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REDUCING THE RISK OF NEAR-NEUTRAL PH SCC FAILURE THROUGH OPERATION PRESSURE OPTIMIZATION
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ABSTRACT

This PRCI project was specifically designed to address the effect of pressure fluctuations on the growth rate of NNpH SCC. In particular, the project will determine the kinds of pressure fluctuations that represent the greatest risk for increasing the potential for SCC to form and propagate, the different types of mechanisms that are operative in the NNpH environment, and the factors that control and determine the extent and degree to which the mechanisms will occur. Operation pressure magnitude and fluctuations affect near-neutral pH stress corrosion cracking differently depending upon three different identified stages of cracking. Progress made in the understanding and modelling pressure effects of each stage of near-neutral pH SCC cracking is introduced. Other service conditions, such as cathodic protection, ground water chemistry, pipe surface conditions, coating practice, and steel metallurgy, all interact with pressure effects on near-neutral pH cracking. As a result of the research, a software tool was developed to determine which kinds of pressure fluctuations represent the greatest risk of increasing the potential for cracks to form and propagate.

DISCLAIMER

1.INTRODUCTION

Cracking failure of pipeline steels caused by near-neutral pH aqueous solutions surrounding buried pipeline steels is rooted even to the stage of steel plate making and pipe fabrication, where mill scales on steel surface are formed, and residual stresses are introduced, especially when they are distributed heterogeneously on the steel surface, due to the process of pipe forming, welding, pipe handling, and hydrotest for flaw detection. Together with the above conditions of pipe fabrication, pipe installation and commissioning, and initial service operation constitute the stage of preparation for crack initiation, among other stages as illustrated in Figure 1 [1-4].

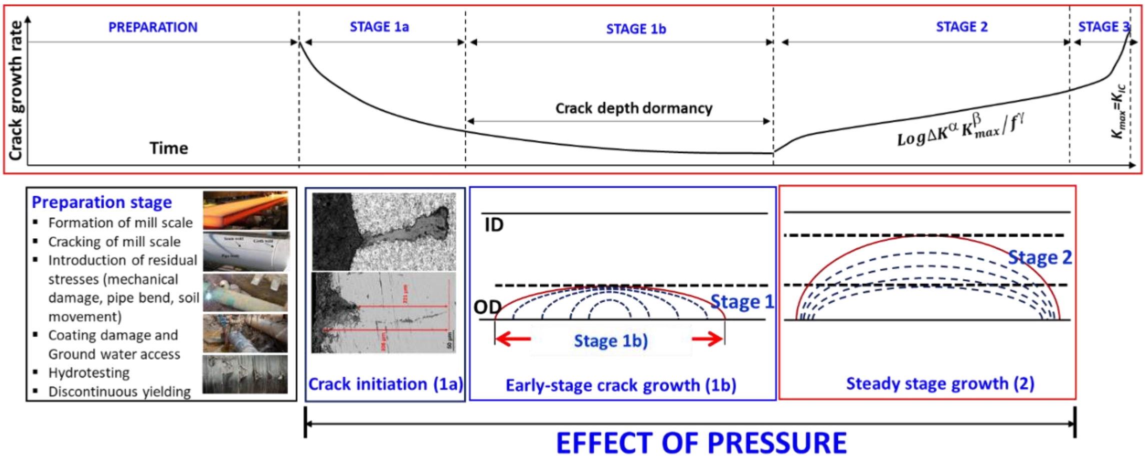


Figure 1 A bathtub model illustrating various stages of crack initiation and growth of pipeline steels in near-neutral pH environments.

The initiation of cracks in near-neutral pH solutions can be relatively short, especially under the following pipe surface conditions:

1) Ground water with relatively lower pH value corresponding to a higher rate of corrosion
2) Presence of high tensile residual stresses on pipe surface
3) Cracked mill scale on steel surfaces that can be preserved over a long time, which promotes and maintain localized corrosion at the bottom of fractured mill scales.
4) The occurrence of corrosion because of coating disbondment and insufficient cathodic protection.

The above process is sensitive to both the magnitude and fluctuation of operation pressure in terms of mill scale cracking. The initiation proceeds through a localized dissolution that is galvanically assisted ownin to mill scale and steel coupling. The process of dissolution, especially, when the depth of crack is getting larger, is also senstive to both the magnitude and fluctuation of operation pressure in terms of mass transfer within crack cravice.

The rate of growth in the depth direction decreases with increasing crack depth, and often cracks cease to grow when the depth of crack reaches about 1 mm. This state of dormancy takes place because of multiple reasons, including but not limited to the factors such as the reduction of tensile residual stresses, the reduced rate of dissoluction, non passivating nature of the near-neutral pH ground water causing crack tip blunting.

Further growth of crack in the depth direction will be limited by the mechanical driving forces that are govenered by hydrogen-enhanced fatigue crack growth mechanisms. However, the mechanical driving forces are usually insufficient to produce measurable crack growth based on the available level of stress intensity factor at the crack tip that is a function of crack dimensions and operation pressures.

The critical level of mechanical driving that can induce Stage 2 crack growth can be reached by extending the length of crack, which leads to an increase of stress intensity factor at the depth even if crack depth tip remains dormant, as presented in Figure 2.

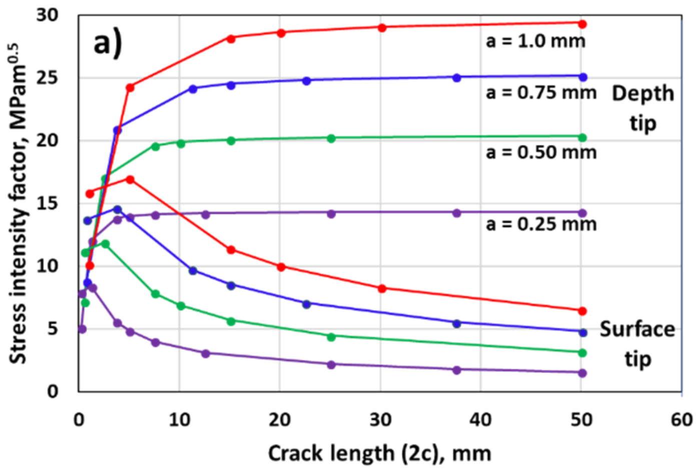


Figure 2 Schematic illustration showing the variation of stress intensity factor at the surface tip and the depth tip for cracks with a given depth but varied crack length (c) [5].

Extension of crack length could be achieved in different ways that can be either operation-pressure dependent or independent. The operation-pressure dependent extension of crack length was found to be self-induced by an existing crack, which is predominent for cracks initiated on pipe body. The extension of crack length is termed as Stage 1b, which, unlike the initial initiation of crack in Stage 1a), could take up a large fraction of service life. Different scenarios of Stage 1b could be achieved:

1) Very limited extension of crack length, which could lead to the following situations:
   a) Permanent crack depth tip dormancy that is usually characterized with very blunt crack tip.
   b) General corrosion on pipe surface that gradually destroy the feature of cracks.
2) Active extension of crack length that is very sensitive to pipe surface conditions and operation pressure.

Stage 1b could also be short, that is, a limited extension of crack length is required. This is largely dependent on the following conditions:
1) The magnitude of tensile residual stresses at the depth tip,
2) The level of diffusible hydrogen at the depth tip, which depends on the level of CO_2 in the environments, the level of cathodic potential, and the chemistry of ground water.
3) The conditions of operation pressures in terms of its magnitude and the degree and the type of fluctuations.

The above factors are critical to the start of Stage 2 crack growth that is not dissolution dependent, but mechanically driven and can be modeled through a combined factor given in Eq. 1 [6-8].

$$\frac{da}{dN} = A\left(\frac{\Delta K^{\alpha} {K_{max}}^{\beta}}{f^{\gamma}}\right)^{n} + h \qquad (1)$$

where A, n, α, β, and γ are all constants, $\alpha + \beta = 1$, and h is the contribution of crack growth by dissolution of crack tip, a situation governed by stress corrosion cracking mechanisms, which was found to be about one order of magnitude lower than the first term in Stage 2 crack growth and can be ignored. $(\Delta K^{\alpha} K_{max}{}^{\beta})/f^{\gamma}$ is termed as the combined factor, ΔK is the change in stress intensity at the crack tip due to cyclic loading, K_{max} is the maximum stress intensity at the crack tip, and γ is a factor representing the influence of the corrosion environment on the crack growth rate. ΔK and K_{max} are strongly dependent on the geometry of the specimen.

It should be pointed out that Equation 1 is strictly applicable to the modeling of crack growth rates obtained from tests under a constant cyclic loading skeme when the loading frequency is higher than a critical value, for example, at around 10^{-3} Hz, as shown in Figure 3 [9].

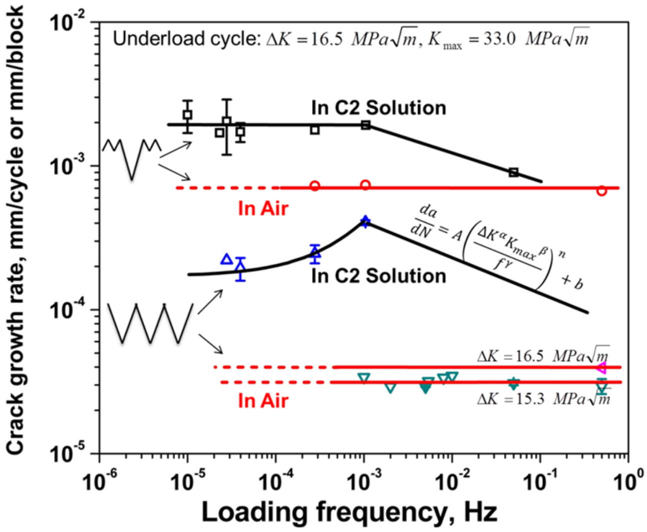


Figure 3 Comparison of the crack growth rate under different loading frequencies for constant amplitude and underload-type variable amplitude waveforms in air and in C2 solution under the conditions: K_{max} = 33 MPa $\sqrt{m}$, $\Delta K_{underload}$ = 16.5 MPa $\sqrt{m}$, $\Delta K_{minor\text{-}cycle}$ = 16.5 MPa $\sqrt{m}$, number of minor cycles = 697, $f_{minor\ cycles}$ = 5.4×10^{-3} Hz (in C2 solution), $f_{minor\ cycles}$ = 5×10^{-1} Hz (in air) [9].

Equation 1 cannot be directly used to model the growth rate of near-neutral pH cracks that are developed in pipeline steels from field services. There are a number of discrepancies that must be considered:

- Type of cracks: It is the surface cracks that are initiated in pipeline steels, not a through-thickness crack simulated by compact tension specimens and modeled by Eq. 1. The set of constants in Eq. 1 will be very different between a through-thickness crack and a surface crack.
- Effect of frequency: The dependence of crack growth rate on loading frequency changes at a critical frequency. The dependence of crack growth rate as modeled by Eq. 1 exists only when the loading frequency is higher than the critical frequency. On the other hand, the critical loading frequency itself is not an intrinsic property of the pipeline steel, but is different dependent of the crack types, temperature, and test environments.
- Nature of pressure cycles: The pressure schemes are very complex and strongly affect crack growth rate through load history interaction effects.
- Effect of corrosion: Corrosion in near-neutral pH environments serve as three-fold roles: crack growth in Stage 1, generation of diffusible hydrogen as a by-product of corrosion, blunting crack tip causing a reduction of mechanical driving forces.
- Level of diffusible hydrogen: Diffusible hydrogen can be generated as a by-product of corrosion and/or through cathodic reactions.
- Metallurgical factors: Certain mechanical loading conditions could lead to low temperature creep and cause repeated occurrence of discontinuous yielding.

This paper will outline first how operation pressure and pressure fluctuations could play a role in affecting the crack initation and growth through the above listed attributes in all the stages demonstrated in Figure 1. Based on the mechanisms of crack growth affected by operation pressure, methods of reducing the risk of NNpH SCC failures through operation pressure optimizatin will be introduced.

2. CHARACTERISTICS OF OPERATION PRESSURE

The Pipeline steels must be pressurized first to achieve the purpose of gas/liquid transfer. The magnitude of pressure is usually controlled below the design pressure that is regulated depending on the location of pipeline services. As a result, pipeline steels experience the maximum pressure right after a gas compressor or pump station. Because of the design limit of pressure, pressure may fluctuate to a lower value if occurs. This would form a pressure scenario that is termed as underload plus minor cycles, as shown in Figure 4. Because of downstream usage and fluid friction, the magnitude of pressure is decreased below the design limit and pressure fluctuates up and down but below the design limit, which can be best described as a mean load cycle. Further down to the next gas compressor or pump station, the magnitude of pressure is further reduced and overload pressure with a pressure magnitude well below the design limit may be often seen.

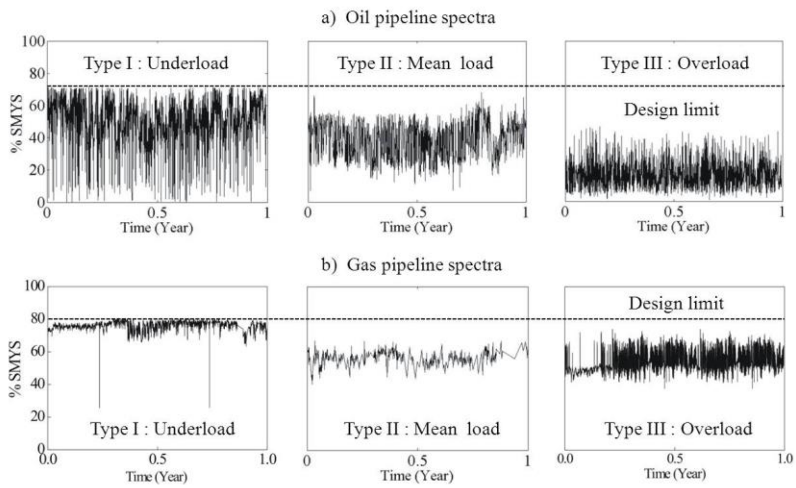


Figure 4Three types of pressure fluctuations [4, 10-11].

In addition, the above indicated three scenarios of service pressure, pipelines can be subjected to hydrotests that are applied periodically for integrity management. A hydrotest is one time pressure cycle with a pressure magnitude much larger than the design limit of pressure that could change the course of crack initiation and growth, and even the property of pipeline steels.

Crack growth in near-neutral pH environments is both cycle-dependent and time-dependent. The cycle-dependent crack growth behavior is consistent with those mechanisms governing fatigue crack growth. The time-dependent crack growth in near-neutral pH environments is related to the following three factors:

1) The time of hydrogen diffusion to and out of the plastic zone ahead of the crack tip in response to stress increase and stress reduction of a pressure cycle, respectively. A low rate of pressurization allows more time of hydrogen diffusion to the plastic zone, resulting in higher crack growth rate; a high rate of depressurization limits the effusion of hydrogen out of the plastic zone and could lead to cracking even during unloading portion of a cycle if the plastic zone is fully charged with hydrogen during loading portion of the pressure cycle.

2) The time of corrosion at the crack tip that cause crack tip corrosion and blunting, which will reduce the mechanical forces for crack growth by the mechanism of hydrogen-enhanced fatigue.

3) The time of low temperature creep that can also cause crack tip blunting, especially when plastic zone is fully charged with hydrogen. The low temperature creep deformation is maximized when crack tip is held at peak stress for a time over one hour.

The time factor of operation pressure is related to the rate of pressurization and depressurization often measured by loading frequency of a pressure cycle. Table 1 is a summary of typical range of loading frequency for oil pipelines and gas pipelines. Oil pipelines are featured with loading frequency over a wide range, while the gas pipelines are usually experienced with very low loading frequencies.

	Oil pipelines	Gas pipelines
# of underload cycles	537/year	8/year
Unloading frequency	6.89×10^{-6} ~ 1.0×10^{-1} Hz	1.30×10^{-6} ~ 9.16×10^{-5} Hz
Loading frequency	5.11×10^{-6} ~ 1.0×10^{-2} Hz	1.34×10^{-6} ~ 5.26×10^{-6} Hz
# of minor cycles	0~26/underload cycle	0~37/underload cycle

Table 1 Characteristics of Type I pressure fluctuations in gas and oil pipelines [10-11].

Since crack propagates through the region of plastic zone but not the virgin material outside of the plastic zone. The residual stresses in the plastic zone and the strain response of the plastic zone material to the applied stress are critical to the rate of crack growth. It has been well established that overloading leads to the generation of large compressive stress in the plastic zone ahead of the crack tip, causing a reduced crack growth rate during subsequent loading.

In pipeline operation, overloading is not a concern as it is beneficial in terms of reducing crack growth rate and is also seen to occur in regions with operation pressure where below the design limit (Type 3 in Figure 4). Overloading also occurs during hydrotests, which can yield a crack growth retardation effect that can reduce the rate of crack growth after hydrotest, although this benefit could be compromised by the reduction of service life of pipelines by 1 or 2 years due to crack growth during hydrostatic loading, especially in the presence of hydrogen [12, 13].

Underloading, on the other hand, is the worst case of pressure fluctuations. It can increase the rate of crack growth during subsequent pressure loading, which can be explained either because of the presence of tensile residual stress induced by underloading in the plastic zone or the Bachinger effect that the yield strength of plastic zone material is reduced after underloading. Therefore, the variable loading scenarios of pressure fluctuations result in either crack growth acceleration or retardation.

3. EFFECT OF OPERATION PRESSURE ON CRACK INTIATION AND GROWTH

3.1. Effect of pressure on crack initiation and early-stage crack growth

Extensive efforts have been made in understanding how cracks are initiatied in pipeline steels in NNpH environments. By reviewing crack intiation investigations published, it was found that there exist two clusters of data in general. These clusters of data are presented in red in Figure 5, together with the crack initiation data found in the field. One cluster shows a crack density close to the upper bound of crack density found in the field, but has a crack growth rate close to an order of magnitude higher than the crack growth rate found in the field. The second cluster of data exhibits a crack density more than two orders of magnitude higher than the field crack density, although some of them have a growth rate comparable to those of field cracks.

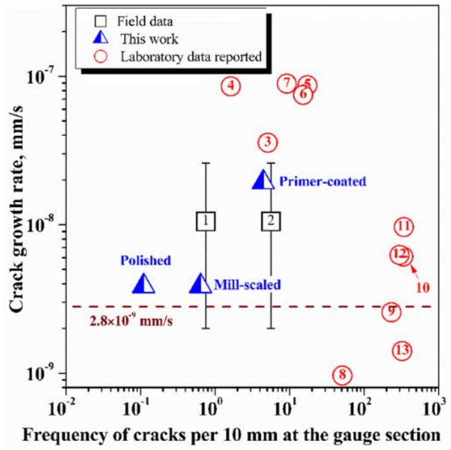


Figure 5. The crack growth rate vs. frequency of cracks statistically analyzed on 10-mm long cross-section within the gauge section for samples after different test conditions [14]. The literature data in the figure can be found in Ref. [14].

The causes of disagreement in laboratory simulations of crack initiation are further analyzed and categorized below:

1) **Inappropriate surface preparation:** A polished or ground surface cannot represent a realistic surface condition for pipeline steels where mill-scale and primer layer are commonly present. A polished surface would either result in a very high or very low density of crack initiation sites and crack growth rates, depending on the location of the surface with respect to the pipe cross section. Sample surfaces that were cut from the middle section of the pipe would yield very high crack density and potentially high growth rates because of microstructure-related galvanic effects [11], while the polished surface from just below the mill scale would have both low crack density and low crack growth rate (current study).

2) **Unrealistic loading conditions:** Gas and oil pipelines are operated under mild pressure fluctuations either in terms of magnitude and/or frequency of pressure fluctuations and with a maximum load of around 70% of SMYS. The stresses applied in some of the simulations are too severe compared to the field conditions, particularly, those simulations using slow strain rate test.

3) **Unrealistic corrosive environments:** Near-neutral pH SCC occurs in a CO_2-containing ground water with a pH ranging from 5.5-7.5. A dilute bicarbonate solution sparged with continuous CO_2 is commonly used. It is inappropriate if the solution is either concentrated or sparged discontinuously.

It has been found from our investigaion that the density of the initiated cracks varied depending on the pit density and depth, pit-to-crack transition and the cathode-anode galvanic sites [15-17]. Crack population in a crack colony was increased with increasing area of mill scale coverage and with the length of time the damaged mill scale can be maintained on the steel surface, which is influenced by the nature of the primer coating. Conditions that can lead to longer retention of mill scale on the pipeline steels increase the susceptibility to crack initiation:

1) Pre-cyclic loading in air, which simulates the mechanical loading before coating damage, led to either local spallation or cracking of mill scale, even though the maximum cyclic stress applied was below the yield strength (Figure 6) [17]. The highest density and depth of pits were found on specimens that were cyclically loaded with a peak stress of 75% SMYS prior to corrosion because these specimens had the longest retention of mill scale on the steel surface.

2) Strain ageing of pipeline steel: An increase in yield strength and formation of oxide scales more resistant to fracture occur with strain aging. This reduces the spallation and cracking of the mill scale on the heat-treated specimens [17].

3) Application of primer coating: Localized corrosion at damaged mill scale and enhanced corrosion under the mill scale were generated through a galvanic coupling between the mill scale and steel. The primer layer aggravated localized corrosion and pit-formation, because of the prolonged period of time that the mill scale can be retained on the steel surface when primer is present. The calculated crack growth rate for primer-coated specimens was 1.9×10^{-8} mm/s, which is ~ 5 times higher than that of the specimens without primer. The crack growth rate of 1.9×10^{-8} mm/s is much higher than the rate of dissolution but is comparable to the rate of crack growth of SCC cracks found during field service, indicating the transition of pitting corrosion to SCC (Fig. 7) [16].

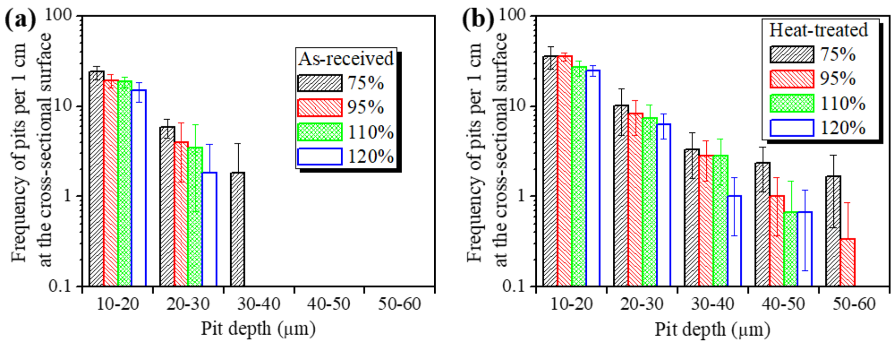


Figure 6 Frequency of pits versus pit depth at the cross-sectional surface of pre-cyclically loaded specimens after immersion in C2 solution for 60 days: a) as-received, b) heat treated specimens [17].

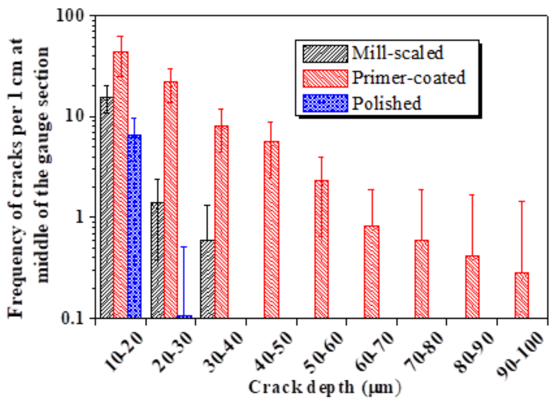


Figure 7 The frequency of cracks statistically analyzed on 1 cm length at the middle of the gauge section with different crack depths for specimens after testing [16].

The early stage crack growth refers to the crack growth that occurs before measurable crack growth driven by the combined factor is detected at the depth tip. As introduced previously, crack growth in this stage primarily occurs at the surface tip by corrosion. The increase of crack length on pipe surface will increase the stress intensity factor at the depth tip even though crack growth at the depth tip is limited (Figure 2). Therefore, mechanisms that can lead to the extension of crack length, especially under the effect of pressure fluctuation, must be studied.

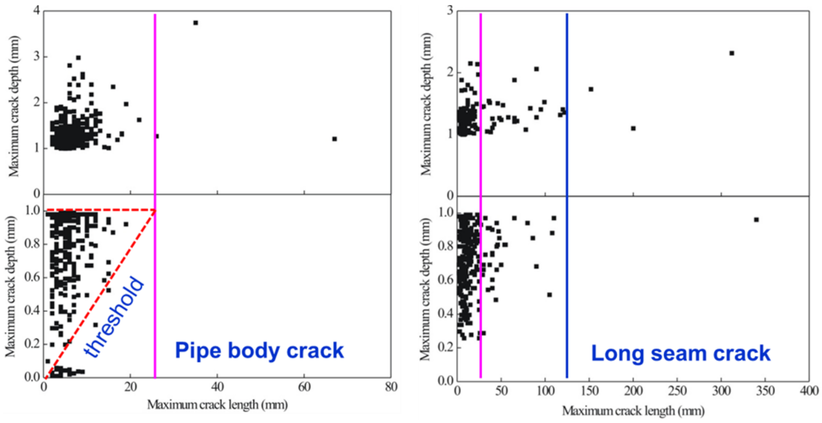


Figure 8 Individual field crack depth vs. crack length for a) cracks found on pipe body, b) cracks found along long seam weld [5].

It is interesting to see from Figure 8 that the crack length, either formed on the pipe body or along a long seam weld, varies little with crack depth when crack depth is greater than 0.5 mm except for a few cracks with much longer crack lengths. This confirms the suggestion that the so-called early-stage crack growth is overwhelmingly the growth of surface crack in its length direction, while the growth in Stage 2 is the growth of cracks in its depth direction.

There are a number ways length of surface cracks can be extended in early-stage crack growth as follows:

1) Determined by the geometry of the coating disbondment

As presented in Figure 8, very long cracks are often found along the long seam weld, which creates a unique tenting geometry of coating disbondment. Initiated cracks are highly populated along coating holidays tented along the seam weld. This promotes their interlinking in the pipe length direction. This type of early-stage crack growth is not affected by mechanical driving forces (the combined factor) and therefore not affected by pressure fluctuations.

2) Stochastic process of crack coalescence

The stochastic process of crack coalescence involves the interlinking of existing cracks being initiated at random positions. Therefore, the possibility of crack extension in crack length direction would be primarily dictated by the population of initiated cracks. As discussed in the previous section, the area density of initiated cracks is related to the number of flaws in the mill scale and the length of time the flawed mill scale can be preserved on the surface of the pipeline steels. Pit-formation and its transition to microcracks occur at the bottom of the flawed mill scale.

The density of flaws in mill scale and the length of time that mill scale can be retained on the surface of pipeline steels are affected by the history of applied pressure and/or mechanical damage applied to the surface of pipeline steel before the coating holiday occurs and the conditions of corrosion on the pipe surface are established. This has been already presented in Figures 6 and 7.

It should be noted that this stage of crack coalescence is different from crack coalescence in Stage 2. A stochastic process of crack coalescence in early stage of crack growth is critical to the onset of Stage 2 crack growth since it will increase the stress intensity factor at the depth tip. The faster the crack grows in the length direction, the earlier the onset of the Stage 2 crack growth. In contrast, interlinking of Stage 2 cracks causes little effect on the stress intensity factor at the depth tip and therefore the growth rate of depth tip is little affected, since the effect of length has already reached a plateau.

3) Existing cracks inducing further crack initiation and growth
When the population of microcracks being initiated is low, the extension of crack length can be self-induced. Examples of self-induced crack growth at the surface tip are evident in crack colonies from the field, as shown in Figure 9a).

The self-induced crack growth at the surface tip of an existing surface crack occurs through the following steps of sequence:

a) An existing surface crack can grow by dissolution and mechanical driving force, namely, the combined factor, however, is too small to produce meaningful or measurable growth.
b) However, high stress exists in the plastic zone ahead of the main crack tip where microcrack could be initiated.
c) The growth of microcracks in the plastic zone with high stresses leads to the interlinking to the tip of the main crack, producing surface crack extension in the length direction.
d) The above events repeat, especially during large pressure fluctuation.

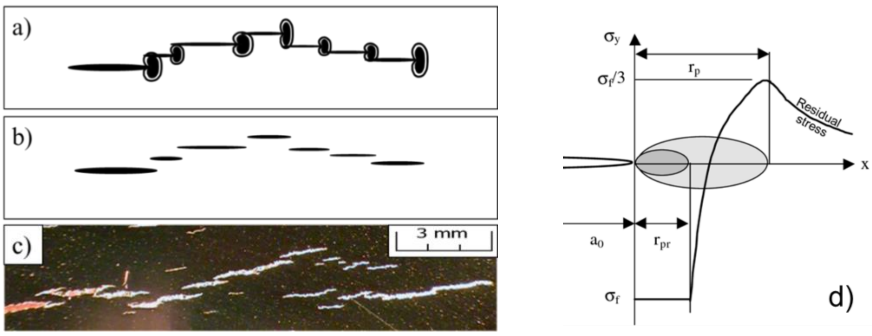


Fig. 9 Schematic illustration showing a)'daughter' crack initiation within the vicinity of an existing 'mother' crack, b) the resultant crack clusters in the pipe length direction, and c) an actual crack cluster from the field highlighted with magnetic particles. d) Schematic illustration showing the distribution of residual stresses in the plastic zone ahead of a crack tip [3, 18].

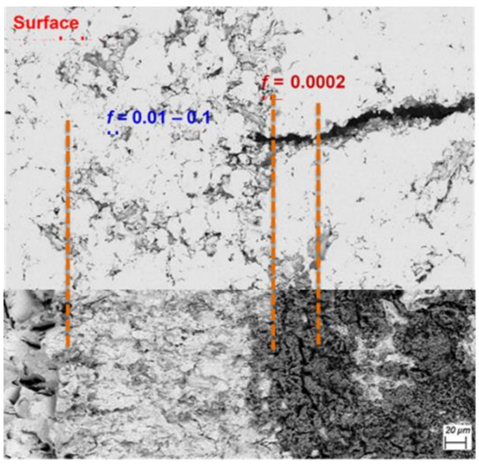


Figure 10 Microcracks developed in the plastic zone ahead of the main surface tip have interlinked to the main surface tip [3].

Experimental evidence of the above growth steps is shown in Figure 10 in which the growth of crack surface tip is not possible because of very low combined factor simulating mechanical driving forces at Stage 1b. Under the circumstances, the surface crack tip is blunt because of dissolution. However, the material in the plastic zone ahead of the surface tip is in contact with near-neutral pH solution and also under high stresses.

By fracturing the surface crack tip at liquid nitrogen temperatures, it is seen that the microcracks in the plastic ahead of the main blunt surface tip are substantial in length, over 100 µm, and have joined the main crack tip. This forms a mechanism of crack growth at the surface tip in low combined factor regime. More precisely, this is one of the major mechanisms of early-stage of crack growth before the onset of the Stage 2 crack growth. Such a mechanism occurs at the surface tip but is not possible at the depth tip because the plastic zone ahead of the depth tip is not exposed to the NNpH environments.

The overall mechanisms and processes of the growth under low combined factor are further discussed below:

1) Crack tip blunting by corrosion: Because of a reduced combined factor, the growth of the main crack tip become slower and more time for corrosion is also available to cause crack tip blunting. This would further reduce growth of the main surface tip.
2) Formation of microcracks in the plastic zone ahead of the crack tip: The steel in the plastic zone is under high stress and also exposed to NNpH solution. Initiation of microcracks in the plastic zone becomes probable. As microcracks grow, they will coalescence with the main crack tip and result in sharpening of the main crack tip.
3) Repetition of blunting and re-sharpening: Processes 1) and 2) repeat, leading to the growth of the surface crack tip.

The formation of microcracks in the plastic zone ahead of the surface tip should be primarily by corrosion at selected locations such as regions with high tensile residual stresses. Figure 9b) is an example of typical distribution of residual stresses in the plastic zone ahead of the crack tip. There are regions of compressive residual stresses and regions of tensile residual stresses. Crack initiation occurs in the region with tensile residual stresses and is enhanced because of stress cells. This is consistent with the fact that new cracks are initiated at sites surrounding the plastic zone where the residual stresses are in tensile. Therefore, any situations that can enlarge the size of plastic zone and enhance the magnitude of tensile residual stresses in the plastic zone would yield larger and quicker new crack initation in the plastic zone ahead of the surface tip of an existing crack.

3.2. Effect of pressure on Stage 2 crack growth

In near-neutral pH environments, crack growth is strongly dependent of loading frequency (Figure 3). There exists a critical loading frequency, above which crack growth rate increases with decreasing loading frequency but decreases with decreasing loading freque below the critical frequency. This critical frequency was found to be at around 10^{-3} Hz based on the results obtained from testing using compact tension specimens.

Typical regimes of loading frequency corresponding to pressure fluctuations during pipeline line operation have been extensively charactered and reported previously. Oil pipelines are operated with pressure fluctuation over a very wide range, typically from 10^{-1} to 10^{-6} Hz, while gas pipelines are in the range of from 10^{-5} to 10^{-6} Hz [10-11]. Therefore, different crack growth rate dependence of loading frequency can be expected between oil pipelines and gas pipelines.

When crack growth rate in near-neutral pH environments is studied using specimens with surface cracks, the critical loading frequency delineating different crack growth behavior is found to occur at around 10^{-2} Hz, as shown in Figure 11, respectively, for the growth at the surface tip and depth tip. This critical loading frequency is about one order of magnitude higher than the critical frequency found from testing using compact tension specimens (Figure 3) [9]. This discrepancy suggests that the critical loading frequency is not an intrinsic property of pipeline steels.

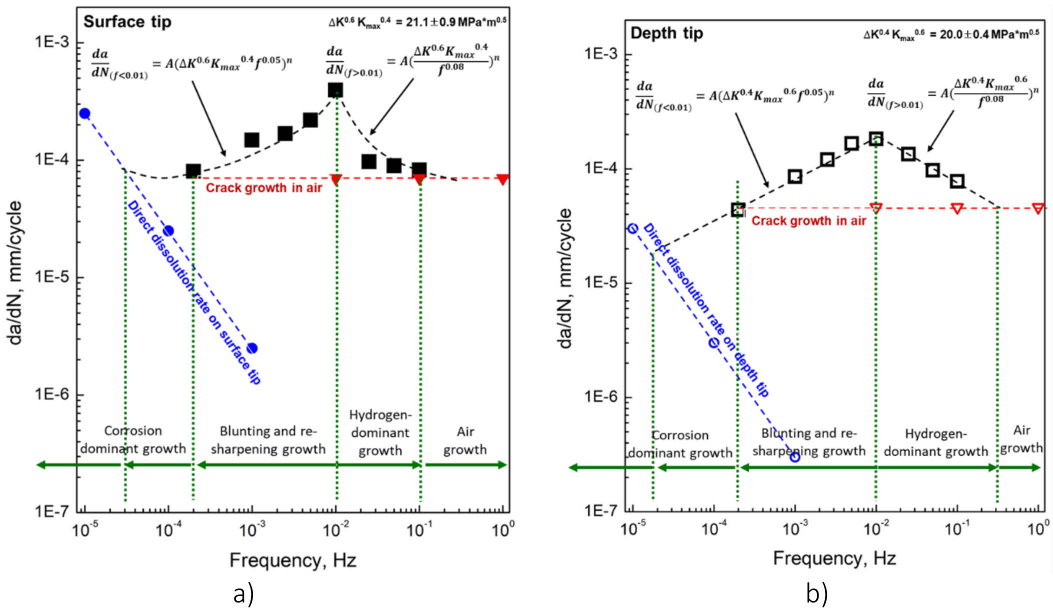


Figure 11 Analysis of critical frequency and different mechanism of crack growth on the surface tip (a) and depth tip (b) under frequency range 1 – 10^{-5} Hz [3].

The transition of crack growth behavior from the high-frequency regime to the low-frequency regime is believed to be related to the saturation of hydrogen segregation and a crack-tip blunting effect. The hydrogen facilitated crack growth is expected to be positively related to a decrease of frequency, but the lower frequency, on the other hand, is also positively related to the crack tip blunting effect, which is a retardation effect on crack growth rate. Thus, at frequencies below the critical frequency, the corrosion effect dominates the crack growth mechanism, meanwhile, at frequencies above the critical frequency, the hydrogen facilitated crack growth dominates the crack growth mechanism. From Figure 11, four different crack growth mechanisms can be identified in both the high-frequency regime and low-frequency regime as outlined below:

1) Air growth: It occurs when loading frequency is very high (>10^{-1} Hz), under which the time available for hydrogen diffusion to the crack tip and the effect of corrosion on crack tip blunting are all limited. Crack growth rate is insensitive to loading frequency as found in air.
2) Hydrogen dominant growth: In this regime of loading frequency, the crack growth rate is enhanced because of hydrogen-diffusion to the crack tip during the loading cycle of a pressure fluctuation cycle. Note that it is the stress (load) that causes the hydrogen diffusion to the crack tip and when stress is removed the hydrogen tends to diffuse away. At the same time, crack tip blunting caused by corrosion is still limited. As a result, crack growth is predominantly determined by the amount of hydrogen that can be segregated to the crack tip, which appears to be saturated when loading frequency is reduced to 10^{-2} Hz.
3) Blunting and re-sharpening growth: In this regime of loading frequency, crack tip has been saturated with diffusible hydrogen during loading cycle, however, crack tip blunting starts to play a role because of the increased time of corrosion at the crack tip that blunts the crack tip and

therefore reduces the mechanical driving forces for crack growth. Under these circumstances, the blunt crack tip could be re-sharpened by the microcracks formed in the plastic zone ahead of the blunt crack tip and their propagation to the blunt main crack tip. This blunting and re-sharpening repeats and drives crack to grow at a rate decreasing with decreasing loading frequency [1].

4) Corrosion dominant growth: When loading frequency is lower than 10^{-4} Hz, the growth rate is reduced to a value below 10^{-8} mm/s. A growth rate at an order of 10^{-9} mm/s matches the growth rate caused by direct dissolution of iron at the crack tip.

The critical loading frequency determined using specimens with surface cracks is an order of magnitude higher than for CT specimens. The occurrence of peak crack growth corresponding to the critical loading frequency was attributed to the time required for the plastic zone to be fully saturated with diffusible hydrogen and the time available for the occurrence of corrosion that leads to crack tip blunting. Since the rate of diffusion is governed by Fick's law, the critical loading frequency should be the same regardless of the type of cracks being evaluated as long as the test temperature is the same. With this argument, it is believed that the critical loading frequency is not a crack growth property solely governed by the Fick's law. It is believed that the rate of corrosion that can lead to crack tip blunting is different between the type of cracks (through-thickness crack of compact tension (CT) specimen vs. surface cracks). The thickness of CT specimen used in results shown in Figure 3 was about 9.0 mm, and the chemical path from specimen surface to the middle of specimen would be 4.5 mm, while it is about 2 mm to the depth tip of a surface crack. It is well established that the rate of corrosion in NNpH environment is dependent on CO_2 level, which reduces quickly with crack depth. As a result, the blunting of crack tip in the middle of CT-specimen is reduced and would require an increased time of exposure.

Crack growth behavior has also been found to be different at the surface tip and the depth tip. At the latter position, crack growth rate appears lower. This could result from a balance of the following factors: the level of hydrogen, the stress state at the crack tip, the contribution of corrosion to crack growth rate.

Pipelines are operated under variable pressure fluctuations as shown in Figure 4. Attention was paid to the crack growth behavior of the three-types of pressure fluctuations using specimens with surface cracks. Initial efforts were made to understand the role of minor fluctuations and hold time on crack propagation of pipeline steel. Table 2 lists the loading waveforms being used for loading. Loading waveforms with higher frequencies and shorter time for minor cycles are most representative of pressure schemes of oil pipelines, while those having lower frequencies and longer hold time for minor cycles are typical of gas pipelines.

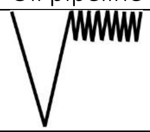
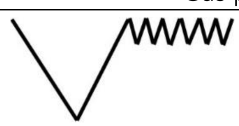
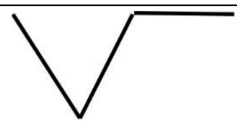
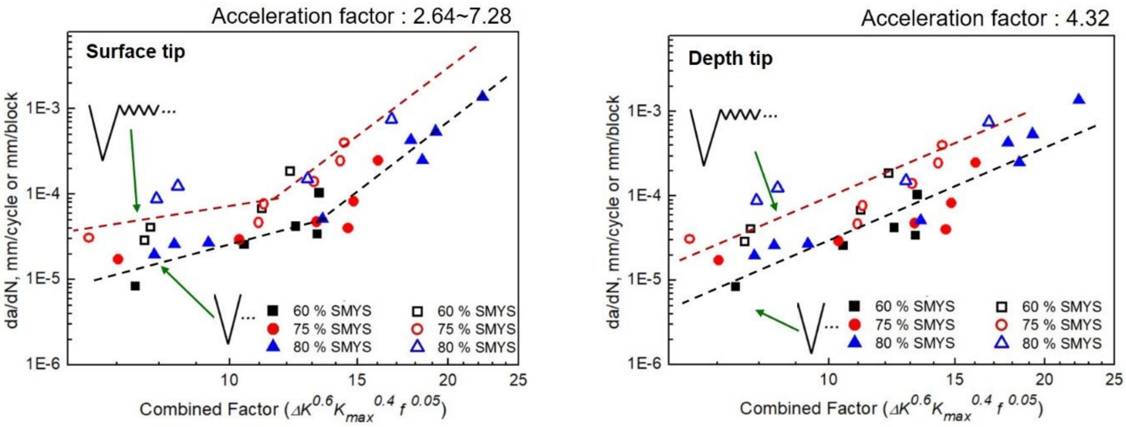
	Oil pipeline	Gas pipeline	
			
$f_{major\ cycle}$	1E-3 Hz	1E-4 Hz	1E-4 Hz
$f_{minor\ cycles}$	5E-2 Hz	5E-4 Hz	-
$R_{major\ cycle}$	0.6 – 0.1	0.5	0.5
$R_{minor\ cycles}$	0.95 – 0.7	0.9	-
Time for minor cycles	0.56 hour	2h, 8h, 24h, 52h	2h, 24h
Maximum stress	60%, 75%, 80% SMYS	80% SMYS	80% SMYS

Table 2 Experimental conditions of underload type variable amplitude loading tests [3]

A comparison of the crack growth rate (da/dN) under both constant amplitude and underload plus minor load cycles is shown in Figure 12. For crack growth at the surface tip, both loading scenarios show the same trend of dependence of the crack growth rate on the combined factor, except that a higher crack growth rate is found under underload plus minor load cycle loading. For the crack growth at the depth tip, the change of loading schemes has not altered the overall growth behavior, except for the higher growth rate of the underload + minor load cycles scheme, which is similar to the situation of the surface tip.



(a) Crack growth on the surface tip (b) Crack growth on the depth tip

Figure 12 Comparison of the crack growth rate of constant amplitude and underload with minor cycles in the fully exposed condition (da/dN) [3]

To understand special load interaction on crack growth rates during gas pipeline operation, crack growth simulations with lower frequencies of major cycles and minor cycles, longer time for minor cycles and hold time were performed. Details of the test conditions are listed in Table 2.

Figure 13 shows the effect of the length of time with minor cycles ranging from 2h to 52h on crack growth rate under various combined factors. There is an increase of crack growth rate with increasing time of minor cycles for a given block consisting of one underload cycle plus minor cycles. The crack growth rate measured under underload plus static hold is also shown in Figure 13. The increase of crack growth rate with increasing static hold time is low.

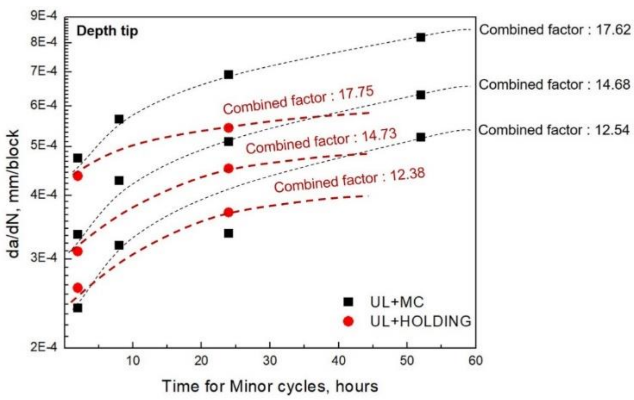


Figure 13 Effect of time duration of the minor cycles and static hold on crack growth rate under various combined factor on both underload plus minor cycles and underload plus static hold. [3]

The data shown in Figure 13 are composed of the following two components for the case of underload plus minor cycles loading:

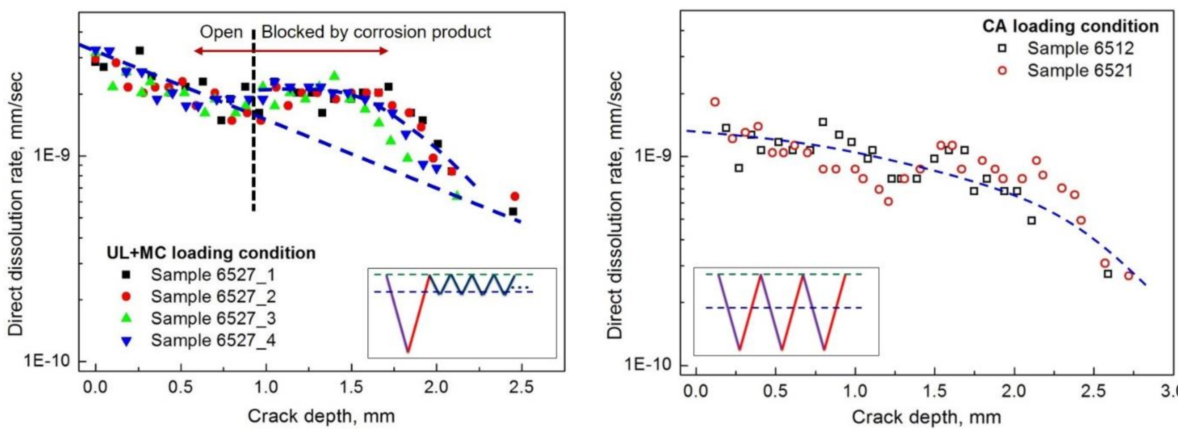
1) Crack growth caused by underload plus minor load cycle
2) Potential crack growth during extended length of time with minor cycle loading.

The purpose of examining crack growth rate under the underload plus minor cycles with extremely long period of minor cycle loading is to understand if additional crack growth will take place during the period of long minor cycle loading. Similarly, the crack growth rate under the underload plus static hold would also consist of two components: the crack growth caused by underload cycle and potential crack growth during a static hold.

4. CONTRIBUTION OF CRACK GROWTH BY CORROSION AFFECTED BY PRESSURE FLUCTUASTIONS

Initiation of NNpHSCC cracks and their growth during the first stage are believed to be caused by direct dissolution of the steel. The rate of corrosion is directly related to the partial pressure of CO_2 gas pressure in the aqueous solutions. It has been clearly shown that the rate of corrosion in the crack crevice decreases with increasing crack depth. This confirms that the growth of the crack depth tip is not caused primarily by the dissolution of crack tip material but by alternative mechanisms since the depth tip is growing faster.

To incorporate the contribution to crack growth by direct dissolution of the crack tip, the value of *h* in Equation 1 must be determined. Although the rate of direct dissolution is lower than the hydrogen facilitated mechanical force driven growth, in consideration of the long service period of the pipeline, this rate is a non-negligible component of the overall crack growth rate, especially during the early stage of crack growth where crack growth driven by the combined factor is relatively low.



(a) Variable loading conditions (b) Constant amplitude loading conditions

Figure 14 Direct dissolution rate under various combined factor: a) under variable loading conditions, b) under constant amplitude loading [3].

Figure 14 shows the change of direct dissolution rate in the depth direction. Figure 14a) was constructed using data from tests under the scheme of underload plus minor cycles, which simulates a pressure scenario encountered during operation of gas pipelines. Figure 14b) consists of data from testing under constant amplitude loading, a situation similar to pressure fluctuations during oil pipeline operation.

Under the underload plus minor cycles loading scheme, the corrosion rate decreases linearly with increasing crack depth up to 1 mm, beyond which a constant width of crack crevice/corrosion rate was measured. This constant width of crack crevice exists over a depth of about 0.5 mm and is followed by linear decrease in the width of crack crevice with increasing crack depth.

In contrast, a continuous decrease in the width of crack crevice was found when crack growth testing was under constant amplitude cyclic loading. The overall rate of corrosion in the case of constant amplitude loading is lower than that found under the underload plus minor cycle scheme.

The measured data of dissolution rates shown in Figure 14 can be expressed as a function of crack depth using polynomial regression. The resulting polynomial equations will be inserted into Equation 1) to determine the value of *h*. The superposition of the crack growth rate driven by the combined factor and that by direct dissolution at the crack tip further confirms the two different crack growth mechanisms illustrated in Figure 1:

1) When the crack is shallow in depth, for example, near and less than 1.0 mm, the contribution to crack growth rate by the combined factor would be very small. This initial crack growth by dissolution is critical to the occurrence of the latter stage of crack growth driven by the combined factor. Because of reduced dissolution rate, crack dormancy may occur at the depth tip when a depth of about 1.0 mm is reached, provided that the mechanical driving forces are still too benign to yield any meaningful crack growth.

2) When the crack growth rate driven by the combined factor become appreciable, the contribution to crack growth by direct dissolution becomes negligible.

3) The contribution to the crack growth rate caused by direct dissolution in gas pipelines is much more significant than that in oil pipelines. First of all, the rate of dissolution is higher, almost twice the rate of dissolution measured in oil pipelines; secondly, the depth with high rate of dissolution in gas pipelines is much longer. These differences are critical to the failure of gas pipelines as they are operated with much reduced pressure fluctuations, that is, much lower combined factor-driven crack growth at the same depth of crack.

The above observations and discussion clearly indicate that the dependence of crack growth rate caused by direct dissolution is also pressure-fluctuation-sensitive. The higher rate of dissolution in the early stage of crack growth found in gas pipelines could be related to the fact that the crack mouth is widely opened during operation, allowing stable mass transfer of corrosion species between the crack open month and the crack depth tip. In contrast, the constant opening and closing actions in liquids pipelines may have hindered mass transfer of corrosion species, leading to a reduced rate of dissolution.

5. PIPEONLINE SOFTWARE TO ASSESS THE EFFECT OF PRESSURE FLUCATIONS ON CRACK GROWTH

The effect of pressure flucutations on crack growth is very complex. A software (PipeOnline* trade mark pending) was developed to calculate the overall crack growth rate as affected by various factors including the effect of pressure flucutations, CO_2 level, materials properties, cathodic protentials, and type of pipeline operation (gas vs. Oil). The overall structure of the software is shown in Figure 15. The interface of the software is shown in Figure 16.

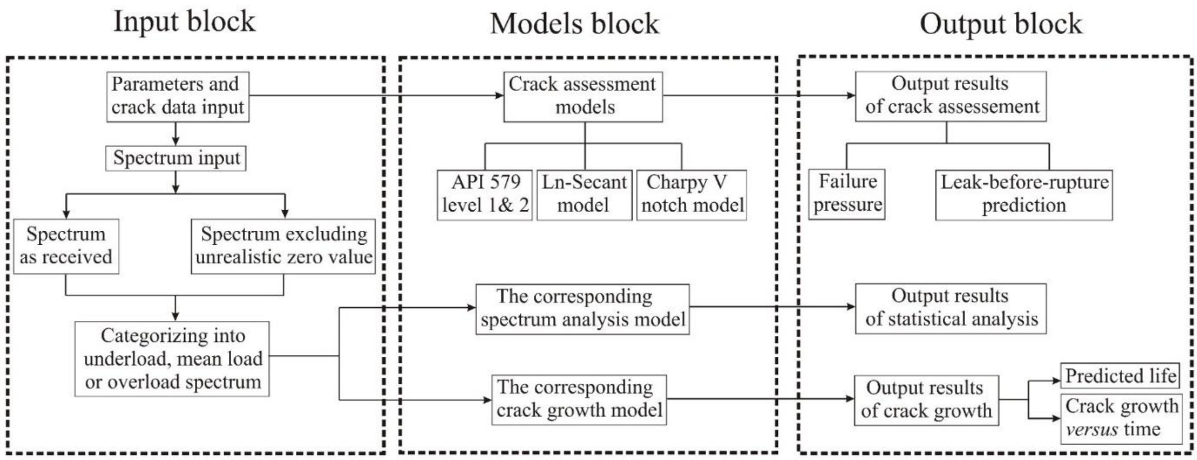


Figure 15 Structure of PipeOnline software.

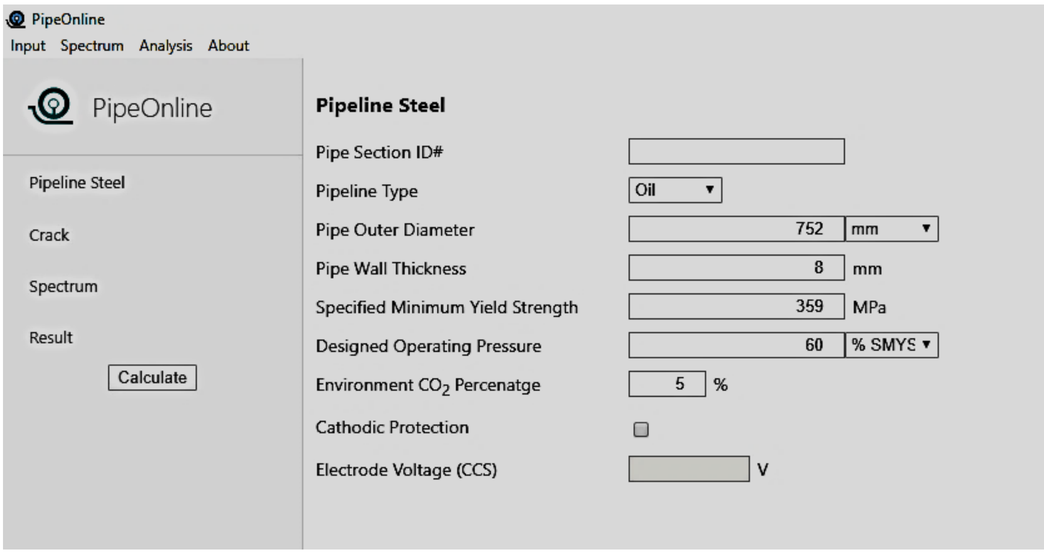


Figure 16 Image of PipeOnline software interface page.

6. REDUCING FAILURE THROUGH PRESSURE OPTIMIZATION

It is clear from the knowledge introduction in the previous section that the development of strategies and models of achieving crack dormancy and prevention of crack from growth must be cracking- stage sensitive. To better develop these strategies and models, the working principles on crack dormancy and crack growth control are elucidated in Table 3.

Category	Describtions
Common working principle	• By the concept of crack growth retardation effect or the so-called overloading effect, which is achieved by temporarily increasing the operation pressure higher than the maximum operating recorded over a period before the temporary increase of operation pressure. • Crack tip blunting induced by low temperature creep and plastic deformation • Crack tip blunting caused by excessive corrosion at the crack tip, especially when pipelines are not pressurized. • A combination of 1) to 3) achieved with minimum crack growth during the process overloading and with reduced crack growth after the process of overloading.
Working principle	• Blunting crack tip by corrosion prior to or after overloading. • A hydrotest or overloading scheme that could cause minimum H trapping during

specific of near-neutral pH solutions	pressurization and maximum H effusion during depressurization. • Perform hydrotest or overloading at higher temperatures, e.g., over 60°C, to minimize the effect of H-embrittlement.
Working principle specific of operating conditions	• Develop a cathodic potential strategy combined with seasonal ground water conditions and operation pressure to achieve crack tip blunting. • Develop pressure operating schemes that are specific to the pressure fluctuation-types, that is, underload, mean load or overload. • Develop an operating strategy for pipe sections with high operation pressure, and frequent and high amplitude underload cycles to prevent crack tip from re-sharpening.
Working principle specific of cracking stages	• For pipeline sections with crack dimensions in the stage of crack initiation and early-stage of growth (Stage 1), efforts should be made to achieve crack tip dormancy at the surface tip of a crack to prevent crack length extension. • For pipeline sections with crack dimensions that are subject to crack growth under mechanical driving forces higher than the threshold (Stage 2), attention should be focused on achieving crack tip dormancy/blunting at the depth tip of a crack. To achieve Stage 1 crack dormancy: • Cathodic protection should be sufficient to avoid the occurrence of corrosion on the surface of pipeline steel. • Pipeline operation should be performed to avoid the occurrence of underload cycles. To achieve Stage 2 crack dormancy: • Perform hydrostatic testing and or an overloading event with a stress higher than the upper point of yield. • A free corrosion condition is achieved to allow crack tip blunting by corrosion before, during and after hydrostatic testing or an event of overloading before resuming regular operation. • A seasonal condition that allows the increased corrosion at the crack tip, especially under zero pressure, for example, right before and/or after a hydrostatic testing for a controlled time before resuming regular operation.

Table 3 A summary of the working principles on crack dormancy and crack growth control

7. CONCLUSIONS

This PRCI project has provided the latest understanding of the stress cracking mechanisms of pipeline steels exposed to near neutral pH environments with a strong emphasis on how pressure fluctuations affect crack initiation and growth. In particular, the project has determined the kinds of pressure fluctuations that represent the greatest risk for increasing the potential for cracks to form and propagate, the different types of mechanisms that are operative in the NNpH environment, and the factors that control and determine the extent and degree to which the mechanisms will occur. Operation pressure magnitude and fluctuations affect near-neutral pH stress cracking differently depending upon three different identified stages of cracking. Progress made in the understanding and modelling pressure effects of each stage of near-neutral pH stress cracking is introduced. Other service conditions, such as cathodic protection, ground water chemistry, pipe surface conditions, coating practice, and steel metallurgy, all interact with pressure effects on near-neutral pH cracking. As a result of the research, a software tool was developed to determine which kinds of pressure fluctuations represent the greatest risk of increasing the potential for cracks to form and propagate.

1) Near neutral pH crack initiation is pressure fluctuation dependent. Severe pressure fluctuations accelerate the fracture and spallation of mill scale on the pipeline steel surfaces, making it harder to initiate SCC cracks from the bottom of pits that tend to develop at flawed mill scale sites. On the other, the presence of the primer layer before applying the protective coating preserves the mill scale on the pipe steel surface and promotes crack initiation.

2) The early-stage crack growth primarily occurs by crack length extension along the pipe surface but limited crack growth in the depth direction. Three different mechanisms of crack length extension have been identified, including determination by coating disbondment, stochastic process of crack coalescence, and crack initiation and growth induced by the existing cracks. The latter process is pressure fluctuation sensitive.

3) A complete set of equations governing crack growth in Stage 2 has been established using specimens with surface cracks under mechanical loading conditions that were similar to pressure fluctuations that had been measured during the operation of oil and gas pipelines.

4) The contribution to crack growth by direct dissolution of iron at the crack tip has been determined, which has been found to be crack depth-dependent and pressure fluctuation-sensitive. Gas pipelines operated under high mean pressures show higher rates of dissolution.

5) The severity of crack growth and the accuracy of the predictive model can be significantly affected by crack tip morphology, either sharp or blunt, and this would yield different threshold values for the onset of Stage 2 crack growth and therefore different estimates of remaining life.

6) The PipeOnline software has been revised to incorporate the new experimental results obtained from the current PRCI project. This PipeOnline software was previously developed from the two earlier phases of the PRCI project.

7) Based on the understanding of cracking mechanisms, strategies, and models of achieving crack dormancy and prevention of crack from growth have been proposed.

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