Appendix A

Stress Corrosion Cracking Research Gap Analysis

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A Research Gap Analysis

A.1 Mechanisms of SCC

A.1.1 Mechanism of High pH SCC

There is almost universal agreement that crack initiation and growth in the high pH environment occur by selective dissolution of the grain boundaries, while a passive film forms on the remainder of the surface and on the crack sides to prevent corrosion at those locations. When an unstressed, polished surface of line-pipe steel is exposed to the high pH carbonate/bicarbonate environment at the appropriate potential for SCC, etching of the grain boundaries occurs with no noticeable corrosion of the grain faces (Parkins 1994). A strong correlation has been found between the maximum rate of crack growth and the maximum corrosion rate that can be sustained in that environment (Parkins 1987). The reason for preferential attack at the grain boundaries is thought to be related to some kind of chemical segregation or precipitation at the grain boundaries, but no direct evidence of either has been found.

Additional basic research into the fundamental mechanism of high pH SCC probably would not be justified.

A.1.2 Mechanism of Near-neutral pH SCC

Some researchers have suggested that the mechanism of initiation of near-neutral pH SCC may be different from that of crack growth (Fessler and Krist 2000). Neither stage of the cracking process is as well understood as is the mechanism of high pH SCC.

Crack Initiation. The mechanism for stress corrosion crack initiation in the near-neutral pH environment is not completely understood, but evidence from field failures suggests that corrosion pits might be a common site for crack initiation. In some cases the cracks were found in broad, shallow corroded areas. More commonly, there was very little corrosion visible to the naked eye, but very small corrosion pits at each crack have been seen with microscopic examination. Thus, many researchers believe that a corrosion pit may act as a stress raiser to initiate the stress corrosion crack. Also, the environment at the bottom of a pit will become more acidic.

Initiating near-neutral pH SCC in the laboratory under stressing conditions that are representative of those on an operating gas pipeline has proven very difficult. In experiments with polished, smooth specimens, researchers at CANMET produced clusters of transgranular cracks that appear very similar to near-neutral pH stress-corrosion cracks that have occurred in the field (Elboujdainia et al. 2000). The earliest cracks to appear initiated at corrosion pits that formed around nonmetallic inclusions, and later cracks grew from corrosion pits that formed randomly on the surface. However, cracks initiated only in tests that involved many thousands of high-amplitude (low-R) stress cycles, a situation that is not typical of gas pipelines. Tests with more realistic stressing conditions did not produce cracks. Therefore, there is a concern that the tests that produced cracks may have involved corrosion fatigue rather than SCC.

Several mechanisms for producing shallow crack-like features at the surface of a sample of line-pipe steel under more realistic loading conditions have been demonstrated by King, et al. (2001). Expanding upon previous work by Wang, et al., (2000) which showed that corrosion pits formed preferentially along the heavily deformed metal in scratches on the surface, it was then shown that the rows of corrosion pits would join and preferentially grow deeper if the scratches were perpendicular to the direction of the tensile stress. Chu, et al. (2004) showed that preferential corrosion occurs at the boundaries of pearlite colonies, and transgranular crack-like features can grow from such surface attack.

Another possible mechanism for initiation involves small cracks oriented approximately 45 degrees to the direction of the tensile stress that were produced on specimens that had been subjected to a series of cyclic stresses patterned after a typical 20-year service life. Presumably, the cracks formed where persistent slip bands intersected the surface of the specimen.

Crack Growth. Whereas a dissolution mechanism for high pH SCC was supported by the agreement between measured crack velocities and those that would be predicted from Faraday's Law and current densities measured in polarization experiments, the same did not appear to hold for near-neutral pH SCC. Anodic current densities measured near the open-circuit potential in near-neutral pH environments were on the order of 10 microamps per square centimeter, which would correspond to a crack velocity of about 10^{-8} mm/sec according to Faraday's Law (Parkins 1998). Whereas that crack velocity is considered to be a reasonable estimate for the maximum rate of crack growth in the field and also corresponds to typical velocities measured on laboratory specimens subjected to realistic stressing conditions, there were reports of measured crack velocities as high as 10^{-6} mm/sec. Therefore, people looked for other mechanisms that might explain a crack velocity that was 2 orders of magnitude larger than would be produced by dissolution according to Faraday's Law. Other mechanisms that are known to produce transgranular fractures in carbon steels include fatigue, corrosion fatigue, and hydrogen embrittlement, the latter mechanism being the one that has been embraced by most researchers.

The hydrogen theory was supported by the results of a variety of slow-strain-rate experiments. For example, Mao, et al. (1998) showed that precharging specimens with hydrogen prior to testing in the near-neutral pH environment caused a decrease in the final reduction in area, which was assumed to indicate more severe SCC. However, as is shown in Figure A-1, the precharged specimens did not exhibit lower ductility when tested in air, so some synergistic effect between the hydrogen and the corrosive environment may be indicated.

More evidence for synergy between corrosion and hydrogen was developed by Parkins (1999) when he used slow-strain-rate tests (SSRT) to measure reduction in area (RA) as a function of potential and compared those results with anodic current densities and hydrogen contents (as determined from permeation experiments) over the same range of potentials. As is shown in Figure A-2, the dip in RA, which presumably corresponds to the region of SCC, between –550 and –700 mV occurs where there are small but significant amounts of both corrosion and hydrogen. At less negative potentials, the hydrogen concentration drops to insignificant levels, and the RA rises to high values, indicating no more SCC. At potentials between –700 and –750 mV, the corrosion rate drops to insignificant levels and there is a local maximum in RA.

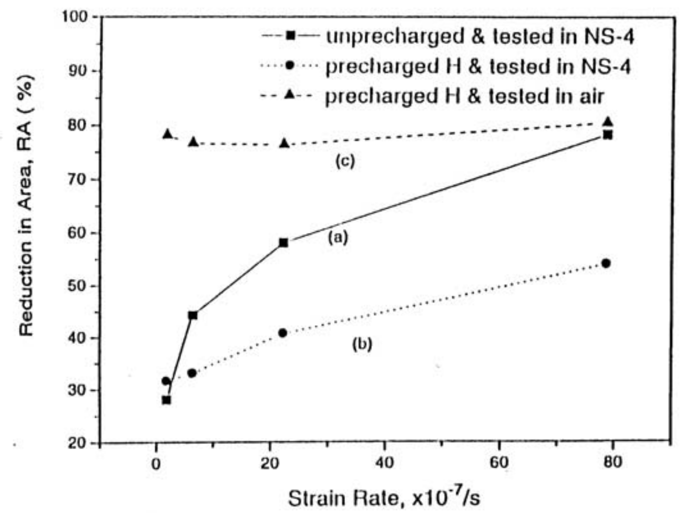


Figure A-13-1 Effect of Precharging with Hydrogen on Reduction in Area of SSRT Specimens Tested in NS4 and Air

The reason for the continual decline in RA at still more negative potentials is not clear. By analogy to the high pH SCC situation, one might believe that the decrease in RA at very negative potentials is due to some hydrogen effect that only occurs at very high levels of continuous plastic deformation and therefore is not relevant to an operating pipeline. Parkins (1998) has indicated that some SSRT specimens with RA values as low as 30 percent contained no detectable cracks, indicating that some embrittling, but not cracking, mechanism was operative. In fact, experience tells us that cathodically protected pipelines do not experience cracking problems where the potentials are adequate and the steel is not shielded from the cathodic-protection currents. An alternate point of view that is held by some researchers is that the SCC reaction continues to negative potentials in laboratory experiments because the stirring prevents the formation of an alkaline environment at the cathode, whereas that alkaline environment in the field will not support SCC at those potentials. Experiments that do not involve high amounts of plastic deformation (e.g. cyclic-load tests rather than SSRT) with stirred and stagnant environments will be required to clarify the significance of the low RA values at very negative potentials.

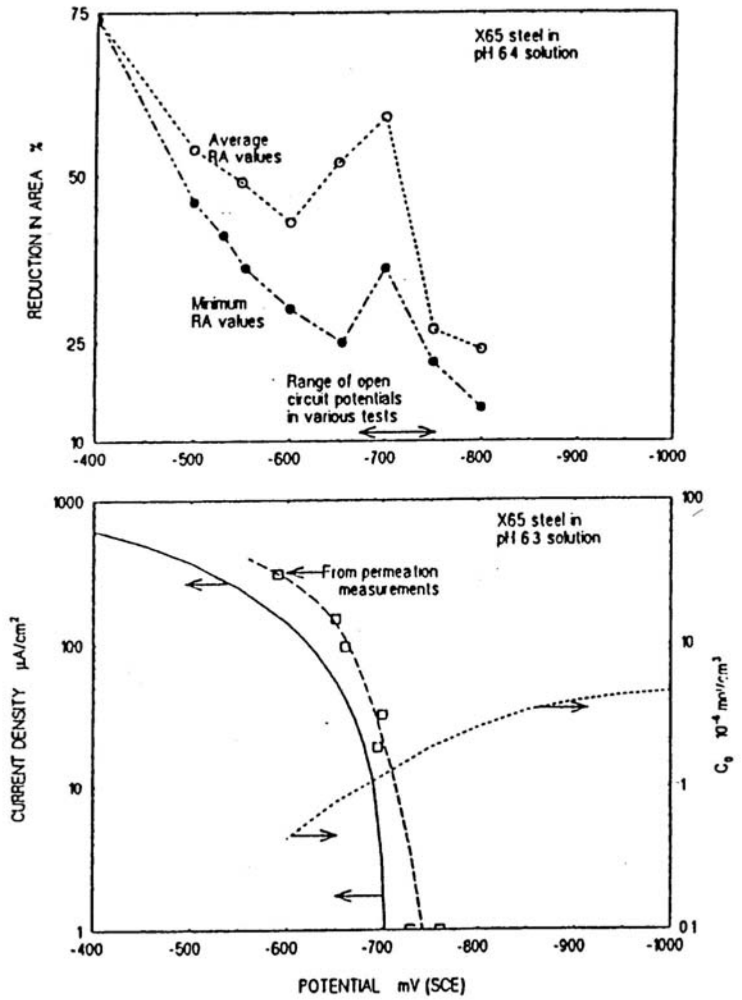


Figure A-13-2 Correlation Between Potential for Most Severe Near-neutral pH SCC and the Narrow Potential Range Where Both Dissolution and Hydrogen Entry Occur at Significant Levels

Even though a hydrogen-based theory is popular with most researchers in this field, there are several reasons that dissolution should not be ignored as possibly a significant part of the mechanism of near-neutral pH SCC:

1. Although hydrogen can cause delayed brittle fracture in very-high-strength steels at stresses below the yield strength, that phenomenon has not been observed in steels with yield strengths below 80 ksi (Fessler, Groeneveld, and Elsea 1973). Hydrogen can reduce the ability of lower-strength steels to tolerate large amounts of plastic deformation, but

pipelines do not experience large amounts of plastic deformation in service. It might not be coincidence that all experiments that seem to demonstrate an effect of hydrogen on SCC have involved SSRT.

2. The high crack velocities on the order of 10^{-6} mm/sec have only been observed on specimens that have been subjected to low-R (typically about 0.5) stress fluctuations. ("R" is "…the ratio of the minimum to the maximum load for each cycle" (King et al, 2001). As is described later in this report, there is reason to believe that the mechanism at low R may be corrosion fatigue rather than SCC. Laboratory experiments at R values of 0.85 and above, which are more typical of gas pipeline operation, usually produce crack velocities of 10^{-8} mm/sec or lower, which would not be inconsistent with Faraday's Law.
3. The anodic current densities that have been used with Faraday's Law were determined on undeformed coupons of steel. However, the steel at the tip of a crack (the plastic zone) is highly deformed. There are some reasons to believe that heavily deformed steel will corrode more rapidly than undeformed steel. It was mentioned previously that corrosion pits formed preferentially in the deformed metal in scratches on the surface of coupons. Foroulis and Uhlig (1964) determined that 50 percent cold work could increase the corrosion rate of carbon steels in 0.1N HCl by about 7 times, and subsequent aging at 100°C for a few hours could double the rate again. However, the effect of cold work on corrosion rate was not observed in neutral solutions. Whether there is an effect at the pH levels between 5 and 7 is not known. It also has been speculated that the pH inside the crack could be much lower than outside, which would tend to magnify the effect. Incidentally, Uhlig (1976) also showed that anodic dissolution enhances the room-temperature creep of cold worked iron and steel, and Oriani (Oriani and Josephic 1981) showed that hydrogen also enhances the room-temperature creep of steel, suggesting the possibility of several synergetic effects at the tip of the crack.
4. Another way that the corrosion rate at the crack tip might be accelerated is due to the fact that the hydrogen that is in the steel will preferentially move into the plastic zone. Mao, et al. (1998) have shown that charging X52 and X80 steels with hydrogen changes the shape of the polarization curves to suggest an increase in corrosion rate due to hydrogen in dilute bicarbonate solutions and NS4. However, while the effect was pronounced at positive potentials, it is difficult to tell from the published data whether the effects near the open-circuit potential, where near-neutral pH SCC occurs, were significant.
5. Near-neutral pH stress-corrosion cracks from the field or from laboratory tests invariably contain a considerable amount of corrosion product.

If hydrogen truly is an important factor in near-neutral pH SCC, a better understanding of the role of hydrogen might lead to better site-selection models if soil environments could be ranked with respect to their propensity to introduce hydrogen into the steel under free-corrosion conditions.

A.2 Causes of SCC in Pipelines

SCC is known to occur in many metallic alloys and polymers that are exposed to a wide variety of environments. However, for each material, there are a limited number of environments that can cause SCC, and certain levels of stress or stress fluctuations are required. Thus, it is a process that involves three interrelated factors: a susceptible *material* exposed to a specific *environment*, and subjected to specific ranges of *stress*. Significant alteration of any one of those factors is sufficient to prevent SCC.

A.2.1 Causes of High pH SCC

Environment. The effects of various environmental factors on high pH SCC are reasonably well understood. High pH SCC has been observed in solutions with various ratios of sodium carbonate to sodium bicarbonate ranging from almost pure sodium bicarbonate to almost pure sodium carbonate (Parkins and Fessler 1978). Those ratios correspond to a pH range from about 8 to 10. SCC is most severe in highly concentrated solutions, but it has been observed in less concentrated solutions having concentrations about one third those usually used in laboratory experiments (Parkins and Zhou 1997).

Although high pH SCC has been observed at temperatures ranging from 20°C to about 90°C, the crack velocity is much higher at the higher temperatures, and it decreases exponentially with decreasing temperature (Fessler 1979).

High pH SCC will occur only in a narrow range of potentials, the specific range depending upon solution composition and temperature. As is shown in Figure A-3, the width of the range decreases as the pH increases (Parkins and Fessler 1978). The width of the potential range for SCC also decreases with decreasing temperature, as is shown in Figure A-4 (Fletcher et al. 1982). In general, the critical potential range for high pH SCC is between the open-circuit potential and cathodic-protection potentials. Such potentials can be achieved on a pipe with normal levels of cathodic protection due to partial shielding of the cathodic-protection current by a disbonded coating. However, laboratory experiments have shown that a heavy oxide, such as mill scale, on the steel surface is necessary to hold the potential in the critical range for appreciable times. If the surface is nearly free of oxides, the potential under the disbonded coating will rapidly move to more negative values in the highly conductive carbonate/bicarbonate environment (Parkins and Fessler 1986).

Stress. The role of stress, including stress fluctuations, is thought to be the promotion of creep deformation at the tip of the crack, which results in rupture of the comparatively brittle passive film, thus exposing bare metal to the corrosive action of the environment. The stress or stress intensity must be above a certain threshold level to produce a sufficient strain rate to exceed the passivation rate. The threshold stress can vary considerably from batch to batch of steel and even for different thermal and mechanical histories of a given batch (Fessler and Barlo 1984).

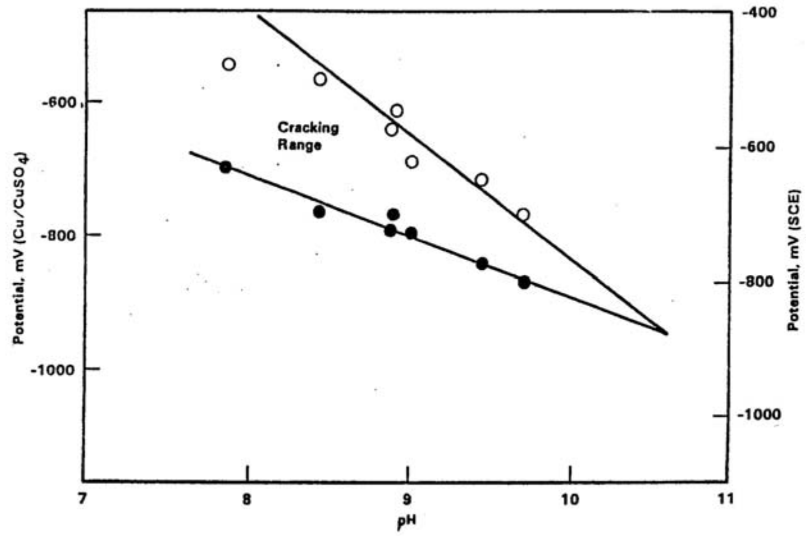


Figure A-13-3 Effect of pH on the Range of Potentials in Which Intergranular SCC can Occur in Line-Pipe Steels at 75°C

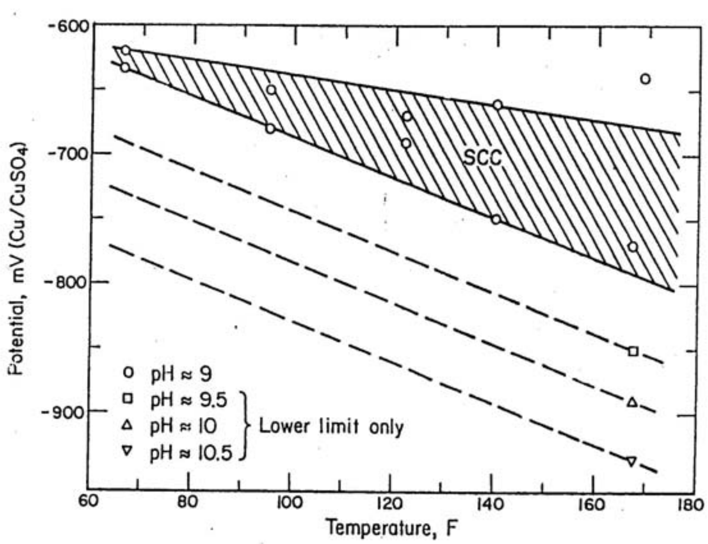


Figure A-13-4 Effect of Temperature on the Critical Potential Range for High pH SCC

The threshold stress can be reduced considerably if small-amplitude, low-frequency stress fluctuations are superimposed on the mean stress. The amount of reduction varies from steel to steel and varies with the amplitude and frequency of the fluctuations. One of the most dramatic effects, which is illustrated in Figure A-5, was a decrease of the threshold stress to 40 percent of the yield strength through the application of fluctuations as low as 1.5 percent of the mean stress twice a month (Fessler 1976).

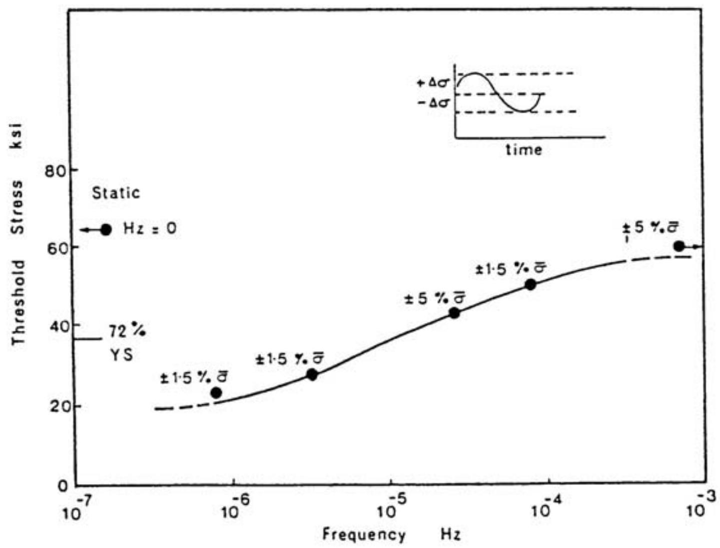


Figure A-13-5 Effect of Low-Amplitude (High-R) Stress Cycles on the Threshold Stress of an X52 Steel Exposed to a 1N Solution Carbonate + 1N Sodium Bicarbonate Solution at 75°C and –650 MV (SCE)

Steel. Although analyses of pipe that failed in service have not revealed any obvious correlations with steel composition, grade, or microstructure (Fessler 1976), there is direct evidence from laboratory studies that certain batches of steel are much more resistant to SCC than others. There are two important parameters associated with steel susceptibility: (1) crack growth rate and (2) threshold stress or stress intensity. Those parameters may be controlled by different mechanisms and, therefore, might not be directly related to each other. In other words, a given steel might have a relatively high threshold stress compared to that of another steel, but the crack growth rate above the threshold stress might not necessarily be lower. For example, in the case of high pH SCC, the crack growth rate probably is primarily controlled by the rate of dissolution, while the threshold stress may be more directly related to the creep resistance of the steel.

In a 1N sodium carbonate + 1N sodium bicarbonate solution at 75°C with a constant applied load, the threshold stresses of 10 different steels were found to be nearly equal to the yield strengths, the maximum differences being about 15 percent (Parkins, Belhimer, and Blanchard 1993). The range of yield strengths was from about 30 to 70 ksi.

Parkins, Belhimer, and Blanchard (1993) correlated the reduction in threshold stress with the strain-hardening behavior of the steel when subjected to cyclic stresses superimposed on a monotonically increasing stress. As is shown schematically in Figure A-6, the superimposed cyclic stress (typically on the order of 2 to 11 ksi) caused plastic deformation to start at much lower levels of mean stress, and the slope of the plastic portion of the stress-strain curve changed abruptly at a certain stress. That stress, where the slope became very low, correlated strongly with the threshold stress as measured under the same magnitude and frequency of superimposed fluctuating stress (see Figure A-7).

Thus, the susceptibility of a steel to high pH SCC appears to be controlled by its cyclic strain-hardening behavior or cyclic creep behavior and possibly by chemical segregation. Unfortunately, the relationships of cyclic strain hardening or cyclic creep or corrosion behavior to microstructure and impurity distribution are not known nor are the relationships of the critical microstructural features and impurity distribution to composition and processing. An understanding of those relationships will be needed to enable one to design steels that are highly resistant to SCC.

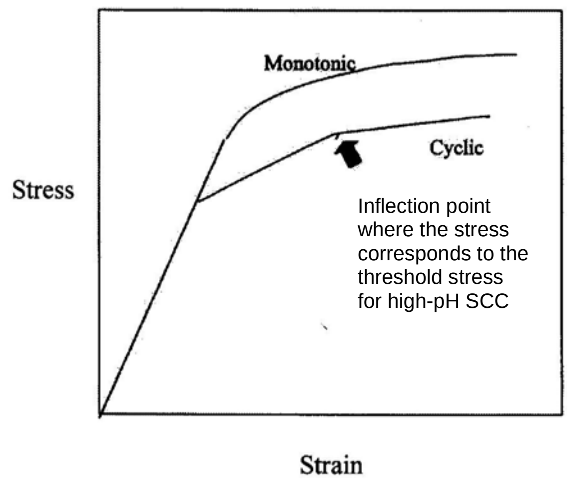


Figure A-13-6 Comparison of Typical Stress-Strain Curves Produced with Monotonic Loading and with Cyclic Loads Superimposed on the Steady Loads

A.2.2 Causes of Near-neutral pH SCC

Environment. The chemical environments surrounding stress-corrosion cracks in the field have been studied far more extensively for near-neutral pH SCC than for high pH SCC. Hundreds of trapped water samples from under coatings and soil samples near the pipe have been analyzed. The results have been summarized by Jack, et al. (2000). The water samples have been very dilute, containing some bicarbonate ions plus lesser amounts of carbonate, chloride, and sulfate. The pH usually has been between 6 and 7. The major cations are sodium, calcium, potassium, and magnesium. Soils near SCC sites have been found to contain 4 to 23 percent CO_2 (Delanty and O'Beirne 1992).

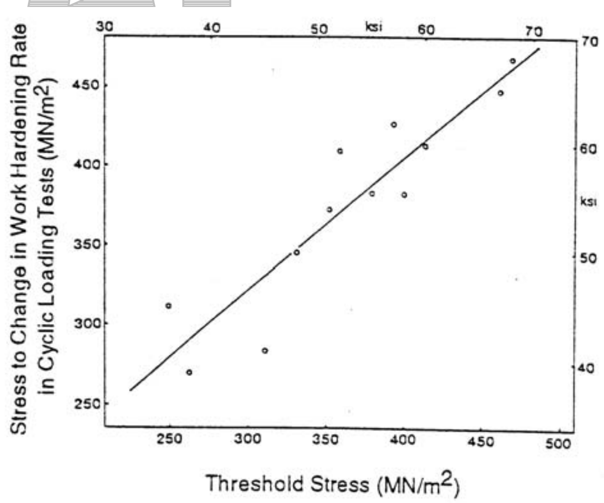


Figure A-13-7 Correlation of the Threshold Stress for High pH SCC and the Stress at which the Work-Hardening Rate in Cyclic-Loading Tests Suddenly Decreases

The fact that the pH of the trapped water is slightly below 7 suggests that little if any cathodic-protection currents reach the pipe where near-neutral pH SCC occurs. Thus, it occurs near the open-circuit potential, which is near –700 mV (SCE) or –770 mV ($Cu/CuSO_4$) for the environments in question.

No pronounced effect of temperature on the kinetics of near-neutral pH SCC has been observed, but the research into temperature effects has been very limited. Parkins, et al. (1994) conducted a series of SSRTs at temperatures between 10 and 45°C. As is shown in Figure A-8, the considerable scatter in the data probably would mask any temperature effect that might exist. Based upon the fact that near-neutral pH stress-corrosion cracks frequently have been found far downstream from compressor stations, some people have concluded that temperature is not important. However, the fact that the most severe SCC (that leading to service failures) usually has been near the discharge of compressor stations (NEB 1996) raises some question about that conclusion.

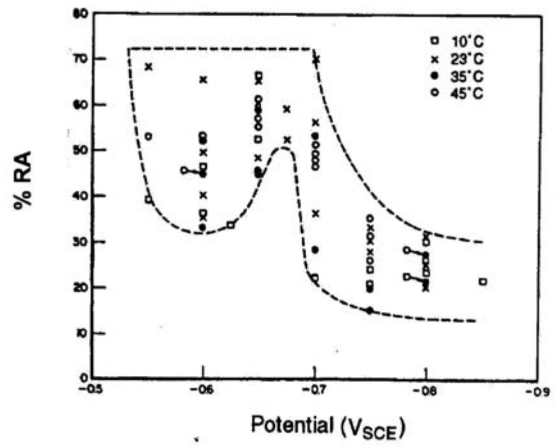


Figure A-13-8 Effect of Temperature on Reduction in Area for an X65 Steel Subjected to Slow-Strain-Rate Tests in NS4 Solution with pH about 6.4

From a mechanistic viewpoint, arguments could be made either way regarding an effect of temperature, depending upon the relative roles of dissolution and hydrogen. As with most chemical reactions, the rate of dissolution would be expected to increase exponentially with increasing temperature. However, the corrosivity of the environment is strongly affected by CO_2, the solubility of which decreases with increasing temperatures. The temperature dependence of hydrogen embrittlement for line-pipe steels is not known, but studies on quenched-and-tempered steels (Tyson 1979) have shown a maximum effect around –100°C, the effect becoming very small above room temperature (see Figure A-9).

Stress. As is the case for high pH SCC, the role of stress appears to be to produce some continual plastic deformation at the crack tip, which also seems to be required for near-neutral pH SCC. Although Zhang, et al. (1999) reported near-neutral pH SCC under static loads, most researchers have found it useful, if not necessary, to vary the stress during the test to promote some continual deformation.

Steel. No obvious relationships between susceptibility to near-neutral pH SCC and the grade, composition, or microstructure of the steel have been apparent from analyses of pipe that developed SCC in service (Dupuis 1998). However, several recent laboratory studies of various batches of steel with different microstructures have suggested that steels with more uniform microstructures may be less susceptible to near-neutral pH SCC (Meyer, et al. 2003). Those results are based upon a very small sampling of steels, so more research in this area would be useful.

Recent studies showing a correlation between residual stresses and locations of SCC on a given joint of pipe (Beavers, Johnson and Sutherby 2000) and between pipe manufacturers and probability of finding SCC in the field (Beavers and Harper 2004) suggest that residual stresses from the manufacturing process may be very important.

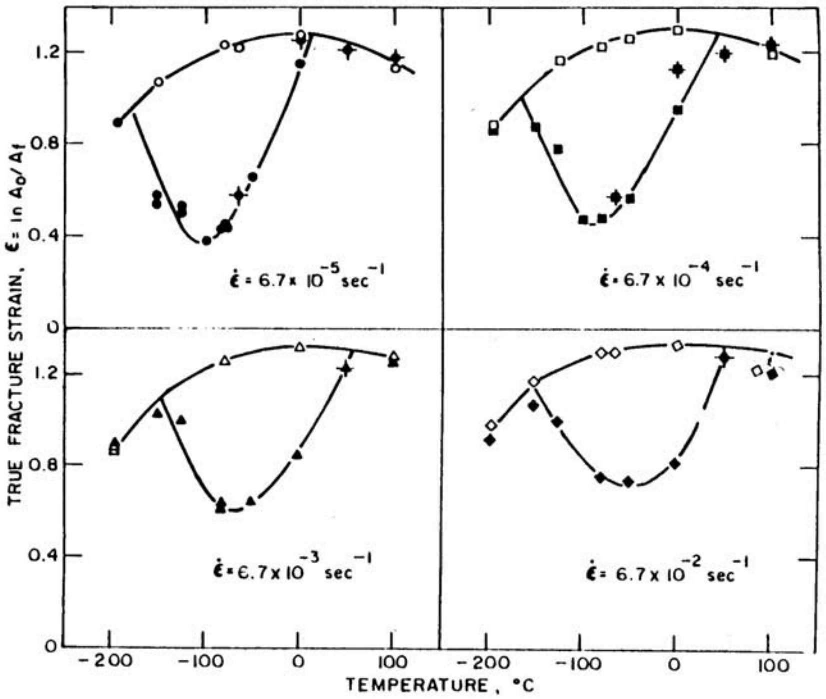


Figure A-13-9 Effect of Temperature on Hydrogen Embrittlement of a Quenched-and-Tempered Steel with a Yield Strength of About 100 Ksi

(Note: Solid points represent hydrogen-charged specimens.)

A.2.3 Summary of Gaps Related to Causes of SCC

Environment. Although the NS4 solution or something similar is being used by most researchers to simulate the environment that causes near-neutral pH SCC in the field, many researchers have experienced difficulties in initiating SCC in that environment under realistic loading conditions and in obtaining reproducible results in terms of crack growth rates. There have been several reports of unexpected and unexplained very high or very low growth rates. One possible explanation is that there are yet some undiscovered constituents in the field environment that may be critical in terms of SCC initiation and growth.

A fundamental understanding of how the environment at the steel surface under a disbonded coating relates to the surrounding soil and other external factors also has not been fully developed.

Stress. Many research projects have shown that low-amplitude pressure (stress) fluctuations and high-amplitude fluctuations can affect the growth of both high pH and near-neutral pH stress-corrosion cracks. However, it is not clear what kinds of pressure fluctuations (amplitude, frequency, and mean stress) are most harmful or how those factors might be related to the properties of the steel.

Steel. Although there can be large variations in susceptibility of different batches of steel to SCC, even within a single grade, it is not yet possible to predict the susceptibility from the composition and microstructure, nor is it possible to design a steel that will be resistant to SCC. Work completed by CEPA demonstrated that residual stresses in the pipe, probably as a result of the pipe manufacturing process, can have a significant impact on SCC susceptibility (Beavers, Johnson and Sutherby 2000).

A.3 Methods for Managing SCC

It is highly unlikely that any single approach to managing SCC will be optimum for all pipeline companies. The choice of one or more approaches will depend on specific characteristics of a pipeline such as the following:

- Is it an existing line or a future one being designed
- Is the more likely threat from high pH SCC or near-neutral pH SCC
- Is the line piggable in its current condition
- What are the feasibility and cost of hydrostatic retesting (as affected by factors such as water supply or disposal, elevation differences, etc.)
- What are the economics of aftercooling gas prior to injection into a pipeline
- What is the ability to control cathodic protection (as affected by factors such as soil resistivity, accessibility, and coating condition)

Following is a list of options that a pipeline company might consider for managing SCC on its system:

<u>Existing pipelines:</u>

- Locate SCC and treat the pipe
  - ⇒ Locate
    - o Bell-hole inspections
    - o Hydrostatic testing
    - o ILI
  - ⇒ Evaluate/size the cracks
    - o Buffing/grinding
    - o Non-destructive evaluation (NDE)
  - ⇒ Treat
    - o Buffing/grinding
    - o Sleeving
    - o Remove the joint
    - o Leave cracks and establish safe re-inspection interval

- Change operating practices
  - ⇒ Lower temperature (for high pH SCC)
  - ⇒ Eliminate harmful pressure fluctuations
  - ⇒ Improve cathodic protection

Additional options for future pipelines:

- Select effective coating
- Consider steel susceptibility
- Optimize operating conditions
  - ⇒ Temperature
  - ⇒ Stress
  - ⇒ Pressure fluctuations
  - ⇒ Cathodic protection

Table A.1 and Table A.2 summarize some of the most important questions that remain regarding each of the options for managing SCC and the research areas that could be pursued to answer those questions.

Table A.1 Questions and Research Areas Relevant to Existing Pipelines

Management Technique	Question	Research Area
Locate and Treat SCC		
Locate SCC	How to increase the effectiveness and reduce the cost by identifying high-probability areas for focusing efforts	Develop improved site-selection models
	How to establish suitable inspection intervals	Develop improved crack-growth models
	How to reduce the cost of ILI for gas pipelines	Develop new ILI techniques that do not require a liquid couplant
Evaluate/size cracks in the ditch	How to obtain accurate measurements with portable equipment	Develop new in-the-ditch sizing technologies
Leave small cracks and establish safe re-inspection interval	How to ensure that interval is short enough to prevent unacceptable amount of growth but not too short as to be unnecessarily expensive	Develop improved crack-growth models
Change Operating Practices		
Lower temperature	Does temperature really have no significant effect on near-neutral pH SCC	Investigate effect of temperature on initiation and growth rates
Eliminate harmful pressure fluctuations	What kinds of pressure fluctuations are most harmful	Develop improved crack-growth models
Improve cathodic protection	Reasonably well understood	None needed

TableA.2 Additional Questions and Research Areas Relevant to Future Pipelines

Management Technique	Question	Research Area
Steel Susceptibility	How does SCC susceptibility depend upon composition, processing, and properties of steel	Empirical comparison of various batches of steel and regression analysis
		Fundamental study to relate susceptibility to properties, composition, and processing
Select effective coating	Are coatings with good service histories prone to failure after longer times	Monitor field-failure experience
Optimize operating conditions	Same as for existing pipelines	Same as for existing pipelines

The following sections describe the current level of understanding and possible future research approaches for each of the research areas listed in Table A.1 and Table A.2.

A.3.1 Site-Selection Models

Very soon after the initial discovery of SCC in pipelines, data collected suggested that the locations of significant SCC were "…strongly related to terrain conditions surrounding the pipe where there was the potential for pipe coatings to have disbonded" (NEB 1996). If SCC is discovered in some location due to a failure, visual inspection, or non-destructive inspection, there is a high probability that SCC can be found in other joints of pipe in the same vicinity. This has led to a continued effort to find ways to predict locations where SCC may be highly likely or other locations where it may be highly unlikely or even impossible. The obvious benefits of such an ability would be to allow pipeline companies to focus their remedial efforts where they would be most effective and not waste time and money in areas where there is no significant threat of SCC.

It should be noted that site-selection models might take different forms from system to system since factors that may be highly significantly on one system might be completely absent from another. For example, while recent work reported in *"Stress Corrosion Cracking Prediction Model"* (Beavers and Harper 2004) demonstrated that the pipe manufacturer was highly statistically significant in the SCC prediction model for one pipeline company, pipe manufacturer might not be highly statistically significant for other companies.

Site-Selection Models for High pH SCC. Based upon statistics of reported incidents of high pH SCC, two models have been proposed to prioritize or rank areas in terms of relative probability of high pH SCC – one by Martinez and Stafford (1994) and the second by Eiber (1998).

Both models consider soil moisture level, coating condition, operating stress, cathodic-protection level, and gas temperature. The Martinez model also considers soil pH, coating age, pipe age, history of SCC leaks and ruptures, and length of time since the most recent hydrostatic retest or bell-hole examination. The Eiber model also considers coating type, clay content of the soil, pipe surface preparation, and magnitude of stress fluctuations. The Eiber model requires less specific knowledge of the conditions at the surface of the pipe.

The Martinez model assigns either zero or one point for each condition and adds the points to get a relative probability. The Eiber model assigns weights to each factor to represent the estimated relative importance and then adds the values.

Both models represent thoughtful, prudent approaches to prioritizing areas for attention with respect to high pH SCC, especially in view of the limited amount of data upon which they could be based and against which they could be judged. Both give relatively high values for known locations of SCC.

However, as more data are collected from the field and a better understanding is gained in the laboratory, there may be several ways in which the models could be modified to make them more reliable:

- When reliable ILI information becomes available, the models could be tested against areas where SCC has not occurred in addition to more areas where it has.
- The weighting factors might then be refined to improve the reliability.
- When dealing with independent factors that affect the probability of an event, the probabilities of the individual factors usually are multiplied together, not added. Some system of multiplying ratings in the models should be considered.
- Although extensive early studies of the soils and geological features that were associated with high pH SCC failures revealed no correlation with chemistry, (Mercer 1979) more recent work by Beavers suggests that soils with high amounts of sodium or potassium would favor high pH SCC because they would allow highly concentrated solutions of carbonates and bicarbonates to be produced (Beavers and Durr 2001). Conversely, high amounts of calcium or magnesium would lower the solubility of carbonates and bicarbonates to very low levels.

Site-Selection Models for Near-neutral pH SCC. In contrast with the site-selection models for high pH SCC, the models for near-neutral pH SCC have been based more on characteristics of the soil and terrain with less emphasis on operating history and other factors.

A limited survey of the industry indicated mixed experience with respect to success rate. As is shown in Table A.3, success rates in terms of correct positive indications for the tape-coated pipe ranged from 12 percent to 80 percent. For a coal-tar-coated line, there were no correct positives in a small number of digs.

Table A.3 Success Rates of Site-Selection Models for Near-Neutral pH SCC

Type Coating	No. of Digs	Correct Positive	Correct Negative	False Positive	False Negative	Comments
Tape	>800	80 percent	?	20%	?	A
Tape	85	12%	54%	18%	16%	
Tape	>100	40%	?	60%	?	B
Coal Tar	7	0	0	100%	0	

A. Tenting at longitudinal double-submerged arc weld.
B. Minor SCC; no "significant" cracks. Similar statistics for random digs.

A more recent study on a U.S. gas pipeline found a significant correlation between locations of SCC and a combination of coating type, soil type, and pipe manufacturer, the latter correlation speculated to be related to residual stresses (Beavers and Harper 2004).

There are a number of reasons why it is difficult to evaluate site-selection models for near-neutral pH SCC:

- They are based on correlating field experiences rather than a fundamental understanding of how the soil and geology contribute to the conditions that promote cracking. Thus, the models tend to improve over time because more data are accumulated, so the reliability this year might be much better than it was several years ago.
- They generally have been based on proprietary data and algorithms.
- They appear to be geographically specific. For example, the algorithms that work for Eastern Canada do not necessarily work for Western Canada.
- There are interdependent factors associated with locations of near-neutral pH SCC. For example, SCC on tape-coated pipe has a tendency to occur more often in poorly drained soils, while SCC on asphalt-coated pipe tends to occur in well-drained soils (CEPA 1998). However, there are exceptions to that rule of thumb as well; for one tape-coated liquid line in Western Canada, the cracking was more frequent and deeper where the soil was well drained (Krishnamurthy et al. 2000). Not surprisingly, algorithms that work for tape-coated pipe do not work well for asphalt-coated pipe.

Research Gaps Related to Site-Selection Models. Although several important projects currently are being conducted to correlate various soil characteristics with the locations of SCC, there are several other opportunities to improve existing models:

- From the soil extracts that produced exceptionally high or low crack growth rates of near-neutral pH SCC, attempt to identify the critical constituents. Identifying the accelerating constituent would have the added benefit of allowing laboratory tests to be conducted in much shorter times, thus producing more data per dollar.
- As more ILI runs are completed, test the parameters of the pipe and geology from places where SCC is not found against the models. It also may be useful to compare parameters related to large cracks versus shallow cracks.
- Incorporate more operating data into models for near-neutral pH SCC and more soils/geology data into models for high pH SCC. This may include considerations for topographical depression correlation with SCC, and additional data and correlations for SCC occurrence proximate to compressor stations.
- Develop a fundamental mechanistic model for the relationship between the nature of the environment at the pipe and factors such as soil chemistry, soil resistivity, cathodic-protection values, moisture levels, and coating conditions, rather than relying solely on empirical correlations. The model should be able to predict different areas where either high pH SCC or near-neutral pH SCC is more probable.

A.3.2 Crack-Growth Models

Ability to predict crack growth rates is important to predicting remaining life, assessing risk, determining what kinds of operating practices (such as pressure fluctuations) are harmful or beneficial, and establishing reasonable intervals for hydrostatic retesting or ILI. B31.8S states "When time-dependent anomalies such as ... stress corrosion cracking are being evaluated, an analysis using appropriate assumptions about growth rates shall be used to assure that the defect will not attain critical dimensions prior to the scheduled repair or next inspection." It further states that, if an SCC failure has occurred, the pipeline company must have a documented hydrostatic retest program with a technically justified retest interval.

Models of High pH SCC Growth Kinetics. A four-stage model of high pH SCC that was proposed by Parkins (1988) is illustrated in Figure A-10. Stage 1 represents the time required to deteriorate the coating and build up the necessary environmental conditions for SCC. It probably is the least predictable stage, and it probably varies by several orders of magnitude from one pipeline to another depending upon the condition of the coating, the nature of the backfill, and many other factors. If a crack-growth model is used to estimate the remaining life of a pipeline that is known to contain stress-corrosion cracks, then knowledge of Stage 1 is irrelevant. However, if one is trying to predict the total life of a pipeline, then it will be necessary to make an arbitrary assumption about the length of Stage 1.

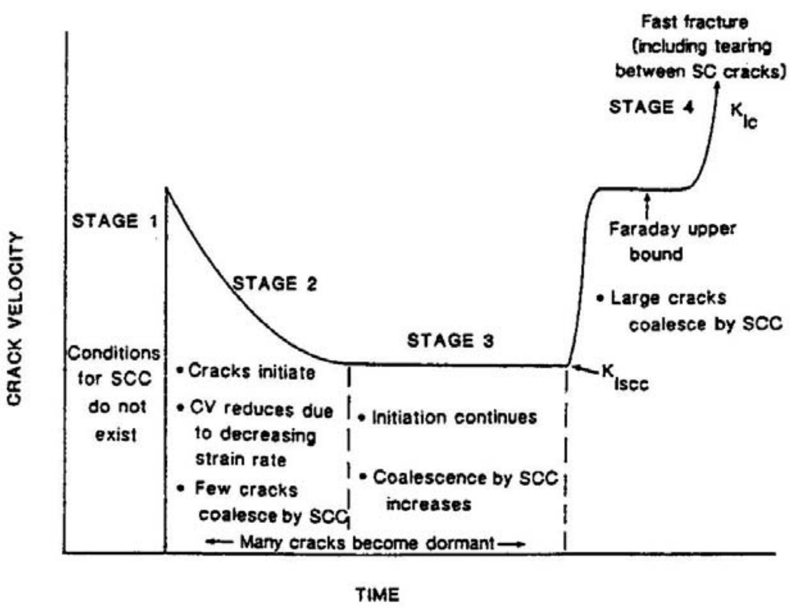


Figure A-13-10 Four-Stage Model of High pH SCC

The final event in Stage 1 is the initiation of a stress-corrosion crack. Parkins has shown evidence that the initiation mechanism is simply selective dissolution of the grain boundaries, which is the same mechanism as that for crack growth (Parkins 1994).

Stage 2 represents the exponential decrease in crack growth rate with time and may cover only a few days for an individual crack. The schematic illustration in Figure 9.10 greatly exaggerates the length of Stage 2.

Stage 4 represents the final part of the growth process where the crack is so large that a small amount of growth reduces the remaining wall thickness enough to cause the driving force to increase fast enough to overcome the effect of work hardening. Parkins has shown that the growth rate in Stage 4 can be calculated from Faraday's Law and the corrosion rate as measured from a polarization curve (Leis and Parkins 1998). For the carbonate/bicarbonate environment at 75°C, it typically is around $2x10^{-6}$ mm/sec. Stage 4 is followed by rapid mechanical penetration of the pipe wall to produce a leak or rupture. Both Parkins (2000) and Leis (1995) have argued convincingly that the time spent in Stage 4 is a relatively small fraction of the total time to failure.

The key to predicting the remaining life of a pipe with small stress-corrosion cracks lies with Stage 3, which probably involves sporadic crack growth due either to crack coalescence or cyclic softening or both.

In laboratory experiments, average crack growth rates typically are calculated by measuring the crack depth at the end of the test and dividing by the total test time. Since it is known that cracks initiate continuously during a test, (Parkins 1988) the deepest crack usually is used for reporting a maximum average growth rate.

Several investigators have found that the average crack growth rate decreases exponentially with time for initially plain specimens or fatigue-precracked specimens where the precrack does not extend to the edges of the specimen (Parkins 1987; Parkins and Zhou 1997; Parkins, Belhimer, and Blanchard 1993; Baker, Rochfort, and Parkins 1986; Marshall 1984). A typical behavior pattern is illustrated in Figure A-11, where the slope of the line usually is between –0.8 and –1.0. A slope of –1.0 would indicate zero growth, and a crack characterized by a slope of –0.9 would be less than 0.1 mm deep in 100 years. Thus, the measured crack growth rates in the laboratory become negligibly small in a few days.

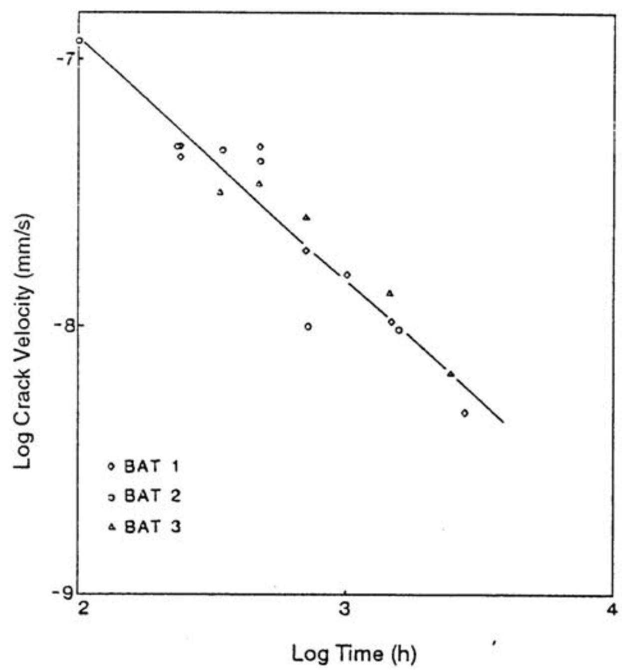


Figure A-13-11 Effect of Time on Average Velocity of a Single High pH Stress-Corrosion Crack

One possible explanation for how cracks that move so rapidly toward dormancy can eventually grow large enough to cause a service failure in a pipeline has been given by Leis (Leis and Parkins 1993) who monitored the lengths of cracks on the surface of a specimen exposed to the carbonate/bicarbonate solution. As is shown in Figure A-12, crack growth stopped and restarted a number of times during the experiment. The periodic halting of the crack was attributed to creep exhaustion, and the restarting was attributed to coalescence of a dormant crack with other cracks that had initiated near the ends of the first crack. It has been demonstrated that cracks continue to nucleate as time goes on (Parkins 1988). Computer simulations of crack growth were carried out for five different initial random distributions of cracks assuming the exponential decreases in growth rate and nucleation rate with time but allowing for crack coalescence whenever the separations were less than 14 percent of the average lengths (Leis and Parkins 1993). The results, shown in Figure A-13, compare remarkably well with the measurements shown in Figure A-12. The dashed line in Figure A-13 represents the crack growth that would be expected in the absence of coalescence.

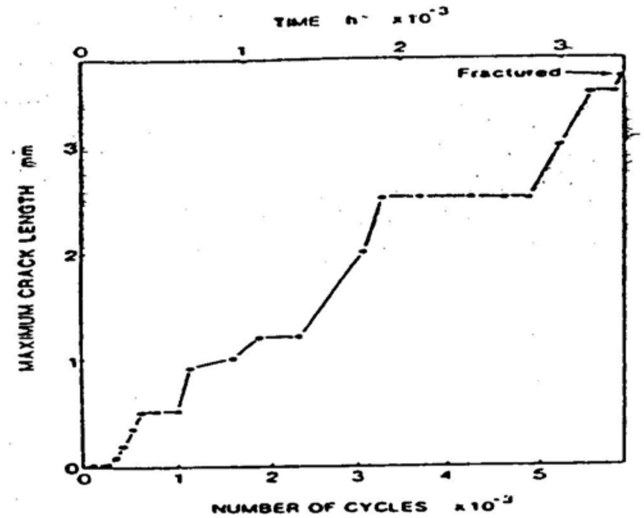


Figure A-13-12 Intermittent Growth of High pH Stress-Corrosion Cracks

Leis, et al. have developed a quantitative crack growth model for high pH SCC (Leis, Forte, and Ghadiali 1995) that reproduces the general features of Stages 2, 3, and 4 in Parkins' model. Called SCCLPM (stress-corrosion-cracking life-prediction model), it involves the following steps:

1. Generating a random array of cracks where the cracks depths and number of cracks per unit area are functions of the stress on the pipe, the yield strength of the steel, and the proportional limit of the steel, the relationships being determined from laboratory tests.
2. Updating the nucleated array of cracks to account for additional crack nucleation near the ends of the first cracks due to the increased stress concentration there.
3. Allowing the cracks to grow according to some kinetic relationship. This is the only part of the model that is specific to

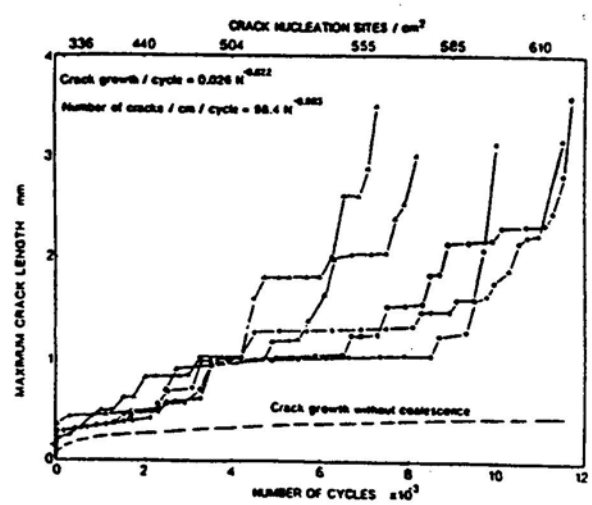


Figure A-13-13 Simulated Growth of High pH Stress-Corrosion Cracks Showing Intermittent Growth Due to Crack Coalescence

ChallengeUs.

high pH SCC. It uses the crack growth rate predicted by Faraday's Law whenever the steel is experiencing a strain rate sufficient to support SCC. The strain rate depends upon the cyclic stresses and the mean stress, and it decreases over time due to work hardening. Continued crack growth depends upon crack coalescence. The effects of cyclic softening can be included in the model for a specific steel, but they have not been included in a generic sense. As Leis points out, it would be desirable to do so.

4. The cracks are allowed to grow until they, as a group within the cluster, reach a critical size for mechanical extension by tearing.

The model is pipeline specific with respect to size, grade, toughness, service conditions, and hydrostatic-test history.

Predictions from the model have been compared with the behavior of an actual operating pipeline that contained SCC. The predictions agreed well with the aspect ratio, time to failure, crack depth, and relative incidence of dense to sparse cracking (Leis 1997). The model also can predict dormancy and re-initiation of cracks. It predicted that reductions in pressure cycling and discharge temperature were the most important parameters to extend the service life of pipelines suffering high pH SCC.

A more complicated probabilistic model had been formulated based upon the deterministic model SCCLPM but considering random variations or uncertainties in mechanical properties of the pipe, gas pressure, temperature, and electrochemical potential (Leis and Kurth 1999). This model has been used to quantify the beneficial effects of lowering discharge temperatures and to develop guidelines for optimizing hydrostatic-retest procedures. Those results will be described in more detail later in this document.

Models of Near-neutral pH SCC Growth Kinetics. A variety of possible initiation mechanisms for near-neutral pH SCC have been proposed by several investigators. (Parkins and Delanty 1996; King, et al., 2001) For the most part, crack-like features that were produced at the surface failed to extend more than 0.02 mm below the surface and did not closely resemble typical deep stress-corrosion cracks. Currently, there is no well-accepted model for initiation of near-neutral pH SCC.

In laboratory bend tests with specimens from the field that contained service-induced stress-corrosion cracks, only 8.5 percent of the cracks could be activated, and 80 percent of the growing cracks were near the edges of the clusters (Jack et al. 1994).

Beavers and Jaske (2002) measured instantaneous crack growth rates with an electric-potential-drop technique and found that crack velocities decreased continuously after the start of a test with low-frequency, high-R stress fluctuations typical of those on a gas pipeline. As is shown in Figure A-14, higher-frequency, lower-R fluctuations, which probably caused corrosion fatigue, resulted in increasing crack velocities. Decreasing crack velocities with time also have been observed by Parkins, (2002) as is shown in Figure A-15, where the slopes of the lines are between -0.8 and -0.9, indicating that crack growth had almost stopped by the end of the tests.

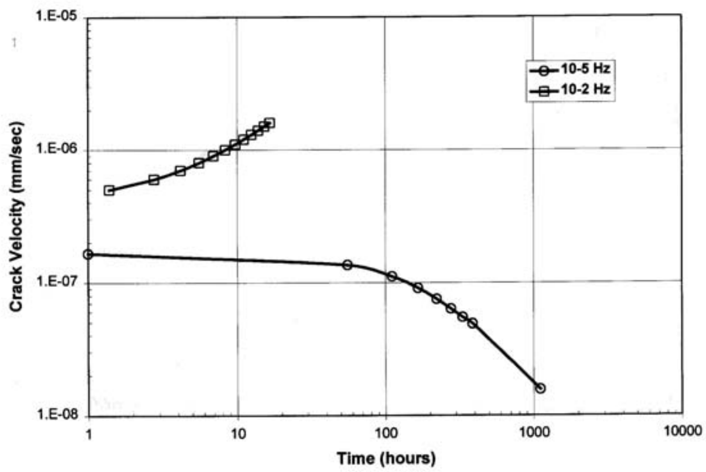


Figure A-13-14 Variations of Crack Velocity with Time for Near-Neutral pH SCC

Chudnovsky (Zhang et al. 2000) has attempted to develop a thermodynamic model for the growth of near-neutral pH stress-corrosion cracks. The approach starts with a sophisticated mathematical formalism that ultimately depends upon laboratory experiments to determine key parameters such as the electro-chemical driving force. Those parameters are in question because they were determined under conditions of high-frequency, low-R stress fluctuations and cathodic charging. Thus it is more likely that he was producing data for corrosion fatigue rather than stress-corrosion cracking. Other problems with his approach are that it does not consider decreasing crack velocity with time, the importance of plastic strain as opposed to stress intensity, and kinetic considerations such as diffusion in the liquid or in the steel.

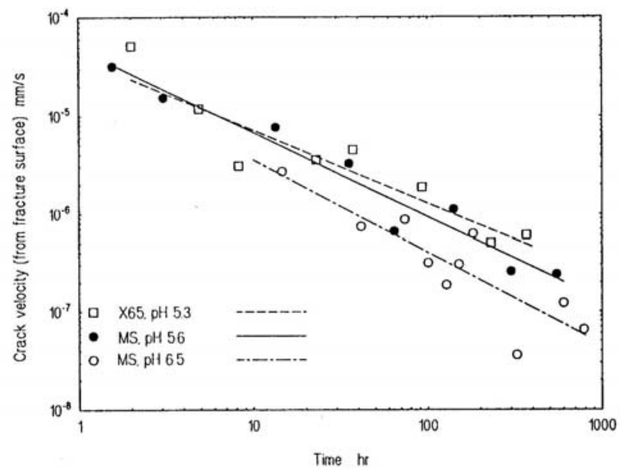
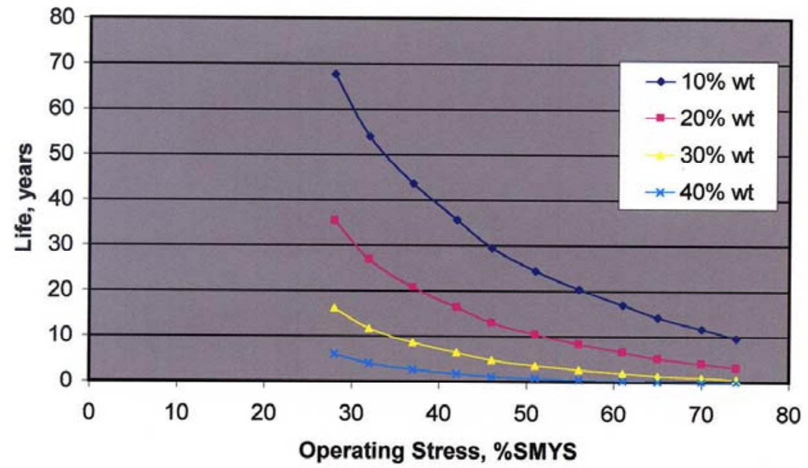


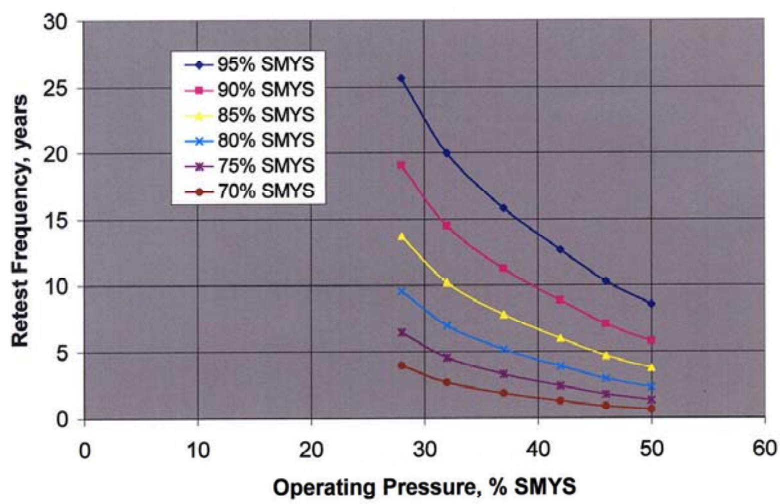
Figure A-13-15 Decrease in Average Crack Velocity with Time for Near-Neutral pH SCC

Krishnamurthy, et al. (1996) used an elastic-plastic (J-integral) analysis to calculate the safe remaining life of pipe with near-neutral pH stress-corrosion cracks of known depths. Results of their calculations are shown in Figure A-16 for predicted remaining life of a pipe with different size cracks and recommended hydrostatic-retest frequency as a function of retest pressure and maximum operating pressure. The results probably are somewhat conservative because the calculations involved two conservative assumptions: (1) that the cracks were infinitely long, and (2) that crack velocity as a function of J could be extrapolated from some tests by Harle, et al., (1994) which were conducted with very aggressive stressing conditions, conditions that produced substantial crack growth even in the absence of a liquid environment. Nevertheless, the model allows the company to make justifiable decisions about operating the pipeline and scheduling remedial measures. It also provides an interesting framework that could be refined to make it less conservative.

For pipelines that experience both high-frequency, low-R stress fluctuations and low-frequency, high-R fluctuations, Lambert and others (Lambert et al. 2000) have proposed a superposition model, where the amount of corrosion-fatigue crack growth from the low-R fluctuations is simply added to the amount of stress-corrosion crack growth from the high-R fluctuations. While that approach seems reasonable, plots of the data, as shown in Figure A-17, contain so much scatter that it is difficult to judge the quality of agreement between experiment and theory. Part of the problem might stem from the fact that they do not consider variations of the rate of SCC with time.



a. Remaining life as a function of crack depth and operating stress



b. Retest frequency as a function of retest pressure and operating pressure

Figure A-13-16 Results of Elastic-Plastic Analysis for a Specific Liquid Pipeline with Near-Neutral pH SCC
(Note: These results are pipeline specific; they do not apply to any pipeline in general.)

In fact, none of the models for near-neutral pH SCC that have been proposed to date consider or predict the decrease in crack growth rate with time.

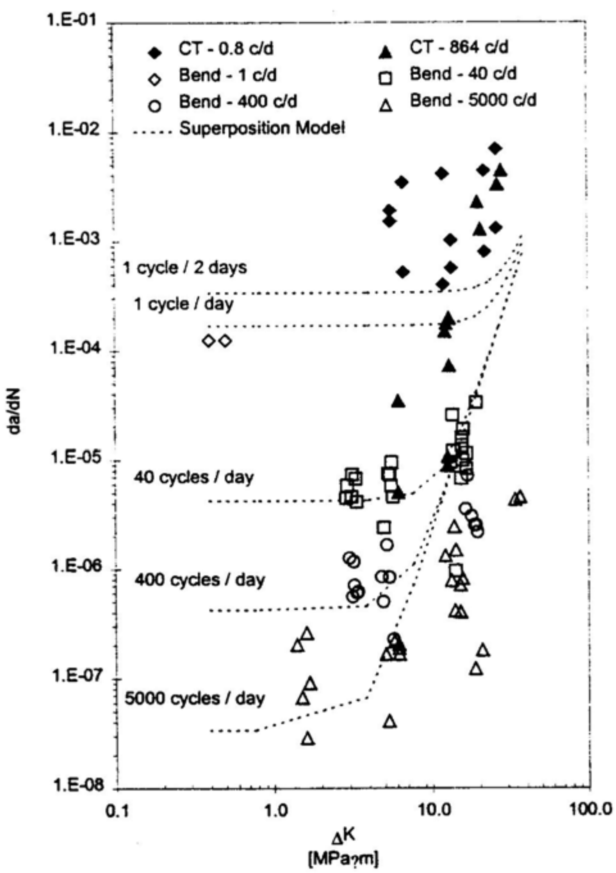


Figure A-13-17 Crack-Growth Data Generated in a Near-Neutral pH Environment

Gaps Related to Crack-Growth Models. Determining how frequently to test requires reliable crack growth models. The advantages and disadvantages of current models have been discussed above. Leis (Leis and Kurth 1999) used his probabilistic life-prediction model to calculate that the time to the first retest could vary from 10 to 70 years depending upon the aggressiveness of the environment and the operating conditions. Subsequent retest intervals could vary from 3 to 30 years depending upon those same parameters plus the previous retest pressure. The calculations must be customized to each pipeline. Refining the model to make it more user friendly would help in this matter. The above calculations were for high pH SCC, but a comparable interval for near-neutral pH SCC in "highly susceptible valve sections" of 2 to 3 years was determined from observations of crack growth following a hydrostatic retest (Delanty and O'Beirne 1992). A model to predict the effects of operating pressure and retest pressure on retest frequency has been discussed with reference to Figure A-16.

Crack-growth models also are useful for determining optimum pressures and hold times. Using his probabilistic life-prediction model, Leis showed that retesting to 95 percent of the specified minimum yield strength (SMYS) or below produces almost no benefit in terms of increasing remaining life, but higher retest pressures can be very beneficial. Pressures between 105 and 110 percent SMYS for 1 hour followed by a longer, lower-pressure leak test appeared to be optimum. A totally independent model for near-neutral pH SCC also shows a pronounced effect of retest pressure and demonstrates the need to exceed 95 percent SMYS if future operating stresses are going to exceed 50 to 60 percent SMYS (see Figure A-16). It is difficult to see how additional research would add to our knowledge in this area.

There are a number of significant challenges to developing a quantitative model for the kinetics of crack growth for either high pH or near-neutral pH SCC. The first is the inability to calculate the length of Stage 1, the time required to establish the necessary environmental conditions at the surface of the steel. That is, in fact, just a subset of the larger problem of not having specific knowledge about the severity of the environmental conditions anywhere along the pipe.

Another challenge is modeling the acceleration or re-initiation of a crack that is moving rapidly toward dormancy. Several possible mechanisms have been suggested:

1. Crack coalescence, which has been discussed above.
2. Re-initiation of creep strain due to softening as the result of continued cyclic loading. Figure A-13-18 shows an example of this, (Leis and Parkins 1993) where creep essentially stopped after about 400 cycles but then resumed after about 1000 cycles.
3. Re-initiation of creep due to a single large stress cycle, such as complete unloading and reloading. Figure A-13-19 shows an example of that phenomenon (Leis and Parkins 1993) and Figure A-20 shows how such unloading and reloading can result in bursts of additional crack growth (Beavers and Jaske 2002).

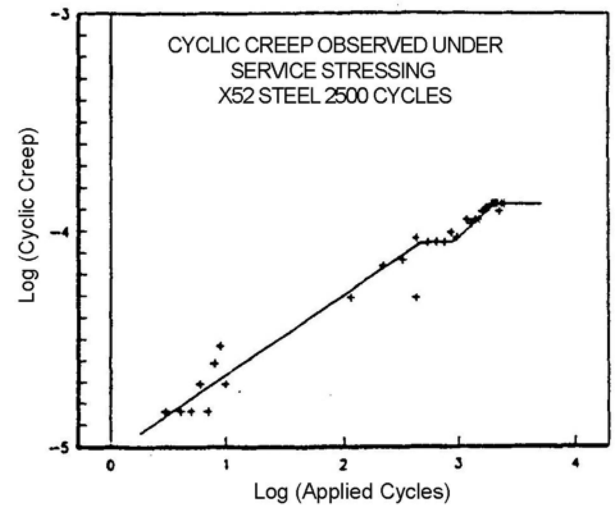


Figure A-13-18 Creep Exhaustion Followed by Re-Initiation of Creep Due to Additional Stress Cycles

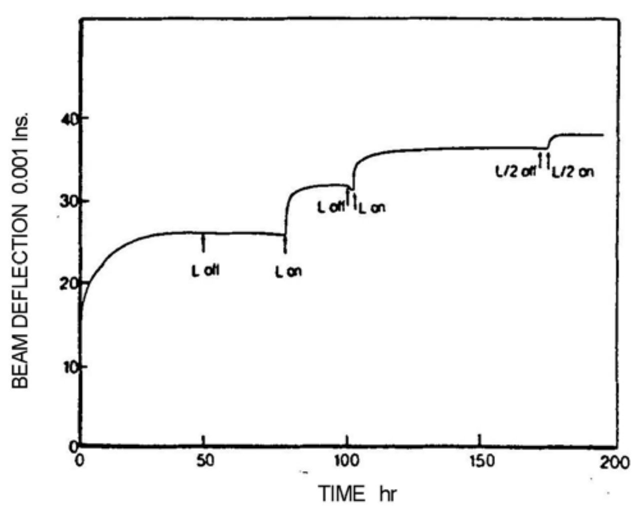


Figure A-13-19 Creep Exhaustion Followed by Re-Initiation of Creep Due to Loading and Unloading

The first of those mechanisms is considered in Leis's SCCLPM; all three may be important for operating pipelines.

Leis's probabilistic model for high pH SCC is the most sophisticated and complete, but its complexity is a discouragement to wide-spread use. It might be more useful if its results could be illustrated in charts or tables for typical operating conditions. Also, as the Leis has suggested, it should be expanded to include the effects of cyclic softening.

That same model might also be appropriate for near-neutral pH SCC if the appropriate growth mechanism for a single crack were better understood.

In spite of all the difficulties, by making reasonable but conservative estimates about some of the unknown parameters, existing models have provided useful insight and guidance to pipeline companies.

Possible improvements to existing crack growth models include the following:

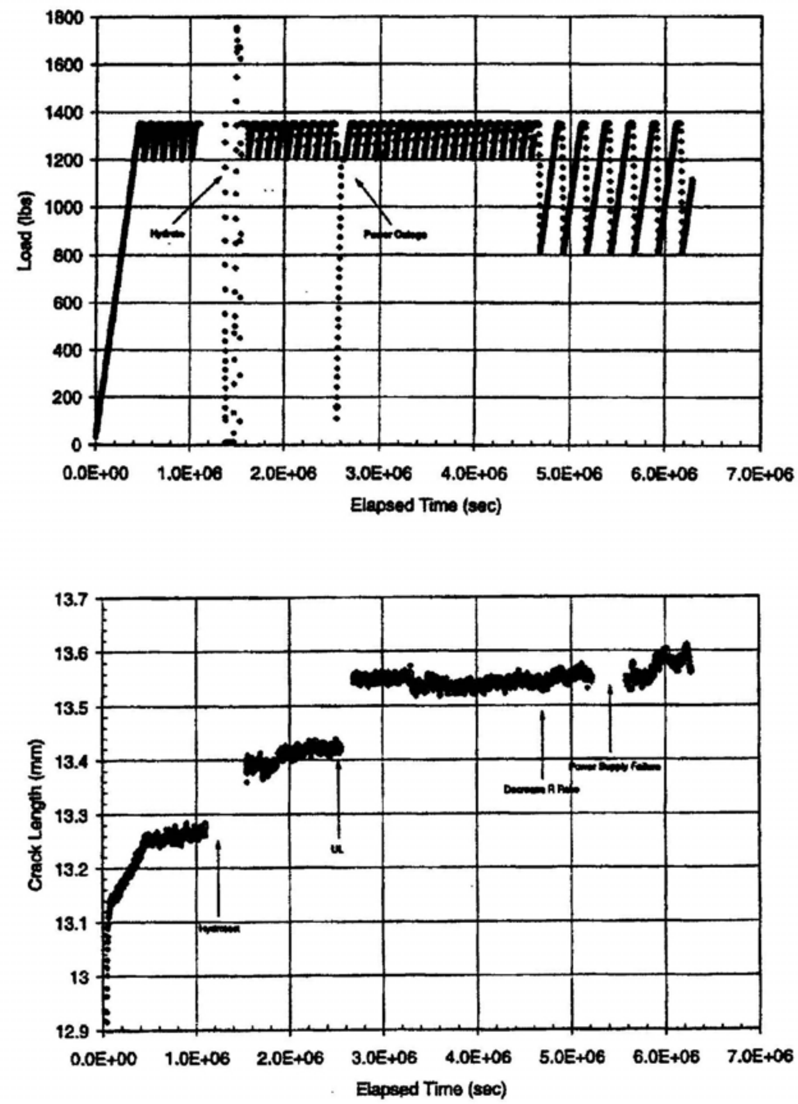


Figure A-13-20 Bursts of Crack Growth (Lower Graph) Due to Unloading and Reloading (Upper Graph)

- Incorporate the effects of cyclic softening and high-amplitude stress cycles into SCCLPM and the probabilistic model for high pH SCC.
- Use the probabilistic model to investigate reasonable ranges of the important parameters and present the results in tables or charts that can provide the basis for at least "rule-of-thumb" guidelines to pipeline operators.
- Expand SCCLPM and the probabilistic model to cover near-neutral pH SCC.

- Incorporate more realistic crack growth rates into the elastic-plastic model for near-neutral pH SCC.
- Expand the elastic-plastic model to cover high pH SCC.
- Compare the predictions from SCCLPM and the probabilistic model with those from the elastic-plastic model.

A.3.3 ILI Technologies

ILI technologies for detecting, characterizing, and sizing stress-corrosion cracks in pipelines are described in Section 6.2.2 of this document. ILI obviously is important in locating SCC and offers an attractive substitute for hydrostatic retesting in some situations. In principle, ILI can provide much more information, especially about locations and sizes of cracks or crack clusters that are too small to cause a failure during a hydrostatic test. ILI also is important for risk assessment.

ILI crack-detection tools have been built based upon liquid-coupled ultrasonics, wheel-coupled ultrasonics, magnetic-flux leakage, and electromagnetic acoustic transducers (EMAT). The only technology that has been satisfactory in terms of locating, identifying, and sizing cracks is liquid-coupled ultrasonics. Unfortunately, it is very difficult (many would say impractical) to use in gas pipelines because it requires surrounding the tool with a slug of water. Procedures to do so may be more trouble than conducting a hydrostatic retest. Considerable hope has been placed on the development of a new technology based upon EMAT that does not require the pipe to be filled with a liquid. At least two vendors are developing such a tool, and they will need pipeline companies to provide manpower, equipment, and pipelines to evaluate them in their final stages of development.

The highly competitive, proprietary nature of the ILI industry makes it difficult for public organizations to participate in developing new technologies or tools. The vendors seem willing to do so if the pipeline companies will commit to using the tools once they are developed and shown to be reliable and durable. The industry should stimulate the academic and/or basic-research community to suggest new technologies that might be overlooked by the ILI vendors.

A.3.4 In-the-Ditch Sizing

In principle, it should be much easier to size cracks in the ditch than from an ILI tool moving down the pipe. However, in a recent critical evaluation of ten technologies, "none of the measurement technologies completely met the goal of simple, low cost, operator-independent crack sizing." (Francini et al. 2000) Ultrasonic techniques appeared to have the most promise. Electromagnetic methods consistently under estimated the sizes of the stress-corrosion cracks. New, innovative approaches should be pursued.

A.3.5 Effect of Temperature

The effect of temperature is a part of crack-growth modeling. The effect on high pH SCC is well known, and additional research in this area probably would have little benefit. The effect for near-neutral pH SCC is not so clearly established, but it does not appear to be a major factor.

A.3.6 Steel Susceptibility

Some people in the industry are convinced that enough is known about the beneficial effects of surface treatments (shot or grit blasting) and certain types of coatings that future pipelines can be designed to be safe from SCC regardless of the inherent susceptibility of the steel. Others prefer a "belt-and-suspenders" approach for cases where the coating is damaged or deteriorates in service.

Susceptibility to High pH SCC. Because high pH SCC involves selective dissolution at grain boundaries, a number of researchers have looked for chemical segregation to the grain boundaries to explain why they are more susceptible to corrosion. Based upon past work with other kinds of steels in other environments, the principal suspects were sulfur, phosphorus, and carbon. Danielson, et al. (2000) tried to produce intergranular fractures in pipe-steel specimens while they were in an Auger spectrometer to analyze the compositions at grain boundaries, but they were unable to produce intergranular fractures, Wang, et al. (2001) used electron energy-loss spectroscopy in a high-resolution analytical electron microscope to look at cross-sections through grain boundaries, and they were unable to detect any segregation of S, P, or C in samples of X42, X52, and X65 steel. Hunt (1988) prepared a number of steels with various levels of P, S, Cu, Sn, and Ni and compared their susceptibilities to high pH SCC by comparing times to failure in slow-strain-rate tests. Although he was able to detect phosphorous segregation to some of the grain boundaries, he found longer failure times (implying lower susceptibilities) for all of the steels with added impurities.

Also using slow-strain-rate tests, Parkins, et al. (1981) studied the effects of Mo, Cr, Ni, and Ti additions. Under these test conditions, it required unacceptably large additions (e.g., 1 percent titanium) to impart high resistance to high pH SCC. However, any improvement to the creep resistance of the steels would not have been detected in those tests.

Using tapered-tensile-specimen tests with superimposed, high-R, cyclic loads to measure the threshold stresses of six line-pipe steels ranging from Grade X42 to X70, Wells (1993) found no correlation between susceptibility (as measured by the ratio of threshold stress to SMYS or actual yield strength) and pipe grade. Using a similar approach with two X70 steels and an X80 steel, Christman (1988a) measured threshold stresses between 42 and 60 ksi, and the susceptibility decreased somewhat with increasing yield strength and grade. The susceptibility was judged to be comparable to, or better than, that of many X52 steels.

In sharp contrast to those results, Danielson, et al., (2001) using precracked, compact-tension specimens, found the critical stress-intensity (K_{Iscc}) for three randomly selected heats of X65, X70, and X80 steels to be at least 20 percent lower than those of six heats of older X52 steel. The heats of X52 steel were selected to have as broad a range of compositions as possible so as to produce a range of susceptibilities, but all six had comparable critical stress-intensity factors and crack growth rates.

Asahi, et al., (1996) measured the threshold stress of five different steels that were processed differently to produce different microstructures. The steels included an X80 and X65 steel that were thermomechanically controlled processed (TMCP), an X65 steel that was quenched and tempered (QT), and an X65 steel and X52 steel that were controlled rolled (CR). Results of threshold-stress measurements from four different laboratories are shown in Figure A-21. The authors concluded that the TMCP and QT steels, which had more uniform microstructures, were less susceptible to high pH

SCC than were the other two steels. In view of the lack of large differences among the steels, lab-to-lab variations for a single steel, and the limited number of steels in the study, a general conclusion about the effect of microstructure would be questionable.

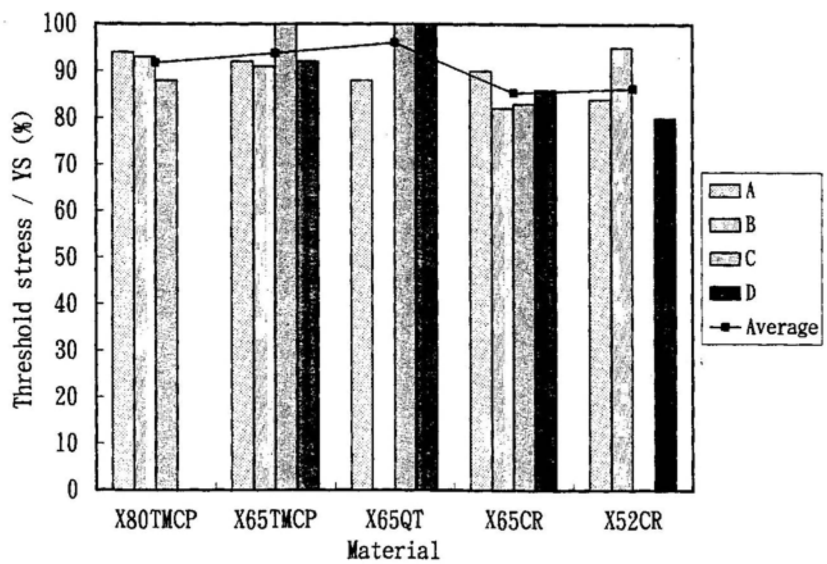


Figure A-13-21 Susceptibilities of Five Steels to High pH SCC as Measured in Four Laboratories (Designated A Through D in the legend)

For any given steel, small amounts of plastic strain, on the order of that which would be produced by forming and cold expanding a pipe, can have a large effect on the threshold stress. Examples for four steels are shown in Figure A-22, where it also can be seen that there is no consistent trend with grade (Fessler and Barlo 1984). Subsequent heating of the type that might be experienced in a coating operation also can affect the threshold stress, as is illustrated in Figure A-23 (Barlo 1979). It is interesting that the coating temperatures for fusion-bonded epoxy, which has not been associated with SCC, produces a much higher threshold stress than does the coating temperature for coal tar, with which most of the high pH SCC failures have been associated.

Parkins (1979) presented similar data on the effects of straining and aging, and he was able to show a strong correlation between the effects on creep resistance and the effects on threshold stress. That correlation also has been confirmed in a study of three X52 steels by Christman (1988b).

Susceptibility to Near-Neutral pH SCC. In a detailed study of 14 joints of pipe (from four pipeline companies) that contained patches of near-neutral pH stress corrosion cracks, no significant differences between the cracked areas and uncracked areas were found in terms of composition, microstructure, and inclusion size, inclusion shape, or inclusion composition. The SCC areas might have been about 3 percent harder on average (Beavers, Johnson, and Sutherby 2000). However, the most significant finding of this study was that the occurrence of SCC was highly correlated with residual stresses in the pipe.

A laboratory study of two X65 steels and an X80 steel indicated no measurable difference in crack growth rates among the three steels, as measured on compact-tension specimens in NS4 solution sparged with 10 percent CO_2/N_2 gas (Meyer and Pontremoli 2001).

A claim has been made that steels with a “more uniform” microstructure (e.g., bainite or bainite plus ferrite) are more resistant to near-neutral pH SCC than are steels with a non-uniform (ferrite plus pearlite) microstructure, (Kushida et al. 2001) but the test conditions involving negative potentials (generally around –930 mV SCE or –1.0 volt $Cu/CuSO_4$) and low stress ratios (R values of 0.5 and 0.7) suggest that the fracture mechanism may have been hydrogen-assisted corrosion fatigue rather

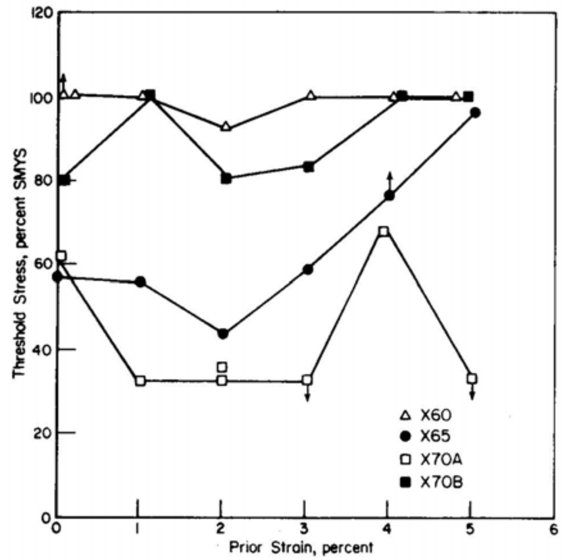


Figure A-13-22 Effect of Prior Strain on Threshold Stress for High pH SCC of Various Line-Pipe Steels

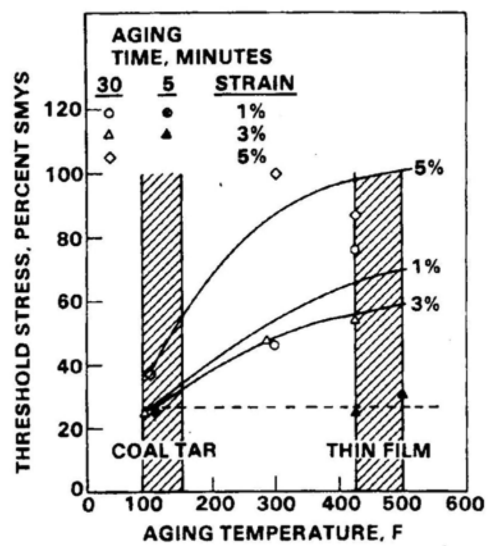


Figure A-13-23 Effects of Thermal Treatments on the Susceptibility of Cold-Worked X65 Steel to High pH SCC

than SCC. However, another study found similar results for more realistic testing conditions (Meyer et al. 2003).

Whereas the bulk microstructure appears to have little effect on SCC susceptibility, the same is not necessarily true for weld heat-affected zones. In one study, the crack growth rate in a coarse-grained weld heat-affected zone was found to be about 4 times higher than in the base metal (Beavers, Durr, and Shademan 1998).

Possible Research Approaches. The key to developing more resistant steels seems to be to increase the resistance to cyclic creep. However, that hypothesis is based on limited direct evidence and some scattered indirect evidence, almost entirely for high pH SCC. More experiments to directly test the hypothesis for both high pH and near-neutral pH SCC probably would be justified before embarking on a long effort to relate the cyclic-creep resistance under a variety of stressing conditions to the composition, processing, microstructure, and thermomechanical history. The latter effort probably would require a substantial amount of basic research followed by another significant effort in making and testing experimental steels.

An alternative approach, which is currently being used by researchers in Europe and Japan, is to prepare a number of steels with a variety of microstructures and properties by varying the composition and thermo-mechanical treatment, and then developing empirical correlations between measured susceptibility to SCC and the composition, mechanical properties, and microstructure.

In view of the recent evidence pointing to residual stresses as possible contributing factors to determining where SCC occurs in the field, research into ways to minimize such stresses through modifications of the manufacturing process might be beneficial.

A.4 References

Asahi, H., T. Kushida, M. Kimura, H. Fukai, and S. Okano. 1996. The Investigation on Stress Corrosion Cracking in a Carbonate-Bicarbonate Solution and Its Mechanism for Metallurgical Aspects. In *Proceedings from the Ninth Symposium on Pipeline Research*. PRCI. Catalogue No. L1746. pp.17-1 to 17-18.

Baker, T.R., G.G. Rochfort, and R.N. Parkins. 1986. Investigations Relating to Stress Corrosion Cracking on the Pipeline Authority's Moomba to Sydney Pipeline. In *Proceedings from the Seventh Symposium on Line Pipe Research*. PRCI. Catalogue No. L51495. pp. 27-1 to 27-25.

Barlo, T. 1979. Factors that Influence the Susceptibility of a Steel to Stress-Corrosion Cracking. In *Proceedings from the 6th Symposium on Line Pipe Research*. PRCI Catalogue No. L0175. pp. P-1 to P-17.

Beavers, J.A. and W.V. Harper. 2004. *Stress Corrosion Cracking Prediction Model*. NACE International CORROSION 2004. Paper 04189.

Beavers, J.A., and C.L. Durr. 2001. *Cathodic Protection Conditions Conducive to SCC*. Final Report to PRCI on Project PR 186-9807.

Beavers, J.A., and C. Jaske. 2002. *Effects of Pressure Fluctuations on SCC Propagation*. Final Report to PRCI on Project PR 186-9706. Catalogue No. L51872.

Beavers, J.A., C.L. Durr, and S.S. Shademan. 1998. Mechanistic Studies of Near-neutral pH SCC on Underground Pipelines. In *Materials for Resource Recovery and Transport*. L. Collins, ed. The Metallurgical Society of CIM. pp. 51-69.

Beavers, J.A., J.T. Johnson, and R.L. Sutherby. 2000. Materials Factors Influencing the Initiation of Near-Neutral pH SCC on Underground Pipelines. In *2000 Proceedings of International Pipeline Conference*. ASME. pp. 979-988.

Beavers, J.A., and W.V. Harper. 2004. *Stress Corrosion Cracking Prediction Model*. Corrosion 2004, Paper 04189.

CEPA. 1998. *CEPA Stress Corrosion Cracking Database: First Trending Report*. Submitted to Canadian National Energy Board. January 1998.

Christman, T.K. 1988a. *Evaluation of Stress-Corrosion Cracking Resistance of Newly Developed Grade X70 and X80 Line Pipe Steels*. NG-18 Report 173 to PRC. PRCI. Catalogue No. L51563.

Christman, T.K. 1988b. *Prediction of SCC Susceptibility Based on Mechanical Properties of Line Pipe Steels*. NG-18 Report 180. Catalogue No. L51577.

Chu, R., W. Chen, S.H. Wang, F. King, and R.R. Fessler. 2004. Microstructure Dependence of Stress Corrosion Cracking Initiation in X-65 Pipeline Steel Exposed to a Near-Neutral pH Soil Environment. *Corrosion*. 60. pp. 275-283.

Danielson, M.J., R.H. Jones, and P. Dusek. 2001. *Effect of Microstructure and Microchemistry on the SCC Behavior of Archival and Modern Pipeline Steels in a High pH Environment*. NACE International Corrosion 2001. Paper 01211.

Danielson, M.J., R.H. Jones, and K. Krist. 2000. *Effect of Microstructure and Microchemistry on the SCC Behavior of Pipeline Steels in a High pH Environment*. NACE International Corrosion 2000. Paper 00359.

Delanty, B., and J. O'Beirne. 1992. Major Field Study Compares Pipeline SCC with Coatings. *The Oil and Gas Journal*. June 15. pp. 39-44.

Dupuis, B.R. 1998. The Canadian Energy Pipeline Association Stress Corrosion Cracking Database. In *1998 Proceedings of International Pipeline Conference*. ASME. pp. 589-594.

Eiber, R.J. 1998. *Protocol to Prioritize Sites for High pH Stress-Corrosion Cracking on Gas Pipelines*. Report to PRCI on Project PR-3-9403.

Elboujdaini, M., Y. Z. Wang, R.W. Revie, R.N. Parkins, and M.T. Shehata. 2000. *Stress Corrosion Crack Initiation Processes: Pitting and Microcrack Coalescence*. NACE International Corrosion 2000. Paper No. 00379.

Fessler, R.R. 1976. Combination of Conditions Causes Stress-Corrosion Cracking. *The Oil and Gas Journal*. Vol. 74. No. 7. pp.81-83.

Fessler, R.R. 1979. Stress-Corrosion Cracking Temperature Effects. In *Proceedings from the 6th Symposium on Line Pipe Research*. PRCI. Catalogue No. L30175. pp. R-1 to R-10.

Fessler, R.R., and T.J. Barlo. 1984. *Threshold-Stress Determination Using Tapered Specimens and Cyclic Stresses. Environment-Sensitive Fracture: Evaluation and Comparison of Test Methods*. ASTM STP 821. pp. 368-382.

Fessler, R.R., and K. Krist. 2000. *Research Challenges Regarding Stress-Corrosion Cracking of Pipelines*. NACE International Corrosion 2000. Paper No. 00370.

Fessler, R.R., T. Groeneveld, and A. Elsea. 1973. Stress-Corrosion and Hydrogen-Stress Cracking in Buried Pipelines. International Conference on Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys. Unieux-Firminy. France. June. 1973. Published in *Stress Corrosion Cracking and Hydrogen Embrittlement of Iron Base Alloys*. NACE. 1977.

Fletcher, E.E., T.J. Barlo, A.J. Markworth, E.W. Brooman, W.E. Berry, R.N. Parkins, W.C. McGary, and R.R. Fessler. 1982. *A Study of Interrupted Cathodic Protection As It Relates to Stress-Corrosion Cracking and Corrosion of Buried Pipelines*. NG-18 Report No. 127. Catalogue No. L51425.

Foroulis, Z., and H. Uhlig. 1964. Effect of Cold-Work on Corrosion of Iron and Steel in Hydrochloric Acid. *Journal of Electrochemistry Society*. Vol. 111. pp. 522-528.

Francini, R.B., B.N. Leis, J.B. Nestleroth, and David W. Detly. 2000. *Stress Corrosion Crack Depth Measurement*. Final Report to PRCI on Project PR-3-8718.

Harle, B.A., J.A. Beavers, and C.E. Jaske. 1994. *Low-pH Stress Corrosion Cracking of Natural Gas Pipelines*. NACE International Corrosion 94. Paper No. 242.

Hunt, C.P. 1988. The Effect of Impurities on the Intergranular Stress Corrosion Cracking of a C/Mn Steel. *Corrosion Science*. 28. pp. 901-922.

Jack, T.R., B. Erno, K. Krist, and R.R. Fessler. 2000. *Generation of Near Neutral pH and High pH SCC Environments on Buried Pipelines*. NACE International Corrosion 2000. Paper No. 00362.

Jack, T.R., G. Van Boven, M. Wilmott, and R.L. Sutherby. 1994. Parameters Affecting the Growth of Low pH Stress Corrosion Cracking of Pipeline Steels. In *Proceedings of NACE Western Regional Conference*. Calgary. AB. pp. 504-526.

King, F., T. Jack, W. Chen, S.H. Wang, M. Elboujdaini, W. Revie, R. Worthingham, and P. Dusek. 2001. *Development of Predictive Model for the Initiation and Early-Stage Growth of Near-Neutral pH SCC of Pipeline Steels*. NACE International Corrosion 2001. Paper 01214.

Krishnamurthy, R.M., R.W. MacDonald, and P.M. Marreck. 1996. Stress Corrosion Cracking of a Liquid Transmission Line. In *1996 Proceedings of International Pipeline Conference*. ASME. pp. 495-506.

Krishnamurthy, R.M., B. Martens, S. Feser, P. Marreck, and R. MacDonald. 2000. Liquid Pipeline Stress Corrosion Cracking. In *2000 Proceedings of International Pipeline Conference*. ASME. pp. 1439-1449.

Kushida, T., K. Nose, H. Asahi, M. Kimura, Y. Yamane, S. Endo, and H. Kawano. 2001. *Effects of Metallurgical Factors and Test Conditions on Near Neutral pH SCC of Pipeline Steels*. NACE International Corrosion 2001. Paper No. 01213.

Lambert, S.B., J.A. Beavers, B. Delanty, R. Sutherby, and A. Plumtree. 2000. Mechanical Factors Affecting Stress Corrosion Crack Growth Rates in Buried Pipelines. In *2000 Proceedings of International Pipeline Conference*. ASME. pp. 961-966.

Leis, B.N. 1995. *Characterization of Axial Flaws in Pipelines, with a Focus on Stress-Corrosion Cracking. Volume I: Summary*. NG-18 Report No. 212.

Leis, B.N. 1997. *Validation of a High pH Stress-Corrosion Cracking Life Prediction Model (SCCLPM) for Gas-Transmission Pipelines*. Report to PRCI on Project PR-3-9531.

Leis, B.N., and R.E. Kurth. 1999. *Hydrotest Parameters to Help Control High pH SCC on Gas Transmission Pipelines*. Final Report to PRCI on Project PR-3-9404.

Leis, B.N., and R.N. Parkins. 1993. Modeling Stress-Corrosion Cracking of High-Pressure Gas Pipelines. In *Proceedings from the Eighth Symposium on Line Pipe Research*. PRCI. Catalogue No. L51680. pp. 19-1 to 19-24.

Leis, B.N., and R.N. Parkins. 1998. *Mechanics and Material Aspects in Predicting Serviceability Limited by Stress-Corrosion Cracking. Fatigue and Fracture of Eng. Materials and Structures*. 21. (1998) to be published.

Leis, B.N., T. Forte, and N.D. Ghadiali. 1995. *Stress-Corrosion Cracking Life Prediction Model – SCCLPM: Users Manual and Software. Version 1.0*. NG-18 Report No. 217. PRCI. Catalogue No. L51808.

Mao, S.X., J.L. Luo, B. Gu, and W. Yu. 1998. Hydrogen Facilitated Anodic Dissolution Type Stress Corrosion Cracking of Pipeline Steels in Coating Disbondment Chemistry. In *1998 Proceedings of International Pipeline Conference*. ASME. pp. 485-492.

Marshall, C.W. 1984. *Kinetics of Stress-Corrosion Cracking in Pipe Steels at 175F*. NG-18 Report No. 143. Catalogue No. L51464.

Martinez, F.H., and S.W. Stafford. 1994. EPNG Develops Model to Predict Potential Locations for SCC. *Pipeline Industry*. July 1994. pp. 29-33

Mercer, W.L. 1979. Stress Corrosion Cracking – Control Through Understanding. In *Proceedings from the 6th Symposium on Line Pipe Research*. PRCI. Catalogue No. L30175.

Meyer, M., and M. Pontremoli. 2001. *Comparing of Laboratory Behaviour of Different Pipeline Steels Regarding Their Near-Neutral SCC Susceptibility*. PRCI-EPRG Joint Technical Meeting. New Orleans. Paper 20. May 2001.

Meyer, M., L. Scoppio, B. Rudd, E. Lo Piccolo, S. Matthews, and J.P. Jansen. 2003. *Near-Neutral pH SCC Resistance of Pipeline Steels: Effect of Some Material and Mechanical Parameters* (EPRG-Report). EPRG/PRCI 14th Biennial Joint Technical Meeting on Pipeline Research. Berlin. pp. 5-1 to 5-21.

NEB. 1996. *Public Inquiry Concerning Stress Corrosion Cracking on Canadian Oil and Gas Pipelines*. by Canadian National Energy Board. November. 1996.

Oriani, R.A., and P.H. Josephic. 1981. The Effects of Hydrogen on the Room-Temperature Creep of Spheroidized 1040-Steel. *Acta Metallurgica*. Vol. 29. p. 669.

Parkins, R.N. 1979. Stress-Corrosion Cracking Strain Aging Effects. In *Proceedings from the 6th Symposium on Line Pipe Research*. PRCI. Catalogue No. L30175.

Parkins, R.N. 1987. Factors Influencing Stress Corrosion Crack Growth Kinetics. *Corrosion*. Vol. 43. pp. 130-138.

Parkins, R.N. 1988. Localized Corrosion and Crack Initiation. *Material Science Engineering A*. 103(1). pp. 143-156.

Parkins, R.N. 1994. *Overview of Intergranular Stress Corrosion Cracking Research Activities*. Report on PR-232-9401 to PRCI. Catalogue No. L51719.

Parkins, R.N. 1998. The Influence of Hydrogen on Crack Growth in Pipelines. In *Materials for Resource Recovery and Transport*. L. Collins, ed. The Metallurgical Society of CIM. pp. 35-49.

Parkins, R.N. 1999. *The Involvement of Hydrogen in Low pH Stress Corrosion Cracking of Pipeline Steels*. Presented at PRCI/EPRG Meeting. Groningen, The Netherlands. May 17-21, 1999.

Parkins, R.N. 2000. *A Review of Stress Corrosion Cracking of High Pressure Gas Pipelines*. NACE International Corrosion 2000. Paper No. 00363.

Parkins, R.N. 2002. *Some Effects of Strain Rate on the Transgranular Stress Corrosion Cracking of Ferritic Steels in Dilute Near-Neutral pH Solutions*. Topical Report submitted to PRCI.

Parkins, R.N., and B.S. Delanty. 1996. The Initiation and Early Stages of Growth of Stress Corrosion Cracks in Pipeline Steel Exposed to a Dilute Near-Neutral pH Solution. In *Proceedings from the Ninth Symposium on Pipeline Research*. PRCI. Catalogue No. L51746. pp. 19-1 to 19-14.

Parkins, R.N., and R.R. Fessler. 1978. Stress Corrosion Cracking of High-Pressure Gas Transmission Pipelines. In *Materials in Engineering Applications*. Vol. 1. No. 2. pp. 80-96.

Parkins, R.N., and R.R. Fessler. 1986. *Line Pipe Stress Corrosion Cracking – Mechanisms and Remedies*. NACE Corrosion 86. Paper No. 320.

Parkins, R.N., and S. Zhou. 1997. The Stress Corrosion Cracking of C-Mn Steel in CO_2-HCO_3^--CO_3^{2-} Solutions I: Stress Corrosion Data. *Corrosion Science*. Vol. 39. pp. 159-173.

Parkins, R.N., E. Belhimer, and W.K. Blanchard Jr. 1993. Stress Corrosion Cracking Characteristics of a Range of Pipeline Steels in Carbonate-Bicarbonate Solutions. *Corrosion*. Vol. 49. pp. 951-966.

Parkins, R.N., W.K. Blanchard Jr., and B.S. Delanty. 1994. Transgranular Stress Corrosion Cracking of High-Pressure Pipelines in Contact with Solutions of Near Neutral pH. *Corrosion*. Vol. 50. pp. 394-408.

Parkins, R.N., P.W. Slattery, and P.S. Poulson. 1981. The Effects of Alloying Additions to Ferritic Steels upon Stress Corrosion Cracking Resistance. *Corrosion*. 37. pp. 650-664.

Tyson, W. 1979. Hydrogen in Metals. *Canadian Metallurgical Quarterly*. Vol. 18. pp. 1-11.

Uhlig, H. 1976. Effect of Surface Dissolution on Plastic Deformation of Iron and Steel. *Journal of Electrochemistry Society*. Vol. 123. pp. 1699-1701.

Wang, J.Q., A. Atrens, and D.R.G. Mitchell. 2001. *Grain Boundary Characterization of X42 Pipeline Steel in Relation to IGSCC*. NACE International Corrosion 2001. Paper No. 01210.

Wang, S.H., W. Chen, T. Jack, F. King, R.R. Fessler, and K. Krist. 2000. Role of Prior Cyclic Loading in the Initiation of Stress-Corrosion Cracks in Pipeline Steels Exposed to Near-Neutral pH Environment. In *Proceedings of 2000 International Pipeline Conference*. ASME. pp. 1005-1009.

Wells, D.B. 1993. SCC Threshold Stress in Line Pipe Steels. In *Proceedings from the Eighth Symposium on Line Pipe Research*. PRCI. Catalogue No. L51680. pp. 18-1 to 18-15.

Zhang, B., J. Fan, Y. Gogotsi, A. Chudnovsky, and A. Teitsma. 2000. Theoretical and Experimental Study of Stress Corrosion Cracking of Pipeline Steel in Near Neutral pH Environments. In *Proceedings of 2000 International Pipeline Conference*. ASME. pp. 1013-1020.

Zhang, X.Y., S.B. Lambert, R. Sutherby, and A. Plumtree. 1999. Transgranular Stress Corrosion Cracking of X-60 Pipeline Steel in Simulated Ground Water. *Corrosion*. Vol. 55. pp. 297-305.