STRESS CORROSION CRACKING OF OIL AND GAS PIPELINES: NEW INSIGHTS ON CRACK GROWTH BEHAVIOUR GAINED FROM FULL-SCALE AND SMALL SCALE TESTS

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Abstract

A great deal of research has been conducted in the past two decades on pipeline stress corrosion cracking (SCC) in near-neutral pH environment. Findings on the effects of operating conditions and the soil environment have been very useful in preventing and mitigating failures. The effects of dynamic loading on crack growth were most evidently demonstrated in full-scale tests carried out on pipes of various grades and dimensions. The initial SCC data suggested a correlation of crack growth rate with the rate of energy input into the crack, as expressed by a trend line between the growth rate and the time rate of J.

In the past few years, the focus of research at CANMET-MTL has shifted to crack growth under static loading conditions. Three grades of line pipe steel were tested, namely X-65, X-80 and X-100. Some of the tests lasted for as long as 320 days. It was found that when the applied stress was sufficiently high, albeit well below the yield stress level, cracks can initiate and grow under near-neutral conditions. The incubation time is quite long and the growth rates, in the initial stage at least, are very low. Growth rates generally on the order of 10^{-9} mm/s were found for all three steels. The new test results stimulated our renewed attention to the overall SCC behaviour occurring on oil and gas pipelines. It is clear that the overall growth process consists of slow initiation and growth under relatively stable loading and relatively fast growth when there is dynamic loading, such as repeated cyclic loads. Crack growth modeling needs to take these various load conditions into account.

1. Introduction: SCC in near-neutral pH soil environment.

Since the mid-1980s numerous colonies of transgranular cracks have been found on natural gas and oil pipelines across Canada, and subsequently, in many other countries. As a result, a large number of research projects were initiated around the world. The early Canadian research focused on crack growth behaviour, especially on defining the range of crack growth rates. This was the focus becausebecause the immediate priorities at that time were the estimation of remaining life-time and optimizing the interval time for in-line inspection of affected lines. Soil conditions [1] and operating conditions, in particular, the level of pressure fluctuations [2-4] were subsequently identified as key factors affecting the growth rate of cracks, and this was confirmed by a number of independent studies [5-7]. More recently, the US Office of Pipeline Safety has commissioned a review of SCC in oil and gas pipelines [8]. Several “research gaps” were identified, including modeling of crack growth and the effects of the steel microstructure. New projects have since been started to address these issues.

The recent decision to build new high-pressure pipelines in the northern parts of Canada and USA has triggered a new wave of interest in SCC of high-strength steels, i.e. X-80 and even X-100 grades. SCC studies of these new materials are recently starting to appear [9, 10]. A few reviews in this area have been made by various workers [11-14], which reflected the understanding of the subject at the time of the respective publications. In most SCC data reported in publications, various forms of dynamic loading (cyclic or slow-straining) were used. The issue of crack development under static loading was largely unresolved. In the past few years, work at CANMET-MTL has focused on SCC under static loading conditions. The new finding that cracks do initiate and grow, albeit slowly, without dynamic loading, provides further insight into the cracking problem occurring in oil and gas pipelines. This new result is particularly relevant to the likely high-stress conditions that may occur in pipelines subject to axial loading, such as in those planned for northern Canada and USA.

2. Effects of dynamic loading and crack growth modeling

In recognition of the importance of cyclic loading, a corrosion fatigue approach had been adopted by some workers in analyzing their laboratory results ([15-17], in which the total crack growth was assumed to consist of two parts: a fatigue growth as if the steel were fatigued in air and an SCC growth at a constant rate as if there were no cyclic loading. The total crack growth during a load cycle is expressed by:

$$\frac{da}{dN}(total) = \frac{da}{dN}(fatigue) + \frac{1}{f}\frac{da}{dt}(scc) \qquad (1)$$

However, the initial full-scale SCC tests at CANMET [2, 3] showed no detectable crack growth when the pressure fluctuation component was removed from the load spectrum. It should be pointed out that the crack detection system had a detection sensitivity of about 30 microns; in most of those earlier tests, each test condition was maintained for a relatively short time (up to 2 months or so). In subsequent data analysis, the crack growth rates were correlated with the increase in mechanical driving force that was applied to a given crack [18]. The growth rates were found, on a log-log scale, to increase linearly with the time rate of J, expressed as $\Delta J/\Delta t$ [19], Δt being the reloading time during each cycle:

$$\log(\Delta a/\Delta t) = k \log(\Delta J/\Delta t) + c \qquad (2)$$

where $\Delta a/\Delta t$ is the effective crack growth rate, and k and c are constants that reflect the intrinsic sensitivity of a particular steel to SCC and the overall aggressiveness of the environment.

In another full-scale test, the crack growth rates from a full-scale pipe were analyzed using a similar approach, but with parameters limited to the LEFM level, i.e., using K and K range as the crack tip stress descriptors [20]. In a given load cycle, the rate of increase in J would be related to K range by: $\Delta J/\Delta t = (\Delta K)^2/(E'\Delta t)$ [20]. The test data are presented here as Fig. 1. Note that excessive plastic deformation at very high K levels (K greater than 40 $MPam^{1/2}$) caused the data points to shift away from the linear trend demonstrated by the data at lower loading levels.

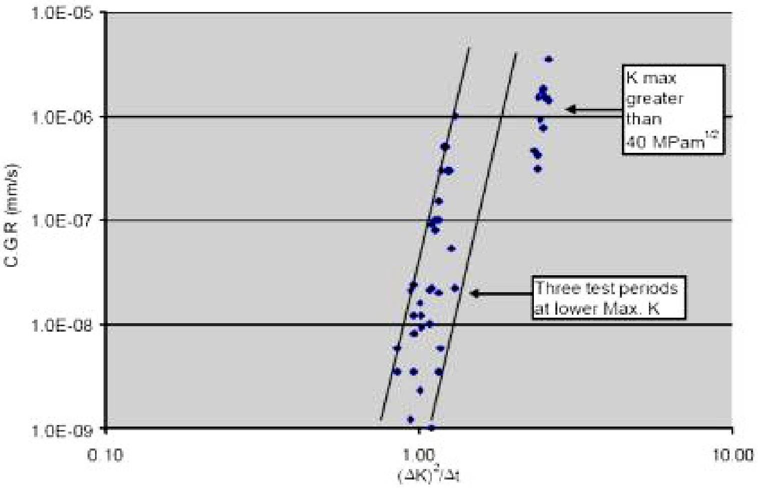

Fig.1 Dependence of growth rates on $(\Delta K)^2/\Delta t$ for an X-52 pipe.

The mechanistic significance of Fig.1 is that the crack growth rate depends on the rate of opening of the crack tip. The total crack growth of a particular pipeline segment would be a simple integration of individual amounts of growth during all loading events, taking into account the duration and the growth rate during each loading event. (The growth rate of a crack in a steel can be calculated once the value of "k" and "c" are determined for that material by laboratory testing.)

The trend of growth rate versus loading rate shown in Figure 1 can also be interpreted as an indication of the sensitivity of the cracking to strain rate. More recently Beavers and Jaske [21] carried out crack growth tests using CT specimens at various stress intensity ranges with various loading frequencies from 10^{-5} to 10^{-2} Hz. The ΔK values were 20, 10 and 7 $MPam^{1/2}$. For ΔK=20 $MPam^{1/2}$, the crack growth rate showed gradual increase with time at all frequencies. For ΔK=10 $MPam^{1/2}$, the crack subject to high cycle rate (10^{-2} Hz) showed faster growth with time while the sample loaded to 10^{-5} Hz showed considerable decrease in the growth rate with test time. For a given ΔK value, the higher the frequency, the higher the rate of crack opening during re-loading. All this work showed the importance of sustaining a certain rate of deformation at the crack tip to maintain the growth of a crack that started from a freshly made pre-crack.

3. Development of SCC under static loading

3.1 Considerations on the actual stress level in a pipeline. Several factors can change the net total stress level at a specific site on a pipeline. A significant one is the stress concentration by any surface profile such as a long seam weld. For example, one finite element calculation for an applied stress of 340 MPa (77% of the specified minimum yield stress (SMYS) for the pipe in question) showed that there is a zone a few millimeters wide near the weld toe in which the actual local stress is close to the SMYS of the base steel [11]. At the very toe of the weld, the stress is in fact above the actual yield point of the material. Even away from the weld, the presence of surface residual stress could raise the net local stress to well above the nominal operating level. In a CANMET study on residual stress in various pipes retrieved from service, tensile residual stresses in the range of 20% SMYS were often found to exist at the surface to a depth of about 1 mm [22]. These factors were considered in the recent CANMET SCC tests of X-80 and X-100 steels, which were loaded to 95% of their respective yield point. This load level would be above the nominal operating stress level, but very likely to be within the actual stress range, given the contribution of residual stresses and stress concentrations.

3.2 SCC tests under static loading. Cortest load rings were used in this type of test. Details of the SCC test setup have been described elsewhere [10]. Three grades of line pipe steel were tested, namely X-65, X-80 and X-100. Several series of tests were designed, lasting for 26, 54, 110 and 220 days. The latest series of tests lasted for as long as 320 days.

Two types of test solutions were used in this test program. The first type was the so-called 'NS4' solution, containing 0.122 g/L KCl, 0.483 g/L $NaHCO_3$, 0.093 g/L anhydrous $CaCl_2$ and 0.131 g/L $MgSO_4.7H_20$. The pH of this solution was maintained between 6.5 and 6.8 by bubbling gas consisting of 5% CO_2 and 95%N_2. All tests were conducted at 25°C at the free corrosion potential, i.e., without any electrochemical potential control of the test steel. The second type of test solution was a mixture of NS4 solution and a clay soil in a 1:2 ratio by volume. The pH of the second test solution was also acidified to a range of 6.5 to 6.8 using the CO_2/N_2 bubbling gas.

At the completion of each test, the SCC sample was cut along the centerline of the gauge length and cold-mounted in low-shrinkage epoxy under vacuum and polished to sub-micron finish in order to observe the fine details of microscopic cracks. At the time of preparation of this paper, a complete statistical analysis of all the test data is still in progress. However, some of the highlights of results are presented below.

3.3 Results for X-80 steels.

Fig 2 shows examples of the cracks in the prototype X-80 steel produced after 110 days of testing in NS4 solution. In order to assess the cracking severity in each test, all cracks found on the centre-line cross-section of the test specimen were imaged using SEM, and their depths of penetration measured one by one. Selected cracks were also studied using focused ion beam microscopy. Figure 3 is an example of the tip region of the X-80 cracks after 110 days of testing at 95% yield stress. The sharpness of the crack tip suggests that the crack was actively growing when the test was stopped.

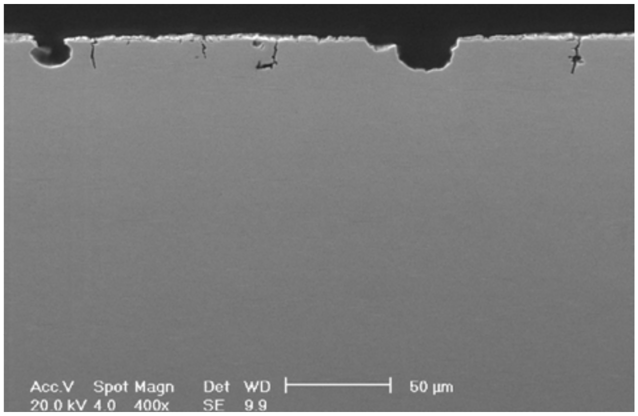

Fig.2 A cross-section of X-80 steel specimen after 110-day SCC tests.

Fig. 4 shows a histogram of crack depth for the 110-day, 54-day and 26-day test series. After 26 days, only one 'crack-like' feature of depth less than 2 micrometers (microns) was observed in the cross-section. Five small cracks of depth ranging from 3 to 8 micrometers were seen after 54 days of testing. After 110 days, the number of cracks increased to 27, and, more significantly, the number of deeper cracks, with depth greater than 10 micrometers, accounted for about half of the total number of cracks observed. The conclusion from this series of tests is that most cracks produced under static loading were likely formed after 54 days of testing.

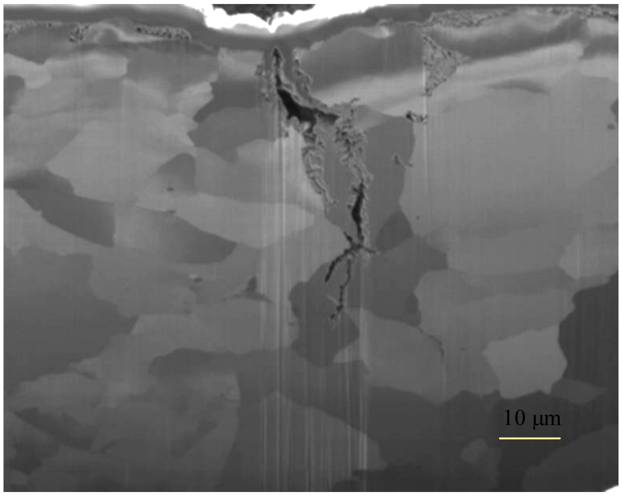

Fig. 3 A FIB cross-sectional view of the crack tip region.

This result highlights the slow nature of cracking in the near-neutral environment, and suggests a need for a minimum test duration when SCC susceptibility of various steels is evaluated. This point is even more evident when the test samples of X-100 steel were examined. As explained in Section 3.5, a longer incubation time is needed for the higher grade of steels.

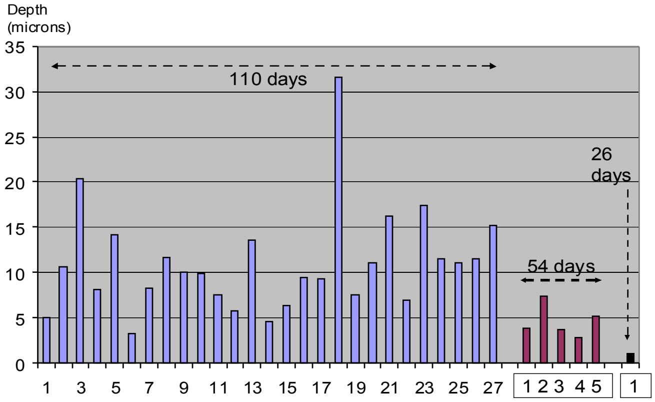

Fig. 4 Results of crack depth survey on cross-sections of X-80 steel tested for 26, 54 and 120 days.

3.4 Effects of test solution

In the 110-day series of the static tests carried out on using the X-80 and the X-65 steels, the effect of adding clay soil to the NS4 solution was quite dramatic. Figure 5 compares the SCC histograms for an X-65 steel in de-aerated solution of very similar pH level. When a clay soil was added to the test cell, to a 50% (v/v) level in the NS4 solution, the number of cracks was significantly reduced. The natural soil water is generally comprised of dissolved gases and various dissolved and un-dissolved soil minerals, and the mechanisms of how the soil chemistry influences SCC can be quite complicated. Cross-sections of the test samples showed a surface corrosion product layer that is generally thicker, and of more porous structure, in the clay-NS4 mixture than in the NS4 solution.

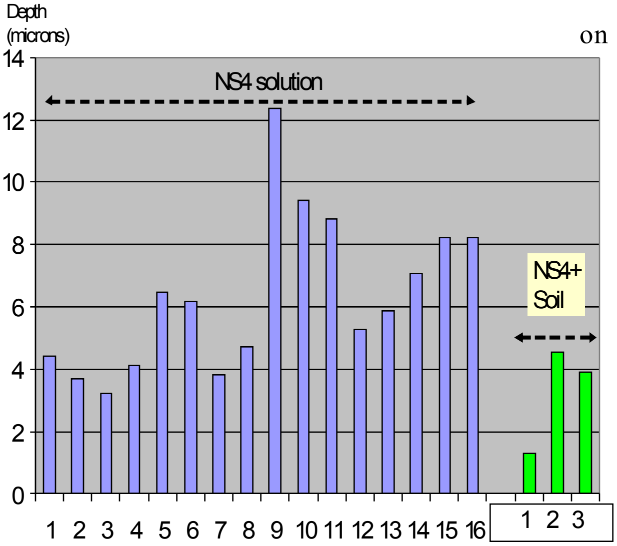

Fig. 5 Comparison of SCC severity for NS4 and NS4+clay.

3.5 Results for X-100 steels

When stressed at 95% of the yield point and immersed in the same NS4 solution, the X-100 steel took even longer time to develop. Fig. 6 shows the cross-section of an X-100 sample tested for 220 days. Only a few shallow cracks were observed to have initiated at the bottom of corrosion product; the overall crack-like morphology was ill-defined as there was a thick layer of corrosion product covering the sample surface.

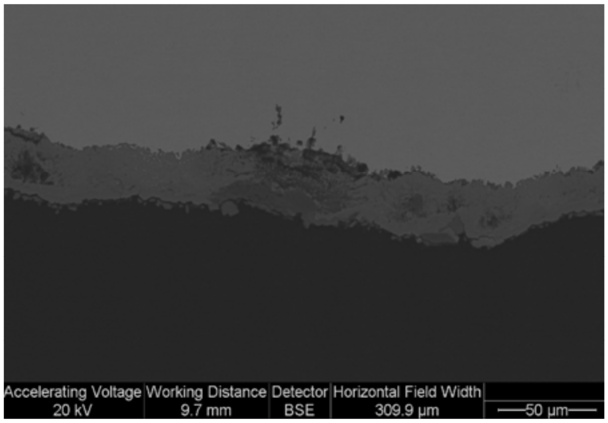

Fig. 6 Cross-section of X-100 steel after 220-day testing.

After the SCC test time was increased to 320 days, more numerous and deeper cracks were found on the X-100 sample. Fig. 7 is a section showing the cracks developed along the gauge length. The deep ones have reached a depth of about 100 microns after 320 days. The presence of a thick corrosion product layer on the X-100 steel is quite pronounced, as indicated by markers A and B in Fig. 7 reflecting the good stability of the iron corrosion products in this NS4 solution.

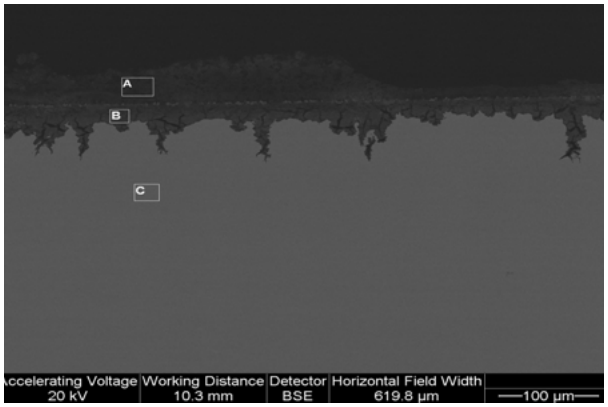

Fig. 7. Cross-section of X-100 steel after 320-day.

An EDS analysis of the coherent corrosion product layer, Zone B in Fig. 7, revealed the presence of some of the alloying elements contained in the X-100 steel. The X-100 steel contains 0.50% Ni and 0.28% Cu, among other minor alloying elements. As shown in Fig. 8, the presence of Ni and Cu is clearly visible in the EDS spectrum. It is possible that these alloying elements, although added to the steel in small quantities, alter the kinetics of corrosion in the near-neutral pH environment. Cu, for example, is well known to enhance the corrosion resistance of steel in natural environment.

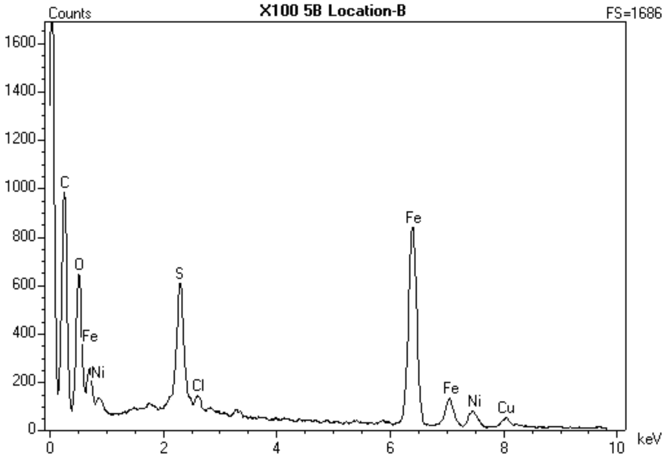

Fig. 8 EDS analysis of the corrosion product adjacent to the X-100 steel surface. Presence of Ni, Cu is shown.

4. Considerations on crack growth modeling

The results from the static tests clearly indicate that crack development, i.e., initiation (or re-initiation) and growth, is an intrinsic part of the stress corrosion cracking in oil and gas pipelines even in the absence of major pressure fluctuations. Owing to the detection limit of the crack detection system used in the full-scale SCC tests, the slow crack growth was not discernible in the on-line crack growth monitoring plots, given the testing time allowed. Testing slow crack growth in a full-scale pipe requires maintaining the pressure loading for an extended period of time (over several months) which is difficult to achieve owing to technical and financial reasons. On the other hand, the cost of carrying out the long-term Cortest ring tests is much lower than the full-scale test.

The fact that SCC can be produced under static loading calls for an update of the growth model shown in Equation (2). Taking into account the natural corrosion process inside a crack, which is unavoidable even if there is no stress applied, a more comprehensive description of the penetration of a crack should be:

$$\Delta a \text{ (total growth in a loading period, } \Delta t) = \int f_1(da/dt) * \Delta t + \int f_2(da/dt) * \Delta t + \int \beta * \Delta t \qquad (3)$$

where $f_1(da/dt)$ is a term that describes the contribution of crack growth due to dynamic loading, as defined in equation (2); $f_2(da/dt)$ is a term that reflects the crack growth under static loading, i.e., when $\Delta J/\Delta t$ is zero. The rate of growth under static load should be a function of the stress level applied and of the microstructural sensitivity of the steel to SCC. As shown in the above section, the time needed to grow cracks in the X-100 and X-80 steels was very different.

The term containing β represents the penetration of a crack by a pure corrosion process alone, i.e., without any significant stress applied. This condition could exist, for example, when a pipeline is shut down for a considerable amount of time or when the stress level in a pipe is below the threshold for cracking. Corrosion of the crack wall leads to blunting of cracks. For a near-neutral-pH soil without excessive microbial activity, this value can be assumed to be in the range of 5 to 50 microns per year or $0.15 \sim 1.7 * 10^{-9}$ mm/s. This term is determined by the corrosivity of the soil. The data from the dozen or so full-scale tests completed at CANMET so far suggest that the growth rates due to dynamic loading, $f_1(da/dt)$, is the most significant part and is generally between $5*10^{-9}$ mm/s and $1*10^{-5}$ mm/s; the second term, $f_2(da/dt)$, which is the cracking under static loading, should be in range of 20 to 150 microns per year or $0.6{\sim}5*10^{-9}$ mm/s, based on the data produced so far in NS4 and NS4-plus-clay solutions.

CONCLUDING REMARKS

A summary is given of key research results in the area of pipeline SCC in the near-neutral pH environment; the results reported are either from CANMET full-scale tests or from long-term static loading tests. The recent findings of SCC under static loading proved that cracking in the near-neutral-pH condition is indeed an 'authentic' SCC process, instead of a corrosion fatigue process as was once believed, but the rate of which is very sensitive to dynamic loading. When the crack growth rates and the time rate of J were plotted on a log-log scale, a nearly linear trend line is observed, suggesting a strong dependence of the inherent cracking process on the crack tip strain rate.

In practice, the pressure in a gas transmission line is relatively stable over time, whereas a liquid line tends to experience more fluctuations. Therefore the relative contributions of crack growth from dynamic loading and from static loading will be different in gas and liquid lines. A generic approach taking into account all possible growth mechanisms is therefore needed.

As the crack growth rates tend to be very slow as laboratory test conditions approach realistic ranges of an operating pipeline, high-quality SCC data require long-term testing and careful planning. In the static tests involving stressing the steels to 95% of the yield point, SCC incubation time in an NS4 solution is longer than 50 days for the X-80 steel and significant cracking in the X-100 steel was only found after 320 days of testing.

References

(1) Delanty, B., and O'Beirne, J. (1992) Oil and Gas Journal June, 15, pp. 39-44.
(2) Zheng, W., Revie, R. W., Tyson, W. R., Shen, G., and Macleod, F. A., "Effects Of Pressure Fluctuation on the Growth of Stress Corrosion Cracks in An X-52 Line pipe Steel," 8th International Conf. on Pressure Vessel Technology, ICPVT-8, ASME, New York, 1996, pp.321-326.
(3) Zheng, W., Macleod, F.A., Revie, R.W., Tyson, W.R., Shen, G., Kiff, D., Skaff, M., and Wong, E.-W. "Recent Progress in the Study of Transgranular SCC in Linepipe Steels", (1996) Corrosion Deformation Interactions CDI '96, P. 282. Ed. T. Magnin (Nice, France: Published for the European Federation of Corrosion by the Institute of Metals)
(4) National Energy Board, Calgary, Alberta, Canada, "Stress Corrosion Cracking on Canadian Oil and Gas Pipelines," Report # MH-2-95, Nov. 1996.
(5) Wilmott, M.J., and Sutherby, R.L. "The Role of Pressure and Pressure Fluctuations in the Growth of SCC In Line Pipe Steels" (1998). International Pipeline Conf., 1, P. 409.
(6) Zhang,X.-Y., Lambert, S.B., Sutherby, R., and Plumtree, A. (1999) Corrosion, 55, P. 297
(7) Wang, Y.Z., Revie, R.W., and Shehata, M.T. "Early Stage of Stress Corrosion Crack Development of X-65 Pipeline Steel in Near-Neutral-pH Solution" (1998), Materials for Resource Recovery and Transport, P. 71. Ed. L. Collins (Montreal, Quebec: The Metallurgical Society of the Canadian Institute of Mining, Metallurgy and Petroleum)
(8) Baker M. Jr. Inc., "Stress Corrosion Cracking Study" (2005), (US) Department Of Transportation, Research And Special Programs Administration, Office Of Pipeline Safety, January, 2005.
(9) Lu, B.T., and Luo, J.L. (2006) Corrosion, 62 (2), pp. 129-140.

(10) Zheng, W., et al., “Near-Neutral pH SCC Of Two Line Pipe Steels Under Quasi-Static Stressing Conditions”, Proc. Of International Pipeline Conf., Calgary, Alberta, Canada, Sept., 2006, Paper#: IPC2006-10084.

(11) Zheng, W., Sutherby, R., and Revie, R.W., (2000), “Stress Corrosion Cracking of Linepipe Steels in Near-Neutral PH Environment: A Review of the Effect of Stress”, pp. 473-483. ASTM Special Technical Publication (1401), ASTM.

(12) R.N.Parkins, “Intergranular and Transgranular Stress Corrosion Cracking of High Pressure Gas Pipelines - Similarities and Differences”, In Proceedings Of NACE Northern Area Eastern Conference, Oct. 24-27, 1999, Ottawa, Ontario, Canada, Pp. 1-22.

(13) Parkins, R.N., “A Review of Stress Corrosion Cracking of High-Pressure Gas Pipelines”, (2000) CORROSION/2000, Paper No. 363 (Houston, TX: NACE International)

(14) Zheng, W., Tyson, B., Shen, G., Revie, R.W., Williams, G., and Bibby, D., Effects of Operating Practices on Crack Dormancy and Growth. GRI-04/0121, January 2005. GRI, Des Plaines, IL.

(15) Plumtree,A., Lambert, S.B. and Sutherby, R., “Stress Corrosion Crack Growth of Pipeline Steels In Simulated Ground Water”, In Corrosion-Deformation Interaction CDI’96, Nice, France, 1996.

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

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

(18) Zheng, W., Macleod, F.A., Revie, R.W., Tyson, W.R., Shen, G., Shehata, M., Roy, G., and Mckinnon, J. (1997), “Growth of Stress Corrosion Cracks in Pipelines in Near-Neutral PH Environment: The CANMET Full-Scale Tests - Final Report to the CANMET/Industry Consortium”, CANMET/MTL, Ottawa, MTL97-48(CF).

(19) Zheng, W. “Stress Corrosion Cracking Of Pipelines: An Overview of Key Factors”, (2001) Second International Conference On Environment Sensitive Cracking And Corrosion Damage, Hiroshima Japan, Oct. 29-Nov.2, 2001.

(20) W. Zheng, W. Revie, F. A. Macleod and O. Dinardo, “Low pH SCC: Environmental Effects on Crack Propagation”, Pipeline Research Council International (PRCI), July 1, 2000. Cat. No. L51791e.

(21) Beavers,J. A. and Jaske,C., “Effects Of Pressure Fluctuations On SCC Propagation. Final Report To PRCI”, On Project PR 186-9706. Catalogue No. L51872 (2002).

(22) Roy, G., Kiff, D., Revie, R. W., Cousineau, E. J.-C., Williams, G., and Sinigaglia, E., "Residual Stresses In Linepipe Specimens", MTL Report 94-17(TR), 1994.