-pH SCC sites was statistically higher (mean 0.46) for high-pH SCC sites than for high-pH SCC sites at which no SCC was found (mean 0.40),
- the meq/L sum of (Na+K) in the soil for high-pH SCC sites was statistically higher (mean 52 meq/L) than for high-pH no SCC sites (24 meq/L)
- (Na+K) preferentially concentrated under both disbonded tape and disbonded asphalt coating, but the concentration factor was ~50 times greater for asphalt coatings

C.3.3 SCADA PRESSURE DATA

Many aspects of both high-pH and near-neutral pH SCC are affected by the fluctuating gas or liquid pressure inside the pipe. The resultant hoop stress is one of a number of sources of stress on the pipe, which also include residual stresses from fabrication and welding or mechanical damage; the effects of stress concentrators such as dents, bends, or corrosion; and axial stresses from ground movement or other external forces. SCADA pressure data of varying frequency should be readily available for compressor and pump stations.

C.3.3.1 Data Analysis

A number of different techniques are available for characterizing time-dependent pressure (or load) series (ASTM 2005). These techniques, which include level-crossing counting, peak counting, simple-range counting, and rainflow counting, are generally used to characterize load-time series in terms of their impact on fatigue processes. However, in the current context information is also needed regarding the rate of change of pressure (load) in order to determine appropriate strain rates. Therefore, it is necessary to extend these traditional peak counting techniques to include time-dependent information.

C.3.3.1.1 Rainflow Counting

Rainflow counting is the most commonly used method for characterizing time-dependent pressure (load) histories. There are a number of variants of rainflow counting which, depending on the nature of the pressure-time series, may or may not produce identical results. ASTM (2005) provides detailed procedures for each of these methods.

As an example of the use of rainflow counting to characterize pressure-time series in a format suitable for use in SCC crack growth modelling, consider the SCADA pressure data in Figure C-5 (King et al. 2003). The figure shows pressure fluctuations for an NPS42 gas transmission pipeline for a 15-month period during which the line operated at a reasonably constant pressure of ~6100 kPa with occasional underloads of up to ~1000 kPa. Rainflow counting identified a total of 2170 cycles during this period (approximately 5 per day) with the distribution of R values (ratio of the minimum to maximum pressure for the cycle) shown in Figure C-6. The majority of cycles (99%) exhibit R values of ≥0.9.

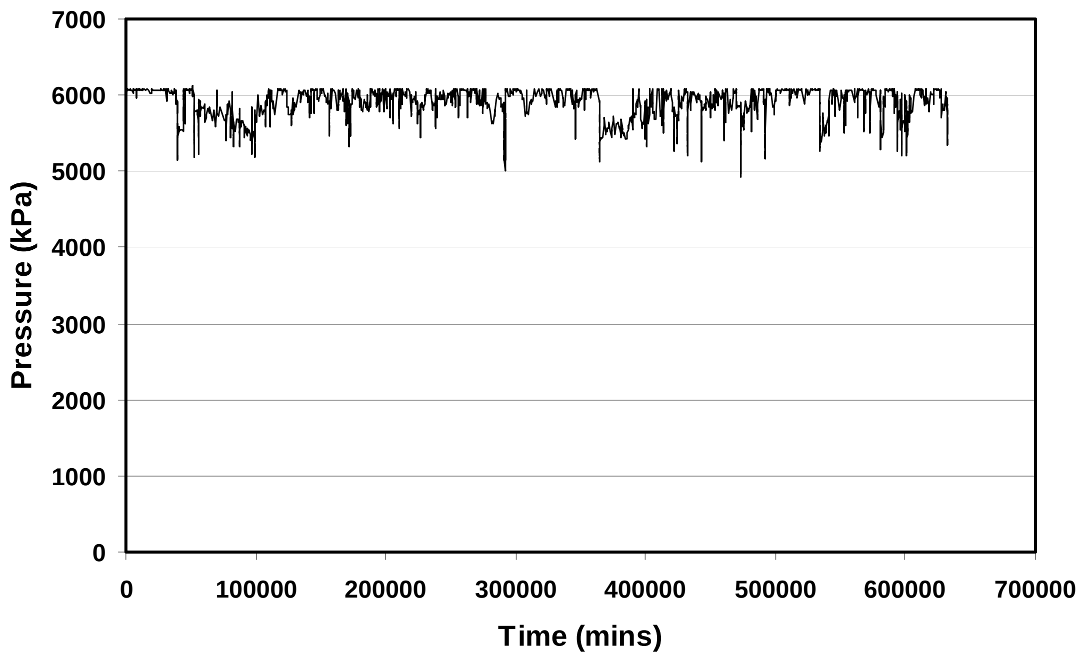


Figure C-5: An Example of the Variation in Pressure for an NPS42 Gas Transmission Pipeline Over a 15-month Period.

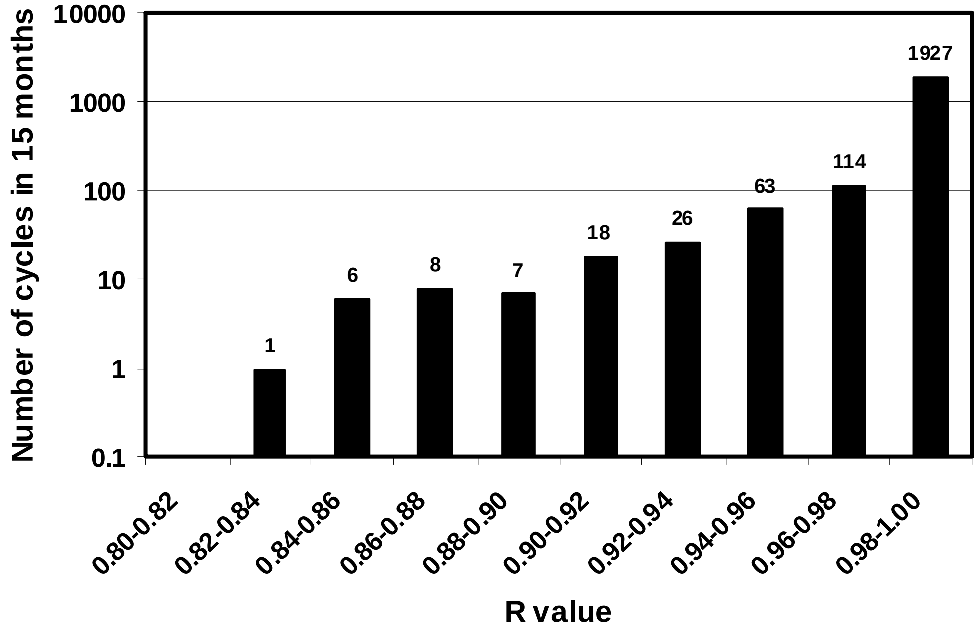


Figure C-6: Distribution of R Values of Pressure Fluctuations Characterized by Rainflow Counting for the Data Shown in Figure C-5.

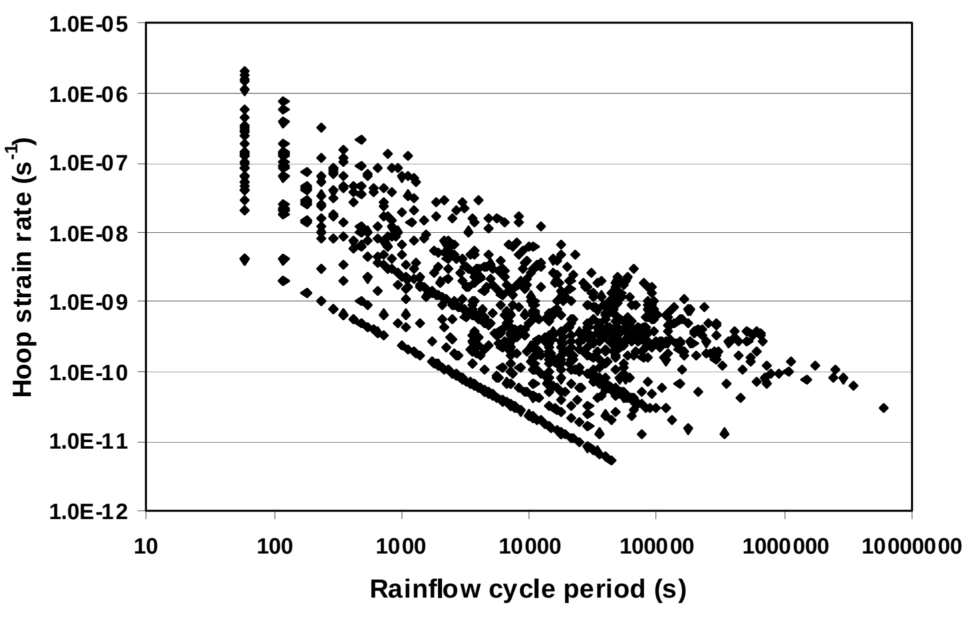


Figure C-7: Distribution of Calculated Hoop Strain Rates as a Function of the Cycle Period for the Data Shown in Figure C-5.

The times associated with the maxima and minima for each cycle are also identified during rainflow counting, permitting the hoop strain rates to be estimated (Figure C-7). (The linear trends observed in the figure are a consequence of the resolution of the SCADA data; for example, the data in Figure C-5 were recorded at 60 s intervals, resulting in the grouping of data in Figure C-7 for periods of 60 s, 120 s, ….). For this particular line, which is typical of the operation of many gas transmission pipelines, hoop strain rates vary between ~10^{-6} s^{-1} to 10^{-11} s^{-1}, with a tendency towards lower strain rates for longer cycles.

Distributions of R values such as that shown in Figure C-6 can be converted to distributions of crack driving forces. Figures C-8 and C-9 show the distribution of the stress intensity range (ΔK) for an assumed 0.5-mm-deep crack for gas and oil pipelines, respectively. In each figure, data are shown separately for mainline transmission pipelines (defined as NPS24 or NPS26 and greater) and for smaller laterals.

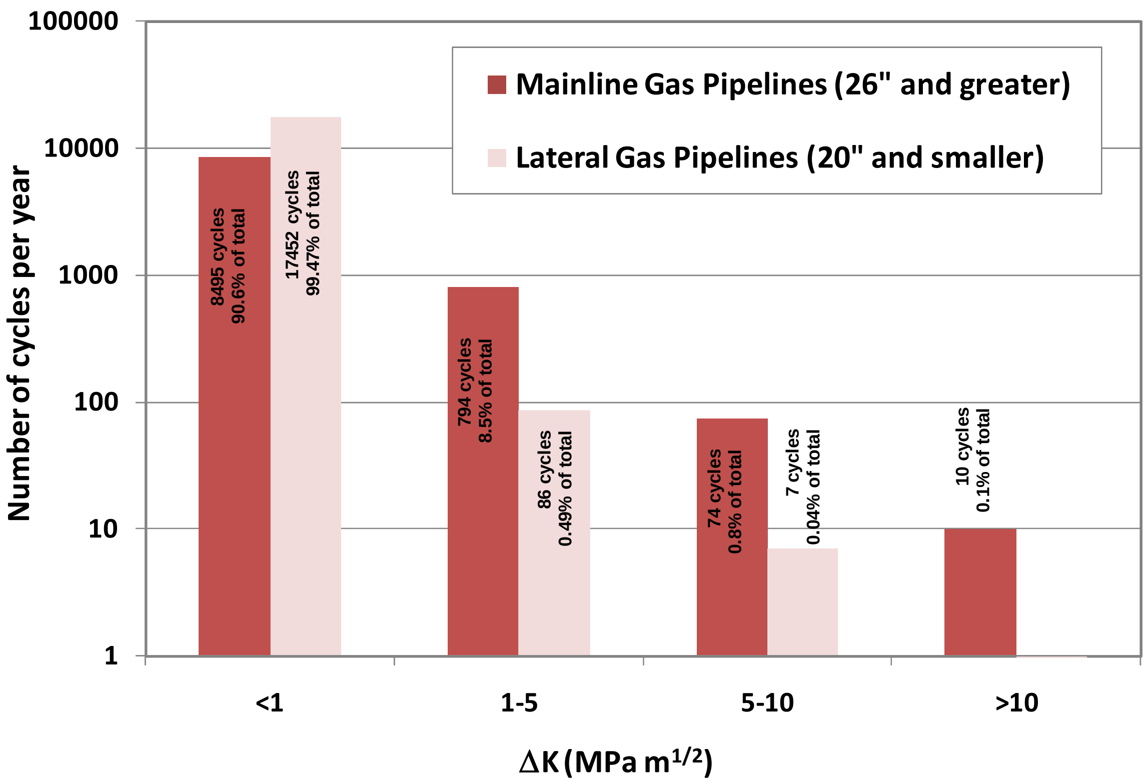


Figure C-8: Typical Distribution of Cycles for Mainline and Lateral Gas Pipelines Expressed as a Change in Stress Intensity Factor for a 0.5-mm-deep Crack (Van Boven et al. 2002).

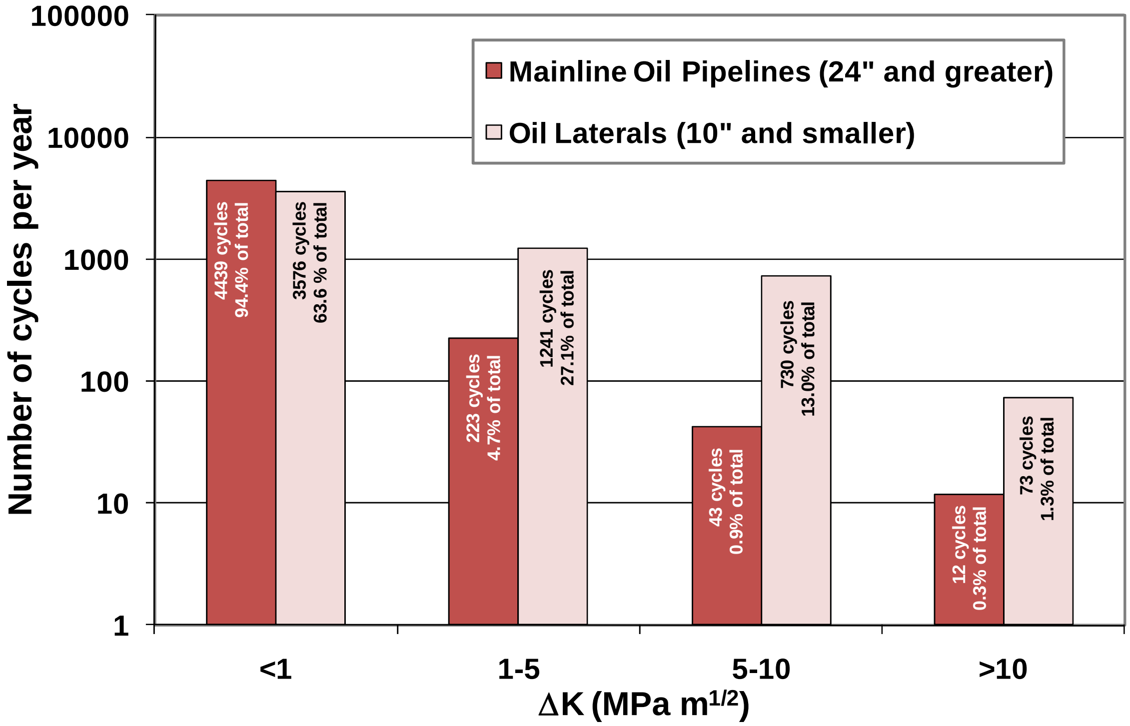


Figure C-9: Typical Distribution of Cycles for Mainline and Lateral Oil Pipelines Expressed as a Change in Stress Intensity Factor for a 0.5-mm-deep Crack (Van Boven et al. 2002).

Based on current corrosion fatigue models for near-neutral pH SCC, damaging cycles are those with a ΔK value of 10 $MPa \cdot m^{1/2}$ or greater. On this basis, it can be seen that liquid lines experience a larger number of damaging cycles than gas lines and oil laterals experience more damaging cycles than oil transmission pipelines. It should be noted that the number of damaging cycles will increase as the crack deepens.

C.3.3.1.2 Intermediate Data

SCADA pressure data are typically available at compressor or pump station discharge and suction locations. Information about pressure fluctuations at intermediate locations can be used to predict the rate of crack growth as a consequence of mechanical loading as a function of distance downstream of the compressor or pump station.

Figure C-10 shows two sets of measured, and three sets of predicted SCADA pressure data for an NPS36 gas transmission pipeline. The two measured sets are from the discharge side of the upstream compressor station (labeled "Inlet" in Figure C-10) and the suction side of the downstream compressor station (labeled "Outlet" in Figure C-10). SCADA pressure data were available for the same times over a 14-month period. The two compressor stations are approximately 60 km apart, with three valve stations in between (a total of four valve sections). The intermediate pressure-time (P-t) plots were calculated using an existing Excel-based algorithm for predicting the pressure at intermediate locations given the synchronized upstream and downstream pressures and information about the pipeline. In this case the intermediate P-t plots were calculated at the valve locations, but could be at any arbitrary location between inlet and outlet.

Although not clear from the scale used in Figure C-10, the five measured and predicted P-t profiles exhibit different number of cycles of varying magnitude. Figure C-11 shows the results of rainflow counting for the inlet and outlet P-t data sets from Figure C-10.

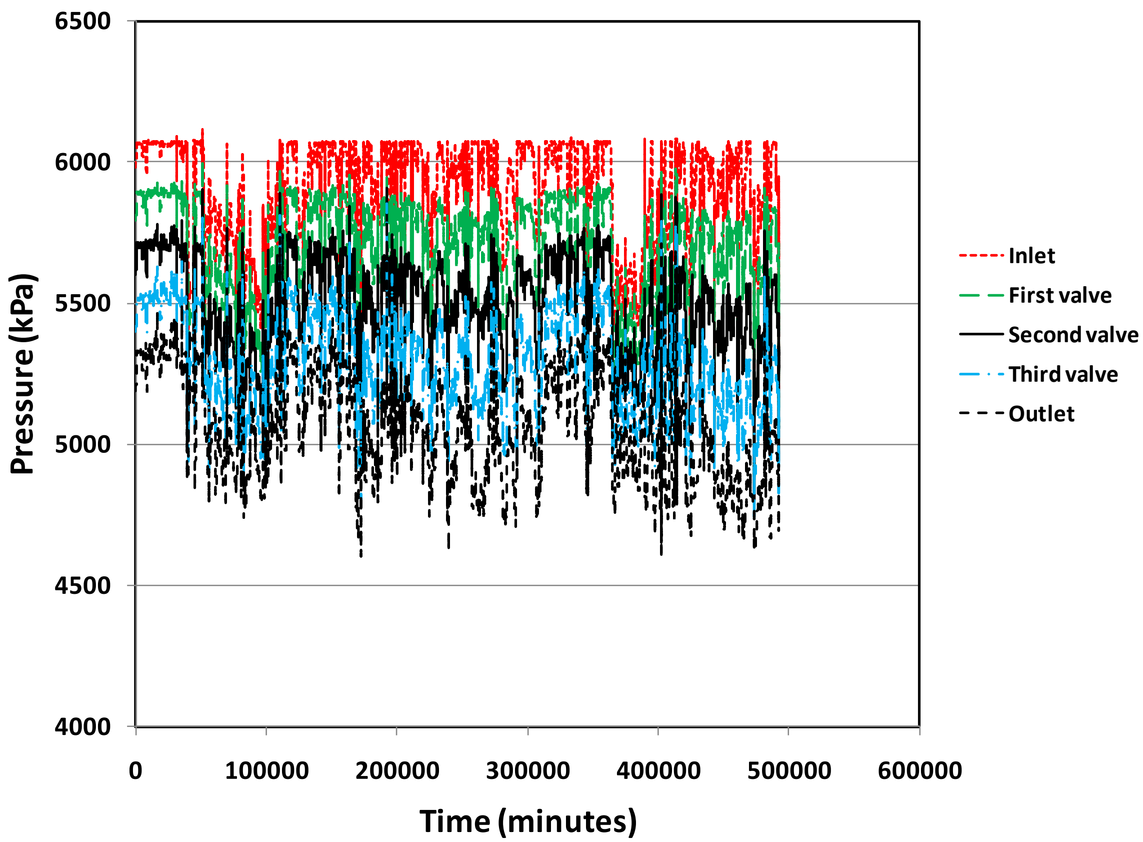


Figure C-10: Measured Inlet and Outlet Time-dependent Pressure Fluctuations for a Gas Transmission Pipeline and the Predicted Dependences at the Intermediate First, Second, and Third Valve Locations.

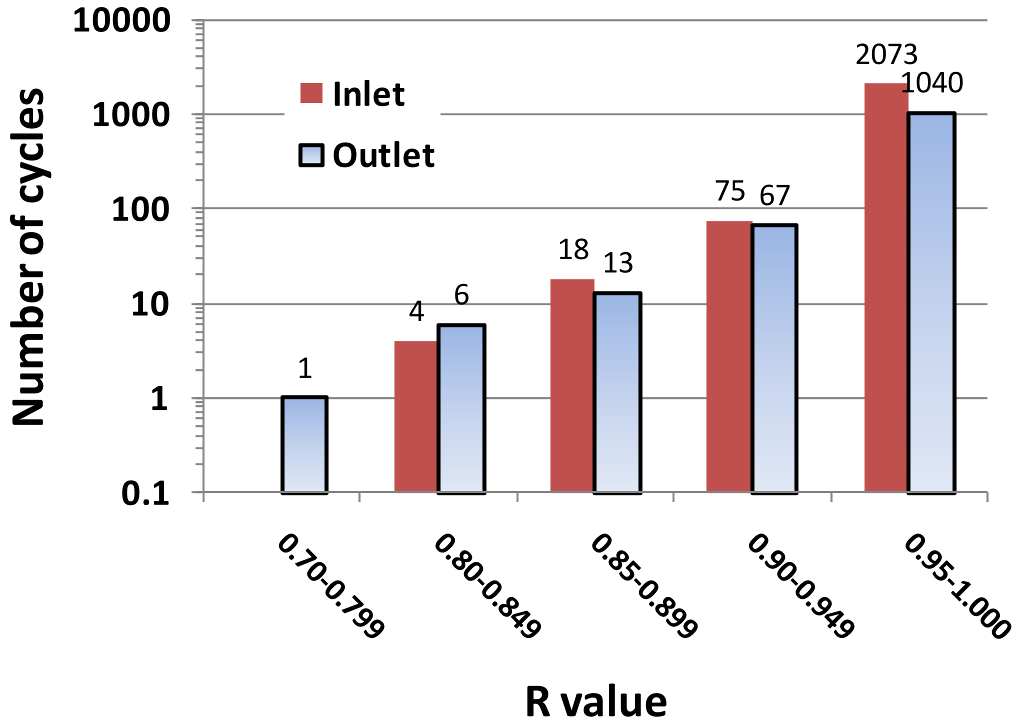


Figure C-11: Distribution of R Values at the Inlet and Outlet Locations Based on Rainflow Counting Analysis of the Pressure Fluctuation Data in Figure C-10.

There are a number of interesting features in the data in Figure C-11:

- there are approximately twice the number of cycles at the discharge (inlet) than on the suction side (outlet),
- in terms of the damaging cycles (R < 0.95), the number of cycles is similar at the inlet and outlet locations, and
- in terms of the most damaging cycles (R < 0.85), there are actually more on the suction (outlet) side than at the inlet, although the lower pressure at the suction side may well result in smaller stress amplitudes.

Although the magnitude of the pressure cycle (the R value) is an important parameter in stress corrosion crack growth, so too are the maximum pressure (stress) and, for some proposed mechanisms, the strain rate (i.e., the rate of pressure change).

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APPENDIX D: DEVELOPMENT OF SCC GUIDELINES AND THEIR VALIDATION

CONTENTS

D.1 SUMMARIES OF DEVELOPMENT AND VALIDATION OF SCC GUIDELINES

Appendix D summarizes the basis for each of the SCC Guidelines discussed in the main text. For each SCC Guideline, the corresponding R&D Guidelines are listed, from which the interested reader can, by reference to Appendices A and B, ascertain the underlying R&D evidence for each of the SCC Guidelines. Tables D-1 to D-5 list the SCC Guidelines for the fundamental principles and FOR each of the stages for high-pH SCC. Tables D-6 to D-10 provide the corresponding information for near-neutral pH SCC.

In addition, the tables provide comments on the extent to which the SCC Guideline is consistent with, or has been more directly validated against, field data. The extent of validation varies for different guidelines. In some cases it is not possible to validate the SCC Guidelines as it would require information that is not available and which would be impossible to obtain. In other cases, validation is implicit as the SCC Guideline was derived partly on the basis of information from the field. In still other cases, validation would be possible but the necessary information is not currently available.

Table D.1: SCC Guidelines – High-pH SCC Fundamental Principles.

SCC Guideline	Underlying R&D Guideline(s)	Development and Validation of SCC Guidelines
Guideline H-0-1: High-pH SCC can be described by a slip dissolution mechanism.	H065	Based on large number of mechanistic R&D studies. Validated based on similar T dependence for dissolution rate and observed distribution of failures downstream of compressor station.
Guideline H-0-2: Elevated temperature is a major contributing factor in many aspects of high-pH SCC.	H007, H012, H026, H039, H074, H119, H192	Decreasing probability of SCC failures with increasing distance downstream of compressor stations has been attributed to the effect of decreasing temperature (see detailed analysis in section D.2.1). Supported by decrease in high-pH SCC failures after introduction of gas coolers.
Guideline H-0-3: CO_2 is required to generate the concentrated carbonate-bicarbonate solution for cracking.		No specific field evidence linking occurrence or severity of high-pH SCC with CO_2 generation, but CO_2 clearly needed for generation of high-pH SCC environment.
Guideline H-0-4: Coalescence of cracks is of fundamental importance to how high-pH SCC cracks grow.	H069, H096, H167	No direct field evidence available. Guideline supported by extensive experimental evidence.
Guideline H-0-5: The majority of the pipe lifetime is spent in Stages 1, 2, and 3 of the overall cracking process.	H073, H133, H170	No direct field evidence available. Guideline supported by "reasonableness" of predictions from mechanics-based models based on 4-stage SCC process.
Guideline H-0-6: There is a continuum of cracking behaviour of pipeline steels in carbonate-bicarbonate environments.	H006, H134, H135, H138, H139, H143	No direct evidence from field data, although mixed intergranular/transgranular cracking is observed. Guideline based on extensive lab evidence.
Guideline H-0-7: Variability is inherent to many aspects of high-pH SCC.	H029, H073	Based on lab evidence, but generally supported by variability observed in the field.
Guideline H-0-8: There are two mechanistic approaches to lifetime prediction, one based on the micro-mechanical properties of the steel and the other on the kinetics of the slip dissolution mechanism.	H071, H072, H073, H078, H097, H105, H131, H189, H193	Lab-derived guideline. The two different approaches have not been compared against field evidence.

Table D.2: SCC Guidelines – High-pH SCC Susceptibility.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-I-1: The probability of finding high-pH SCC increases with increasing temperature.	H007, H012, H026, H039, H074, H119, H192	Supported by field evidence for decreasing frequency of in-service and hydrostatic test failures with increasing distance from compressor station (see section D.2.1).
Guideline H-1-2: The high-pH carbonate-bicarbonate environment can be generated by the evaporation of electrolyte on the hot pipe.	H012, H022, H036	No direct field evidence for this guideline, but it is consistent with the observed effect of temperature on high-pH SCC.
Guideline H-I-3: The application of CP is another major cause of the development of a high-pH carbonate-bicarbonate environment.	H015, H020, H113, H185, H187	No direct evidence indicating how electrolytes are generated in the field, but consistent with known fundamental electrochemical principles and effects of CP.
Guideline H-I-4: For cathodically protected pipe, the pipe must be inadequately protected for the potential to be within the range for cracking.	H008, H009, H016, H021, H046, H049	Based on observation that cracking range is more positive than typical -850 mV CP criterion.
Guideline H-I-5: Maintenance of the high-pH carbonate-bicarbonate environment requires a sufficient and continuous source of CO_2.	H013, H017, H034, H035, H114, H192	No direct field evidence, but extensive evidence from lab studies by various groups.
Guideline H-I-6: Soils with high concentrations of sodium and potassium ions are required to support high-pH SCC.	H019, H118, H171, H172	This guideline is based on evidence from field sites and is, therefore, fully validated (see Beavers and Worthingham 2002).
Guideline H-I-7: Overprotection of the pipe can lead to the formation of H_2 bubbles that block the CP from reaching the pipe.	H010, H027, H075	No direct evidence from field observations.
Guideline H-I-8: In general, the closer the off-potential is to -850 mV_{CSE} the more likely high-pH SCC becomes.	H018	Based on comparison of lab-measured cracking potentials and -850 mV CP criterion. No CP data provided by operators as part of current study.

continued ….

Table D.2: SCC Guidelines – High-pH SCC Susceptibility (continued).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-I-9: Under some circumstances, the -100 mV polarization criterion may not offer protection from high-pH SCC.	H183	Based on comparison of lab-measured cracking potentials and -100 mV CP criterion. No CP data provided by operators as part of current study.
Guideline H-I-10: If CP is lost entirely, the potential can stay within the cracking range for periods of months.	H050	Based on evidence from lab studies. No depolarization data provided as part of current study.
Guideline H-I-11: The most important characteristics of the coating are the resistance to disbondment and the ability of CP to reach the pipe surface.	H083, H084	Consistent with field evidence for high-pH SCC.
Guideline H-I-12: Seasonal or episodic changes in environmental and operating conditions can lead to changes in the cracking environment.	H014	Consistent with observations of King et al. (2004) of transitional nature of high-pH SCC sites.
Guideline H-I-13: The different susceptibility of steels is associated with differences in their cyclic stress-strain behaviour.	H028, H062, H088	No direct field evidence available.
Guideline H-I-14: Steels with uniform microstructures are less susceptible to high-pH SCC.	H098, H099, H104, H152	No direct field evidence supplied as part of survey for current project.
Guideline H-I-15: Pipes retaining the original surface finish are more susceptible than pipes that have a blasted surface.	H008, H047, H048, H077, H087, H102, H103	Consistent with observation that all high-pH SCC failures have occurred on pipe with field-applied coating (Appendix C).
Guideline H-I-16: The susceptibility to high-pH SCC increases with increasing cyclic loading.	H162, H163	Consistent with predominance of high-pH SCC failures close to compressor stations, although this field observation seems to be explainable based on the effect of temperature only.

continued ….

Table D.2: SCC Guidelines – High-pH SCC Susceptibility (concluded).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-I-17: There is a low probability of cracking at locations with mild cyclic loading.	H076	No comparative SCADA pressure data available with which to validate this guideline.
Guideline H-I-18: Unlike near-neutral pH SCC, there is no evidence that stress raisers increase the probability of cracking.	H033	Consistent with, and partly based on, field observations that high-pH SCC occurs no more preferentially at stress raisers than in the body of the pipe.
Guideline H-I-19: High-pH SCC is unlikely to occur on liquid pipelines unless the fluid is heated or the line is located in a warmer region.	H030	Consistent with, and partly based on, field evidence showing absence of high-pH SCC on liquid lines. Consistent with known importance of temperature as the major contributing factor to SCC crack growth.

Table D.3: SCC Guidelines – High-pH SCC Crack Initiation.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-II-1: Cyclic loading promotes crack initiation.	H011, H041, H042, H061, H094, H121, H122, H128, H154	No comparative SCADA pressure data available with which to validate this guideline.
Guideline H-II-2: Under static loading, the threshold stress is approximately equal to the actual yield stress of the pipe.	H060, H161	No field data available for lines operated under static, or near-static, conditions.
Guideline H-II-3: Higher operating pressures lead to a greater number of more-densely spaced cracks in a shorter time.	H056, H092, H112, H147, H156	May be consistent with observed higher failure frequency at higher MAOP (see Appendix C), although the greater the crack density the more likely the cracks are to become dormant due to shielding. Therefore, might expect that this guideline would result in fewer failures with increasing MAOP. However, there are additional factors in play, such as the effect of loading on crack growth rates.
Guideline H-II-4: The rate of crack initiation decreases with time.	H057, H124, H157, H158, H165, H166	No time-dependent information about field crack colonies available. Typically, any initiated cracks that are found are removed during excavations and not allowed to develop further.
Guideline H-II-5: Grit-blasted surfaces exhibit a higher threshold stress.	H059, H155	Consistent with absence of high-pH SCC on lines with mill-applied coating (Appendix C).

Table D.4: SCC Guidelines – High-pH SCC Early-stage Crack Growth and Dormancy.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-III-1: The crack growth rate decreases with time.	H052, H090, H123, H157	No direct field evidence available, as any cracks discovered during excavations are typically removed. Furthermore, there is a lack of reliable repeat ILI data for gas pipelines.
Guideline H-III-2: The maximum crack growth rate increases with strain rate.	H054, H055, H082	No direct field evidence available. However, consistent with observation of higher failure frequency with increasing MAOP (on assumption that strain rate increases with MAOP, i.e., that the period of pressure cycles is independent of load).
Guideline H-III-3: The majority of cracks will become dormant at some stage in their growth.	H053, H067, H091, H107, H132, H145, H150	No time-dependent crack growth information available from field for high-pH SCC.
Guideline H-III-4: Various factors can prevent cracks from becoming dormant.	H058, H108	In the absence of time-resolved crack growth information from field, difficult to conclude whether cracks are, or are not, dormant.
Guideline H-III-5: Dormant cracks can be reactivated.	H067, H069, H160	See above.
Guideline H-III-6: Coalescence of cracks promotes continued crack growth.	H069, H096, H159	Inasmuch as field cracks show evidence for coalescence, then this guideline is validated. However, no direct field evidence for effect of coalescence and crack interactions on crack growth rate.

Table D.5: SCC Guidelines – High-pH SCC Late-stage Crack Growth.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline H-IV-1: Beyond a certain threshold, cracks enter Stage 4 of the overall cracking process.	H051, H097, H106, H168	No direct field evidence.
Guideline H-IV-2: Cracking becomes more severe with increasing temperature.	H007, H119, H140	As noted above, and as discussed in more detail in Section D.2.1, temperature is known to have a predominant effect on crack growth in the field.
Guideline H-IV-3: Cracking occurs in a range of potentials.	H037, H117	Consistent with field observation that cracking does not occur on adequately protected pipe.
Guideline H-IV-4: The crack growth rate depends on the composition of the electrolyte.	H116, H141, H144	Little field evidence available to support conclusion that crack growth rate increases with electrolyte concentration. Primarily a lab observation.
Guideline H-IV-5: The crack growth rate in Stage 4 is independent of the pipeline steel properties.	H079, H080	No direct field observations. Generally, all ferrite-pearlite steels are considered to be equally susceptible to high-pH SCC.

Table D.6: SCC Guidelines – Near-neutral pH SCC Fundamental Principles.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-0-1: Near-neutral pH SCC occurs at (or within 10-20 mV) of the native potential (also referred to as the corrosion, free-corrosion (FCP), or open-circuit (OCP) potential).	N085	Consistent with many, but not all, field studies that show that near-neutral pH SCC is associated with wet, anaerobic sites (see, for example, King et al. 2004, Leeson and Spitzmacher 2006, Wilmott and Diakow 1998).
Guideline N-0-2: Unlike high-pH SCC, there is no apparent effect of temperature for near-neutral pH SCC.	N015, N303	Consistent with various field studies.
Guideline N-0-3: Cyclic loading is important for all aspects of near-neutral pH SCC, including crack initiation, early-stage growth and dormancy, and late-stage crack growth.	N088, N097, N116, N118, N125, N129, N152, N155, N206, N261, N262, N263, N266, N269, N284, N289, N300, N315	Accounts for decreasing failure frequency with increasing distance downstream of compressor and pump stations. Apparent in many field studies, but Leeson and Spitzmacher (2006), in particular, show a strong field correlation between stress and near-neutral pH SCC.
Guideline N-0-4: Near-neutral pH SCC requires the presence of CO_2, but the occurrence of cracking is independent of the concentration of CO_2.	N002, N014, N039, N143, N241, N275, N288, N293, N302	Anecdotal field evidence for effervescence of trapped electrolytes demonstrates presence of CO_2. No field data relating occurrence or severity of cracking to CO_2 concentration.
Guideline N-0-5: Near-neutral pH SCC is often found at locations where environmental conditions change with time, implying cracking need not be continuous.	N078, N094, N179, N180, N181	Evidence from field monitoring studies (e.g., King et al. 2004) for transitional nature of near-neutral pH SCC sites.
Guideline N-0-6: The mechanism and management of SCC on gas and liquid lines may differ because of the difference in severity of cyclic loading.		Implication of SCC mechanism.
Guideline N-0-7: On asphalt and coal-tar enamel coated lines, not all cases of transgranular cracking are necessarily near-neutral pH SCC.	N005, N006, N007, N026, N041, N043, N044, N060, N080, N090, N179	Evidence from French studies (Le Friant et al. 2000) that not all field transgranular failures due to near-neutral pH SCC.

continued …..

Table D.6: SCC Guidelines – Near-neutral pH SCC Fundamental Principles (Concluded).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-0-8: Transition from near-neutral pH SCC to high-pH SCC is possible.	N030, N059, N070, N344	Not specifically reported from field studies but some cracks do exhibit both TG and IG characteristics.
Guideline N-0-9: Hydrogen plays a role in both crack initiation and propagation.	N001, N013, N016, N031, N019, N036, N047, N056, N064, N084, N086, N092, N094, N098, N142, N146, N171, N220, N233, N234, N291, N294, N295, N319, N346	No direct field evidence. Guideline based primarily on overwhelming evidence from lab studies.
Guideline N-0-10: The latter stages of crack growth are controlled by a corrosion fatigue mechanism.	N022, N037, N058, N102, N103, N106, N107, N158, N228	Supported by distribution of failures as a function of distance downstream of compressor stations (Appendix C) and supporting analyses based on corrosion fatigue mechanism.
Guideline N-0-11: All aspects of crack initiation and growth exhibit some degree of variability.	N271, N288, N307	Field-derived mean crack growth rates exhibit variability, as does the occurrence of SCC under apparently similar conditions.

Table D.7: SCC Guidelines – Near-neutral pH SCC Susceptibility.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-I-1: The native potential must be below the H_2/H_2O equilibrium line which, for most soils, is in the range -670 to -790 mV_{CSE}.	N005, N175, N177, N179, N186	Consistent with requirement for redox potential more negative than -0.68 V_{CSE} (Van Boven et al. 2004). Also consistent with redox potentials measured at 9 near-neutral pH SCC sites measured by King et al. (2004).
Guideline N-I-2: No single soil species or property determines the overall SCC susceptibility.	N174	Consistent with the inability of pipeline operators to locate near-neutral pH SCC with confidence based on a limited number of site descriptors.
Guideline N-I-3: Site selection should take into account multiple contributing factors rather than rely only on one or two indicative parameters.	N178, N187	Where they have been successful, site-selection models have included a range of indicative parameters.
Guideline N-I-4: On one particular line, no SCC was found at locations with a soil resistivity greater than 14,000 ohm·cm.	N185	Based directly on field observation (Van Boven et al. 2004).
Guideline N-I-5: There is no conclusive proof that microbes play a role in near-neutral pH SCC.	N189, N198, N247	Microbes are ubiquitous in soil environments and it is difficult to obtain evidence of cause-and-effect from field data.
Guideline N-I-6: The pH associated with near-neutral pH SCC is inconsistent with significant CP reaching the pipe surface.	N301, N332, N334, N335	Based on field measurements of pH under disbonded coating where near-neutral pH SCC has been found.
Guideline N-I-7: Certain electrolytes maintain a sharp crack tip and promote crack growth.	N210	Lab observation for which there is currently no substantive field evidence, although it is known that some field cracks exhibit sharp crack tips.

Continued …

Table D.7: SCC Guidelines – Near-neutral pH SCC Susceptibility (Continued).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-I-8: The only coating that appears to offer resistance to near-neutral pH SCC is fusion bonded epoxy (FBE).	N309, N310, N323, N327	Directly supported by absence of near-neutral pH SCC failures on FBE-coated lines (except for one case in a dent).
Guideline N-I-9: The presence of stress raisers promotes both crack initiation and growth.	N009, N010, N148, N150, N151	Consistent with extensive field observations of near-neutral pH SCC associated with dents, gouges, corrosion, long seam weld, etc. (NEB 1996, Leeson and Spitzmacher 2006, Youzwishen et al. 2004).
Guideline N-I-10: On liquid lines, the occurrence of large amplitude, high-frequency pressure fluctuations promotes mechanically driven initiation and crack growth.	N011	Supported by prevalence of cracking immediately downstream of pump stations (e.g., Leeson and Spitzmacher 2006). Also supported by correlation between pressure fluctuations and occurrence of SCC (Been et al. 2006).
Guideline N-I-11: The incidence of near-neutral pH SCC correlates with areas of high tensile residual stress.	N221, N250, N252, N253	Based on a correlation of field SCC colonies and residual stress on pipe (Beavers et al. 2000).
Guideline N-I-12: Dents lead to high local stresses and can promote near-neutral pH SCC.	N239, N240, N321	Majority of reported cases of SCC (up to that time) associated with some form of stress raiser, including dents (NEB 1996).
Guideline N-I-13: While cyclic loading in general promotes near-neutral pH SCC, certain loading patterns are particularly dangerous.	N261, N262, N263	No direct field evidence as unable to associate crack growth with specific loading events.
Guideline N-I-14: When selecting SCC sites based on stress considerations, all sources of stress need to be taken into account.	N268	Clear evidence for importance of residual and applied stresses on near-neutral pH SCC (NEB 1996, Beavers et al. 2000, Leeson and Spitzmacher 2006, Youzwishen et al. 2004).

Continued …

Table D.7: SCC Guidelines – Near-neutral pH SCC Susceptibility (Concluded).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-I-15: The presence of cold work promotes near-neutral pH SCC.	N028	No direct field evidence, although correlation of cracking with bends (Youzwishen et al. 2004) and dents (NEB 1996) is suggestive.
Guideline N-I-16: Modern steels appear to be less susceptible than older ferrite-pearlite steels.	N067, N176	Circumstantial evidence based on absence of SCC failures on pipe installed since 1981, although this is more likely due to the use of mill-applied coatings and the short elapsed time.
Guideline N-I-17: All grades of older ferrite-pearlite steel appear to be susceptible to near-neutral pH SCC.	N099, N191, N256, N257, N258, N259	No evidence from field that, apart from ERW pipe, there is any difference in susceptibility of pipe. Beavers and Harper (2004) did demonstrate that pipe manufacturer was an indicator of susceptibility, but this was thought to be due to the level of residual stress.
Guideline N-I-18: The presence of millscale on the pipe surface increases susceptibility to near-neutral pH SCC.	N061, N062, N063, N074, N076, N153	Supported by the absence of near-neutral pH SCC failures on lines with mill-applied coating.
Guideline N-I-19: Electric resistance welded (ERW) pipe is particularly susceptible to near-neutral pH SCC.	N264, N286, N318	Supported by evidence from field.
Guideline N-I-20: Low-temperature creep is an important process in various stages of cracking.	N206, N215, N267	No direct supportive field evidence.

Table D.8: SCC Guidelines – Near-neutral pH SCC Crack Initiation.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-II-1: Crack initiation requires some type of stress raiser.	N035, N072, N096, N151, N170, N192	Consistent with relatively uniform distribution of crack colonies with distance downstream of the pump or compressor station (CEPA 2000) since, unlike the operating stress, the distribution of stress raisers would be expected to be uniform along the pipe.
Guideline N-II-2: Cyclic loading, especially of higher frequency and larger amplitude, promotes initiation.	N116, N129, N192, N193, N200, N205, N206, N225, N238, N270, N272, N273, N315, N316	Overwhelming evidence from lab studies for the importance of cyclic loading on crack initiation. Inasmuch as cyclic loading affects all locations along the pipe, consistent with relatively uniform distribution of colonies with shallow cracks (CEPA 2000).
Guideline N-II-3: High levels of tensile residual stress promote crack initiation.	N195, N221	Consistent with report by Beavers et al. (2000) relating regions of high residual tensile stress with crack colonies.
Guideline N-II-4: Pre-existing cracks influence crack initiation resulting in bands of cracks.	N304, N313	No direct field evidence.
Guideline N-II-5: The probability of initiation is enhanced by the presence of millscale.	N017, N060, N076, N114, N128, N278, N349, N350	Consistent with absence of SCC on pipelines with mill-applied coating.
Guideline N-II-6: Steels with high inclusion content, especially manganese sulphide inclusions, are more susceptible to crack initiation.	N034, N047, N054, N065, N081, N083, N087, N120, N121, N122, N126, N226, N256	No direct supportive field data.
Guideline N-II-7: The presence of martensite promotes crack initiation.	N066, N073	No direct supportive field data.
Guideline N-II-8: Crack initiation can occur near the edge of well-bonded coating.	N115, N130	No direct supportive field data, although anecdotal evidence suggests cracks can initiate under apparently well-bonded coating.

Table D.9: SCC Guidelines – Near-neutral pH SCC Early-stage Crack Growth and Dormancy.

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-III-1: Factors that lead to higher absorbed hydrogen concentrations lead to an increase in crack growth rate.	N004, N012, N117, N143, N146, N212, N229, N279	Some evidence linking presence of sulphide with incidence of near-neutral pH SCC, but no systematic study performed.
Guideline N-III-2: Unload/reload cycles can prevent dormancy, re-initiate dormant cracks, and accelerate active cracks.	N053, N163	No systematic field study performed.
Guideline N-III-3: The crack growth rate increases with increasing strain rate.	N088, N097, N156, N157, N161	On the assumption that higher strain rates correlate with larger amplitudes, then observation of higher frequency of failures closer to compressor or pump stations is consistent with guideline.
Guideline N-III-4: For deeper cracks and/or larger amplitude or higher frequency pressure fluctuations, crack growth is largely mechanically driven.	N048, N050, N052, N102, N103	No direct field validation available.
Guideline N-III-5: For mechanically shorter (shallower) cracks and/or smaller amplitude or lower frequency pressure fluctuations, crack growth is influenced more by the strain rate.	N046, N048, N050, N102, N103, N156, N157	No direct supporting field evidence available.
Guideline N-III-6: Environmental, rather than mechanical loading, conditions may determine the growth of mechanically short (shallow) cracks.	N108, N110, N112, N113, N131, N133, N134, N137, N138, N139	Inasmuch as corrosion fatigue models underestimate crack growth rates for gas pipelines, guideline is consistent with cracks on gas pipelines exhibiting short crack behaviour.
Guideline N-III-7: Mechanically short (shallow) cracks can grow below the threshold conditions for deeper cracks.		No direct supporting field evidence available.

Continued …

Table D.9: SCC Guidelines – Near-neutral pH SCC Early-stage Crack Growth and Dormancy (Continued).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-III-8: Factors that promote crack dormancy include: lower-amplitude, lower-frequency pressure fluctuations; the accumulation of corrosion products in cracks; changes in crack chemistry; an increase in the number of cracks; stress shielding due to dense crack spacing (defined as a circumferential spacing of less than 20% of the pipe wall thickness); crack-tip blunting by dissolution and/or creep; regions of compressive or reduced tensile residual stress; near-static loading; exhaustion of the supply of diffusible hydrogen; and harder pearlite grains.	N095, N100, N119, N162, N166, N196, N199, N201, N213, N214, N216, N217, N230, N235, N236, N276, N280, N299, N328	No systematic study to correlate these factors with the population of shallow, dormant cracks has been carried out.
Guideline N-III-9: Factors that can re-activate dormant cracks include: unload/reload cycles, more-aggressive cyclic loading conditions, an increase in CO_2 level, an increase in the flux of diffusible hydrogen, or coalescence with growing cracks.	N154, N162, N163, N166, N167, N237, N314	This guideline would be difficult to validate against field data as it requires detailed knowledge of environment and colony development.
Guideline N-III-10: Environmental factors that promote early-stage crack growth include: the presence of sulphide or SRB activity, increased bicarbonate ion concentration, or increased CO_2.	N124, N137, N139, N144, N167	Some evidence linking SRB to crack growth, but in general there is a lack of environmental data in the currently available field data sets.
Guideline N-III-11: Environmental factors that inhibit early-stage crack growth include: organics.	N142	Consistent with absence of cracking on pipelines fully surrounded in an organic soil as observed, amongst other places, in N. Ontario.
Guideline N-III-12: High tensile residual stress promotes crack growth and prevents dormancy.	N196, N197, N198, N200, N202, N221, N250, N251, N252	Consistent with report by Beavers et al. (2000) relating regions of high residual tensile stress with crack colonies.

Continued ….

Table D.9: SCC Guidelines – Near-neutral pH SCC Early-stage Crack Growth and Dormancy (Concluded).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-III-13: Near-neutral pH SCC on gas transmission pipelines is likely to involve repeated cycles of crack growth and dormancy.	N218	Difficult to validate in the absence of reliable repeat ILI data for gas pipelines.
Guideline N-III-14: Cracks in sparse patches are more likely to continue to grow than densely spaced cracks.	N329	Guideline derived, in part, from examination of field samples. Therefore, implicitly validated against field data.
Guideline N-III-15: Cracks coalesce if their circumferential spacing is less than 0.14 of their length.	N308	Guideline developed on basis of field crack colonies. Therefore, implicitly validated against field data.

Table D.10: SCC Guidelines – Near-neutral pH SCC Late-stage Crack Growth

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-IV-1: Stress raisers, such as dents, increase the crack growth rate.	N009, N010, N011	Consistent with association of the majority of failures with some form of stress raiser (NEB 1996).
Guideline N-IV-2: On liquid lines, the greater number of large-amplitude, high-frequency pressure fluctuations enhance mechanically driven crack growth.	N011, N037, N107	Consistent with apparent success in correlating SCC locations with regions experiencing severe pressure fluctuations on liquid lines (Been et al. 2006).
Guideline N-IV-3: On gas lines, the majority of damage is caused by a few high-amplitude pressure fluctuations.	N106	Consequence of nature of pressure fluctuations on gas lines (Van Boven et al. 2002).
Guideline N-IV-4: Both the frequency and amplitude of pressure fluctuations are important in determining the rate of late-stage crack growth.	N022, N037, N045, N048, N050, N058, N102, N103, N107, N158	Amplitude effect consistent with apparent success in correlating SCC locations with regions experiencing severe pressure fluctuations on liquid lines (Been et al. 2006). However, the same study showed no correlation with strain rate-based models.
Guideline N-IV-5: Variable amplitude cyclic loading is more damaging than relatively constant amplitude pressure cycles.	N118	No detailed examination of this proposed mechanism has been performed.
Guideline N-IV-6: Unload/reload cycles promote crack growth.	N053	Validation would require comparison of crack growth rates on lines experiencing different numbers of unload/reload cycles (e.g., a batched versus non-batched liquid line).

Continued ….

Table D.10: SCC Guidelines – Near-neutral pH SCC Late-stage Crack Growth (Concluded).

SCC Guideline	Underlying R&D Guideline	Development and Validation of SCC Guidelines
Guideline N-IV-7: Underload/reload cycles promote crack growth.	N261	No detailed examination of this proposed mechanism has been performed.
Guideline N-IV-8: Overloads inhibit subsequent crack growth.	N260	Although there is no direct field proof, it is commonly believed that hydrostatic testing inhibits subsequent crack growth, for which there is some evidence from fracture surfaces when subsequent failure has occurred.
Guideline N-IV-9: Cracking occurs during the loading half of the pressure cycle.	N262, N263	This guideline would be difficult to validate in the field as it would require a high resolution on-line crack detection technique.
Guideline N-IV-10: Cracks in sparse crack patches are more likely to continue to grow than cracks in dense patches.	N329	Guideline derived, in part, from examination of field samples. Therefore, implicitly validated against field data.
Guideline N-IV-11: The presence of sulphide enhances crack growth.	N023, N124, N145, N172	Evidence for sulphide species at some, but not all, near-neutral pH SCC failure sites.
Guideline N-IV-12: Organics can suppress crack growth.	N142, N188	Consistent with absence of cracking on pipelines fully surrounded in an organic soil as observed, amongst other places, in N. Ontario.

D.2 DETAILED NOTES ON VALIDATION PROCESS

Detailed analyses of various SCC Guidelines have been carried out and are summarized here.

D.2.1 Temperature Dependence of High-pH SCC

A number of the SCC Guidelines would imply that the occurrence and severity of high-pH SCC on gas transmission lines should decrease as a function of distance downstream from the compressor station. The gas (and, it is assumed, the pipe-wall) temperature is known to decrease approximately exponentially with distance downstream of the compressor station. A simple expression that can be used to estimate the dependence of the temperature on the distance from a compressor station is

$$T_X = T_G + (T_D - T_G)e^{-\alpha x} \qquad \text{(D-1)}$$

where T_D is the gas discharge temperature, T_G is the ground temperature, T_X is the temperature at a distance x from the compressor station, and α is a constant describing the rate of decrease of temperature with distance. Although the precise temperatures for the field data are unknown, let us assume a gas discharge temperature of 45°C, a ground temperature of 15°C, and a value for α of 0.045 $mile^{-1}$. Based on these data, the distance dependence of the temperature can be predicted.

The rate of thermally controlled processes (R) is typically described by the Arrhenius expression

$$\log_{10}\left(\frac{R_2}{R_1}\right) = \frac{\Delta E}{2.3R}\left(\frac{1}{T_1} - \frac{1}{T_2}\right) \qquad \text{(D-2)}$$

where R_1 and R_2 are the rates at temperatures T_1 and T_2, respectively, R is the gas constant, and ΔE is the activation energy. The activation energies for all of the temperature-dependent processes that affect the occurrence and severity of SCC are unknown (although values are known for the crack growth rate for high-pH SCC and the rate of generation of CO_2), but they would typically vary from 15 kJ/mol (typical for aqueous diffusion processes) to 60 kJ/mol (typical of many chemical processes). Based on this range of ΔE values, it is then possible to predict the rate of reaction relative to that at a standard temperature using Equation (D-2).

Figure D-1 shows the theoretical relative rate of reaction for three activation energies of 15, 40, and 60 kJ/mol plotted as a function of distance downstream of the compressor station. In the figure, the rates are plotted relative to that at x = 0, i.e., the compressor station discharge, so that the relative rates downstream have values <1.

Also shown on the figure are three sets of field data from the JIP study (ASME 2008). These data sets represent the occurrence of high-pH SCC relative to that at the compressor station discharge location for different coating types and different sources. The three sets are:

- in-service and hydrostatic test failures on coal-tar enamel (CTE) coated lines,
- the number of excavations in which SCC was found for CTE-coated lines, and
- the number of occurrences of SCC from any source for polyethylene tape-coated lines.

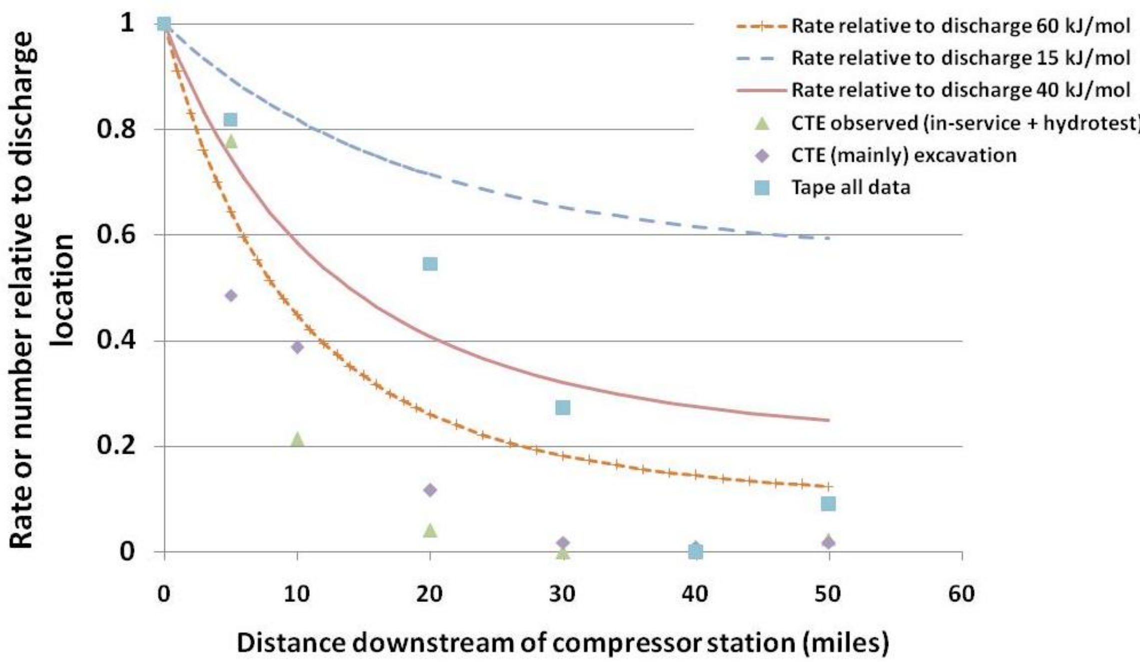

Figure D-1: Comparison of the Relative Occurrence of High-pH SCC as a Function of Distance Downstream of the Compressor Station with Theoretical Dependences Based on a Thermally-activated Rate-controlling Process with Different Assumed Activation Energies. Note that there is a single point for the "Tape all data" at a distance of 10 miles that is off scale at a relative value of 2.7 that is not shown in the figure.

There are a number of interesting features apparent from this comparison:

- For CTE-coated lines, either the value of ΔE is >60 kJ/mol or the field data do not follow a simple Arrhenius relationship. An activation energy of >60 kJ/mol would be unusual for an aqueous system at near-ambient temperature. Alternatively, because the data fit an activation energy of ~60 kJ/mol at short distances but not at distances >10 miles, it is possible that more than one process with differing temperature dependences may be involved. This latter explanation is perhaps both more likely and not surprising, but it is an insight provided by this type of detailed validation exercise.
- For CTE-coated lines, there is some indication that the occurrence of SCC from excavations is more widely spread that SCC failures (in-service and hydrostatic test). Excavations will identify all SCC, whilst failures clearly only relate to the deepest cracks.

- Although the data for tape-coated lines may appear to fit an Arrhenius dependence with an activation energy of ~40 kJ/mol, most occurrences occurred at a distance of 10 miles (not shown on the figure). Therefore, the nature of the cracking process is different for tape-coated lines than for CTE-coated lines. Tape is traditionally considered to be shielding and, since the generation of the high-pH SCC environment is associated with the presence of CP, it is perhaps not unexpected that this coating should show a different behavior from a CP-permeable coating such as CTE. What is important here, however, is that the identification of sites for high-pH SCC depends strongly on the coating type.

Having performed this quantitative validation of the guidelines based on the JIP data, it is apparent that the data can be used for more than a simple validation exercise. Comparison of the field data with the mechanistically-based guidelines provides insight into the factors that determine the location, extent, and severity of cracking. In the particular example given above, it is apparent that different processes affect cracking under the different types of coating. For example, the location and severity of cracking for tape-coated lines is quite different from that for CTE-coated lines.

D.2.2 Near-neutral pH SCC of Liquid Pipelines

Let us assume that the dependence of the probability P_i of cracking downstream of the compressor or pump station for variable i is given by

$$P_i = f_i e^{-a_i x} \qquad \text{(D-3)}$$

where f_i is a pre-exponential factor, a_i describes the distance dependence, and x is the distance from the upstream compressor/pump station. The variable i could describe any one of a number of factors that control the occurrence and severity of SCC, such as the various effects of temperature and pressure. The definition of the probability P_i depends on which of the stages of cracking is being considered, and could refer to the probability (or frequency) of initiated cracks , the frequency of “shallow” crack colonies, or the frequency of failures. The overall probability of cracking P_{SCC} is then given by the product of the probabilities for the controlling variables

$$P_{SCC} = \prod_{i=0}^{n} f_i e^{-a_i x} = f_0 f_1 ... f_n e^{-(a_0 + a_1 ... + a_n)x} \qquad \text{(D-4)}$$

Although the assumption of an exponential dependence of cracking on distance is arbitrary, there is a mechanistic basis for a number of variables.

A number of researchers consider near-neutral pH SCC to be a corrosion-fatigue mechanism, of the general form (Been et al. 2008)

$$\frac{da}{dN} = C\Delta K^{m} \qquad \text{(D-5)}$$

where a is the crack length, N is the number of cycles, C and m are constants, and ΔK is the change in stress intensity factor during the cycle. The crack growth rate da/dt is given by

$$\frac{da}{dt} = f \cdot C\Delta K^{m} \qquad \text{(D-6)}$$

where f is the frequency of loading.

On the basis of Equation (D-6), the rate of cracking would depend on the distance from the compressor station if any of the parameters f, C, ΔK, or m were also to exhibit a distance dependence. Because of the value of m (typically in the range 2-3), the cycles contributing most to crack growth are the larger cycles (e.g., $\Delta K > 10\ MPa \cdot m^{1/2}$). Van Boven et al. (2002) report that the frequency of such large cycles decreases with increasing distance downstream of the pump station. The parameter C is partly determined by environmental factors which, in the absence of specific information, are assumed to not change with location. Therefore, the distance dependence of crack growth by corrosion fatigue is assumed here to be solely due to the distance dependence of the frequency of large cycles. Based on this assumption, the distribution of cycles for an NPS34 liquid transmission line reported by Van Boven et al. (2002) would produce a value for the distance-dependence parameter a in Equation (D-3) of 0.033. In comparison, fitting of CEPA data (CEPA 2000) for the frequency of SCC colonies to the same exponential-type expression produces a value for the distance-dependence parameter of 0.025 for colonies with cracks <10% through wall and 0.031 for colonies >10%, albeit with relatively poor fits (Figure D-2).

Figure D-3 shows the distribution of near-neutral pH SCC colonies along a liquid pipeline with relation to the operating stress (Leeson and Spitzmacher 2006). The exact relationship between the frequency of colonies and the operating stress is not given by the authors, but the close association of cracking with regions of high stress is consistent with the over-riding importance of the mechanical loading conditions for near-neutral pH SCC on liquid lines.

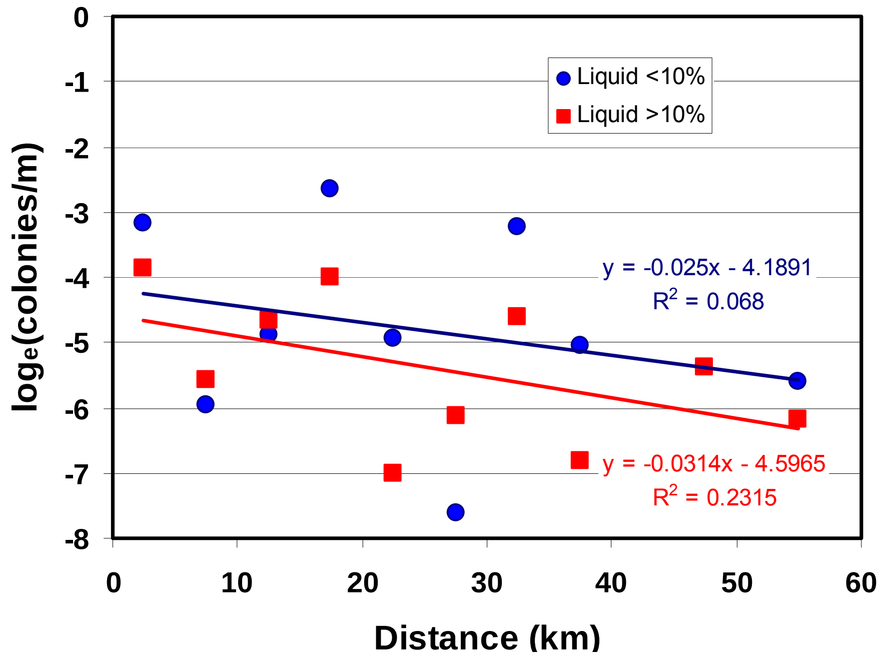

Figure D-2: Fit of the CEPA Near-neutral pH SCC Data for Liquid Lines to an Exponential Distance-dependent Expression.

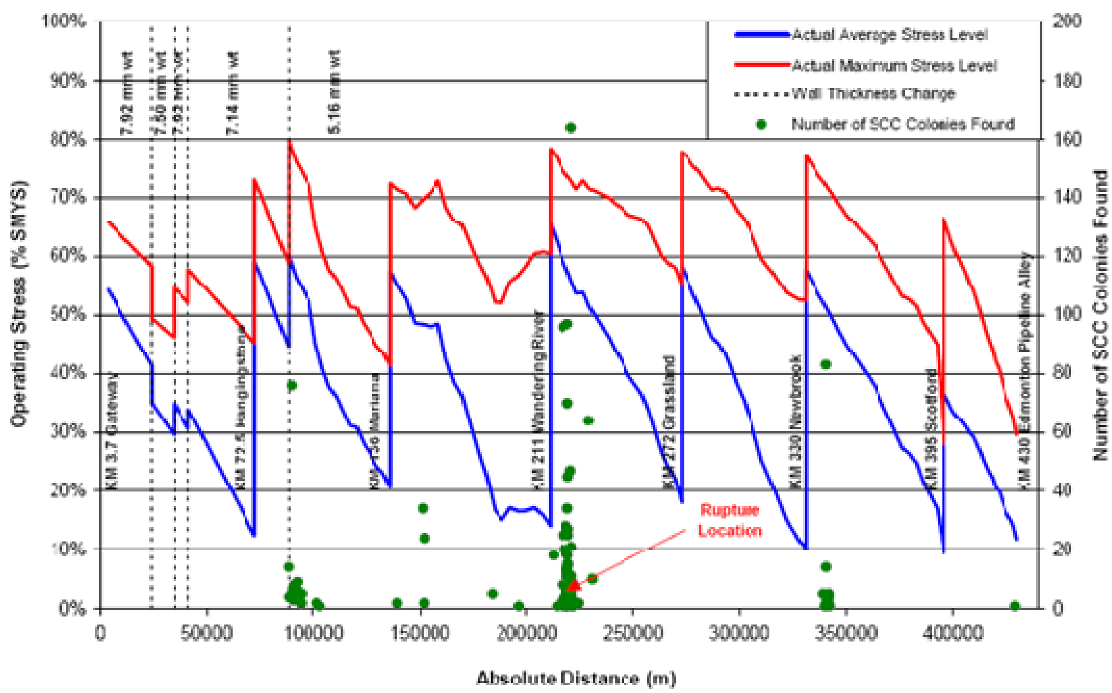

Figure D-3: Dependence of the Number of Near-neutral pH SCC Colonies on Operating Stress for an NPS16 Liquid Pipeline (Leeson and Spitzmacher 2006).

D.2.3 Near-neutral pH SCC of Gas Transmission Pipelines

The situation is somewhat different for the near-neutral pH SCC of gas transmission pipelines. First, there are fewer large cycles observed on gas lines (Van Boven et al. 2002). Second, at least based on the data in Figure D-4, there is a strong dependence of near-neutral pH SCC failures on distance, with a value for the exponential distance dependence parameter of between 0.046 (for distances <35 km downstream) and 0.082 (all data).

The discrepancy between the observed values of a and that inferred from the distribution of damaging cycles (Van Boven et al. 2002) suggests that other processes are also involved in determining the extent of crack growth. Again, in the absence of specific information about the environmental conditions, it is possible that a temperature-dependent process is an important contributor. The observed values of a could be explained by a thermally activated process with an activation energy of ~10 kJ/mol, but what this process might be is not currently understood.

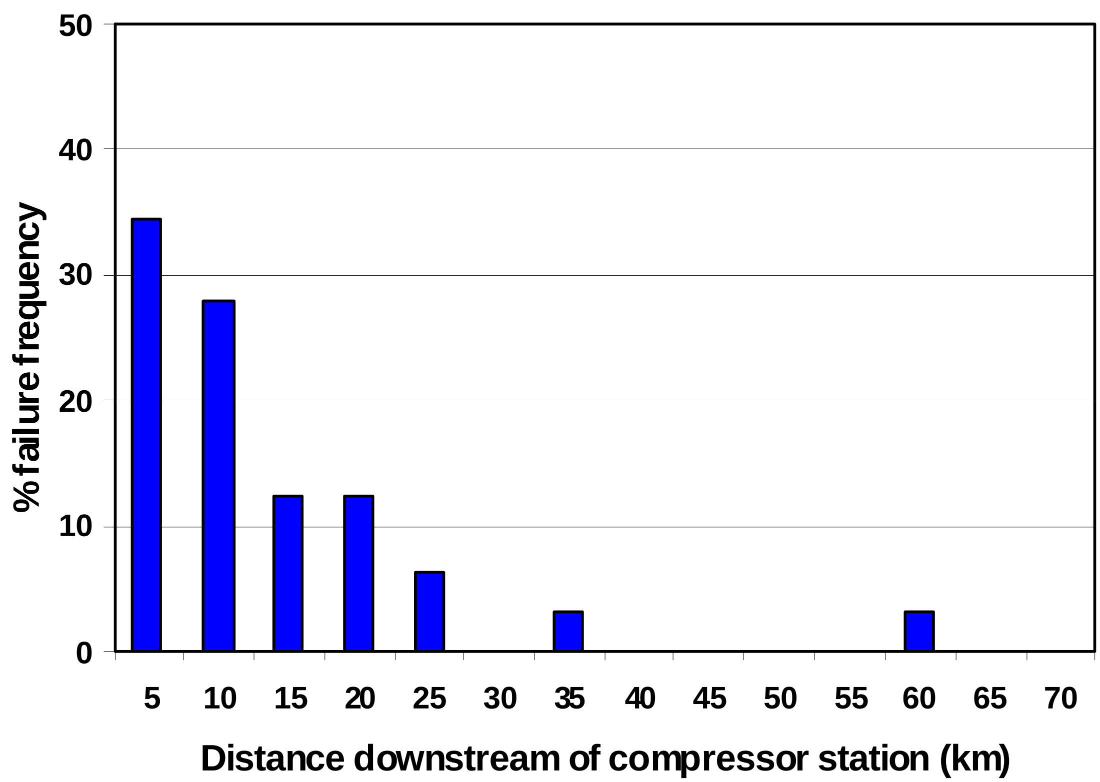

Figure D-4: Distribution of In-service and Hydrostatic Test Near-neutral pH SCC Failures on Gas Transmission Pipelines as a Function of Distance Downstream of the Compressor Station Discharge (King et al. 2003).

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