ADVANCES IN CRACK ASSESSMENT FOR PIPELINE INTEGRITY

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ABSTRACT

Recently, the Office of Pipeline Safety (OPS) of the United States of America issued an advisory notice to all US pipeline owners and operators to consider stress corrosion cracking (SCC) as a safety risk to their pipeline and to include SCC assessment and mitigative measures in their integrity management plans. If a pipeline is susceptible to SCC, an appropriate in-line inspection technology and a hydrostatic testing program are two main options to identify and expose SCC. Fracture mechanics (FM) assessments are then recommended to estimate where in the system an SCC immediate threat might occur and to quantify the life cycle of the pipeline. In this paper, the benefits and limitations of ILI inspection and hydrostatic testing are critically reviewed. Advances in fracture mechanics methodologies for SCC evaluation in pipelines are summarized and specific issues associated with application of FM to pipelines are also discussed.

1 INTRODUCTION

There is an increasing concern of SCC in the United States of America due to recent failures, not only in natural gas pipelines but also in hazardous liquid transporting pipelines. Because of the concern, the Office of Pipeline Safety (OPS, [1]) issued an advisory notice in October 2003 to all US owners and operators to evaluate their systems for the presence of risk factors associated with high-pH (9-11) or near-neutral pH (6-8) SCC. In accordance with ASME B31.8S (ASME [2]), a pipeline segment should be considered susceptible to high-pH SCC if it is (1) operated at a pressure above 60% SMYS, (2) located <10 miles down stream from pump or compressor station, (3) operated at a temperature exceeding 38°C (100ºF) and (4) is more than 10 years old and protected with a coating other than fusion epoxy bonded. For near-neutral pH SCC, the same criteria can be applied with the exclusion of the temperature criterion (NACE SCCDA [3]). If conditions for SCC are present based on the evaluation, an operator should prioritize the application of in-line inspection, hydrostatic testing and other forms of integrity verification (OPS [1]). This should be followed by a fracture mechanics assessment to quantify the life cycle of the pipeline and to take appropriate actions to mitigate areas of concern.

As one of the actions responding to OPS' notice, a critical review of the benefits and limitations of the in-line ultrasonic crack detection (USCD) tool as compared with the hydrostatic testing is given. Advances in fracture mechanics assessment methodologies, particularly, the elastic-plastic fracture mechanics based two-criteria failure assessment diagram approach and applications to pipeline SCC evaluation are reviewed.

2 CRITICAL REVIEW–IN LINE INSPECTION vs HYDROSTATIC TESTING

Hydrostatic testing of existing pipelines has been widely used to demonstrate or revalidate the pipeline integrity and serviceability (Keifner, [4]). Both field experience and full-scale laboratory tests have revealed the benefits and limitations of hydrotesting. On the other hand, numerous in-line inspection (ILI) practices showed that the appropriate ILI technologies are often superior alternatives, for example, the magnetic flux leakage (MFL) tool for the detection of metal loss caused by corrosion. Recent evolution of in-line inspection technologies has provided new tools for detecting much smaller seam weld anomalies than those found by hydrostatic testing of up to 110% SMYS (Grimes [5]).

For SCC detection, the shear wave ultrasonics employed by the USCD tool have successfully been used since its introduction in 1994 for more than 7000km of crack inspection (Marreck [6], Wolf [7,9], Uzelac [8]). It is a proven technology capable of reliably detecting and sizing crack-like features larger than 30mm (1.2 inch) in length and 1mm (0.04 inch) in depth, including incipient of SCC which is significantly better than hydrotesting for crack detection in the critical regime of SCC, Figure 1.

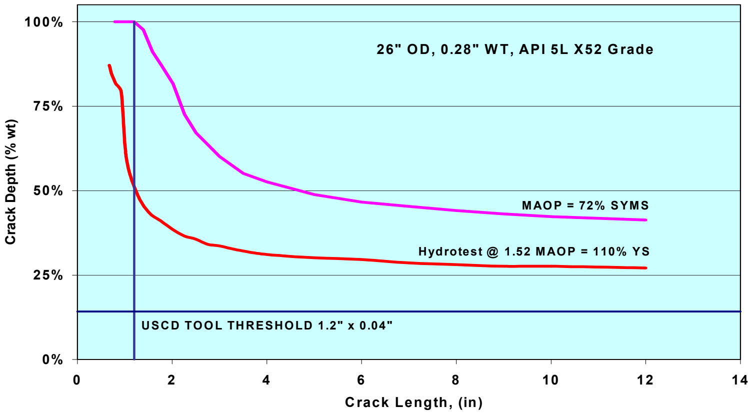

Figure 1: ILI and hydrostatic testing comparison, 26” OD, 0.281” wt, API 5L X52 grade steel.

Another fundamental difference in crack detection and assessment between these two technologies is that the ILI provides detailed information on crack location, size and distribution along the pipeline which can be used for the development of a comprehensive integrity management plan (Marreck [6]), whereas hydrostatic testing is a type of snapshot testing that removes all cracks greater than critical size at the test pressure but provides no information on the remaining sub-critical cracks. Figure 2 illustrates how the cracks were assessed using API 579-2000 Level-III (i.e., material specific) FAD for Williams’ 16-inch natural gas transporting pipeline (Katz [10, 11]). An excavation, monitoring plan and re-inspection interval were developed based on an assumed but commonly used crack growth rate to manage the integrity of the pipeline. No comparable integrity plan could be developed for this line after subjecting to hydrostatic testing in 1993 (Katz [10]).

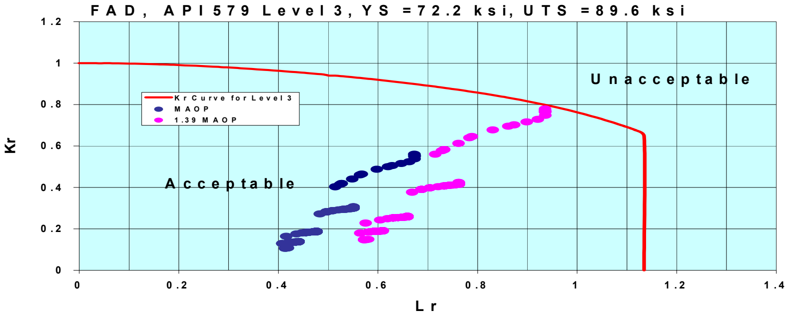

Figure 2: API 579 Level-III FAD showing that all anomalies are acceptable

There are concerns about cracks possibly not being detected by the in-line inspection tools. Field experience has shown that the probability of non-detection is very low. The risk of non-detection is minimized with an appropriate validation excavation program and FM based integrity plan. In the same context, one must also recognized that hydrostatic testing is not foolproof either. Because hydrotesting can leave behind cracks that could be detected by in-line inspection, the use of hydrotest often demonstrates serviceability for only a short period of time if a crack-growth mechanism exists (Kiefner [4]).

3 ADVANCES IN FRACTURE MECHANICS METHOD FOR PIPELINE CRACK ASSESSMENT

Oil and gas transmission pipelines have a good safety records even though SCC is now becoming an increasing concern. This is because the nature and behavior of various defects in pipelines have been the subject of considerable study over the past 40 years. Particularly, for crack or crack like defect assessments, a two-parameter fracture mechanics based approach, known as NG-18 equations (eqs. 1-4), was introduced in late 60s (Hahn [12]) and early 70s (Maxey [13] and Kiefner [14]) using the strip yield model (Dugdale [15]).

$$K_c^2 = (8c(\sigma_{fs})^2/\pi)\ \mathrm{LnSec}\ [\pi M_p \sigma_H/(2\sigma_{fs})] \qquad (1)$$

$$K_c^2 = 12C_v E/A_c \qquad (2)$$

$$12C_v \pi E/[8A_c c(\sigma_{fs})^2] = \mathrm{LnSec}\ [\pi M_p \sigma_H/(2\sigma_{fs})] \qquad (3)$$

$$M_p = [(1-d/t)(M_T)^{-1}]/(1-d/t) \qquad (4)$$

Where K_c = fracture toughness, C_v = upper shelf Charpy impact energy, C = half effective flaw length, E = elastic modulus, σ_H = nominal hoop stress due to internal pressure, σ_{fs} = flow stress, Ac = the cross-sectional area of the Charpy impact specimen, M_p = stress magnification factor, d = flaw depth, t = wall thickness and M_T = Folias bulging factor.

The NG-18 LnSecant method has been widely used for ERW seam weld defects, railroad fatigue crack assessment, and has recently been recommended for material toughness evaluation for low frequency ERW and LAP welded longitudinal seam evaluation (Baker [16]). Generally, the NG-18 LnSecant methods are considered to be very conservative, particularly, for fatigue life predictions. However recent experience in application of this method to SCC found that predictions of failure pressure and critical size could be non-conservative due to the use of overly estimated fracture toughness values for the assessment.

The fracture toughness K_c in the NG-18 equations is calculated from an upper-shelf Charpy impact energy value using an empirical relation (eq. 2) developed from full-scale burst tests of line pipes that contained mechanically machined flaws. Using this empirical relation, the calculated K_c value is found to be two or three times higher than the actual measured value from pre-cracked specimen of the same material. As shown in Figure 3, a significant difference is observed between the calculated K_c values from eq. 2 and the actual measured K_{JMAT} (Anderson [17], Jaske [18]) and those estimated from other empirical relations (Thorby [19], Wilkowski [20], Leis [21]). Consequence, the predicted failure pressure and crack size would be significantly higher and larger, as compared to the respective values if the actual measured K_{JMAT} is used. This influence is shown in Figure 4.

Another drawback of the NG-18 equations is that the stress magnification factor, M_p, (eq. 4) exhibits a singularity at the point of d = t. This provides inconsistent results when the crack approaches a through-wall crack configuration. This inconsistency will result in conservatism in the computation of the failure pressure when $d/t > 0.5$. The singularity nature of eq. 4 combined with the overly estimating fracture toughness for cracked structures, results in a large uncertainty in predicting critical crack sizes and failure pressures.

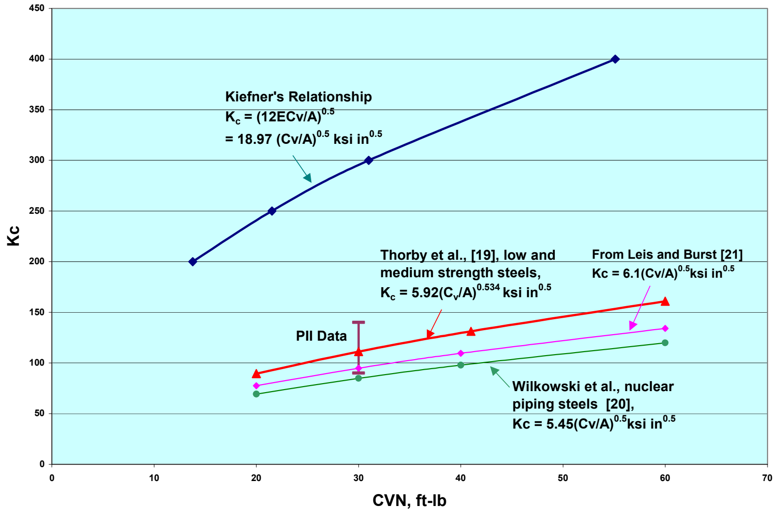

Figure 3: A comparison of K_c between NG-18 method, actually measured and other reported values

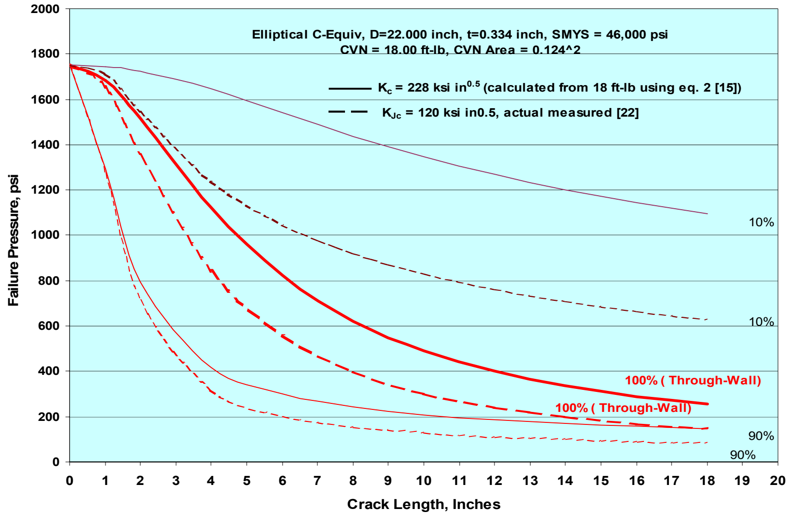

Figure 4: The influence of K_c on the predicted failure pressure and crack size

It is noted that several years after NG-18 methods were introduced, the two-criteria failure assessment diagram concept was further developed by Dowgling et al [22] and Harrison et al [23], which describes the interaction between fracture and plastic collapse. This FAD approach forms a basis for industry practice documents (PD 6493) and standards (BS7910:1999 [24], API 579-2000 [25]) that can be applied to assessment of cracks or crack-like flaws in pipelines. In addition to the Rainbow Pipeline system (Krishnamurthy [26]), limited experience gained from the Williams pipelines has shown that the FAD method provides conservative but consistent predictions for fitness-for-purpose (FFP) evaluation and more accurate results for failure analysis if a material specific FAD is utilized. For example, a rupture failure mode is predicted when the defect size is about 6.4-inch long and 71% deep in a 26-inch OD API 5L X52 pipe based on the tearing instability analysis, Figure 5. This prediction is consistent with the field observations. However, for the same operating and pipe conditions, a leak failure mode would have been predicted by NG-18 equations. Moreover, API 579 provides reliable results for surface defects d/t > 0.5.

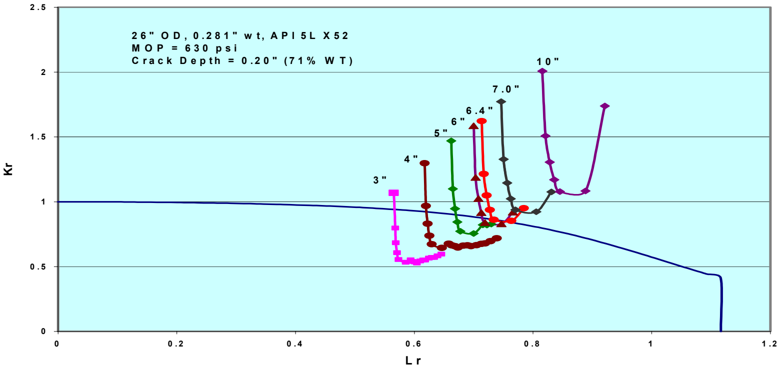

Figure 5: Ductile tearing analysis predicts a rupture mode for cracks longer than 5 inches

Finally, the predicted critical crack size between API 579 FAD approach and NG-18 method at two pressures (i.e., 0.72% and 110% SMYS) is compared and shown in Figure 6. It is seen that the difference in predictions is significant. The NG-18 method provides more conservative results for longer cracks but the opposite for shorter cracks. This could be attributed to the NG-18 equations' combined effect of overly estimated fracture toughness and the singularity of M_p. Another difference between these two methods is that API 579 predicts critical depth relatively insensitive to crack length when it gets longer than 6-inches while NG-18 does not, Fig. 6. This difference appears to result from the fact that the NG-18 equations were originally derived from a through-wall crack configuration based on the Dugdale strip yield model. The modification of the NG-18 equations for surface cracks was made by introducing a stress magnification factor M_p for stress calculation without considering the change in stress intensity field at the crack tip (Kiefner [14]). On the contrary, the API 579 FAD method includes both [25].

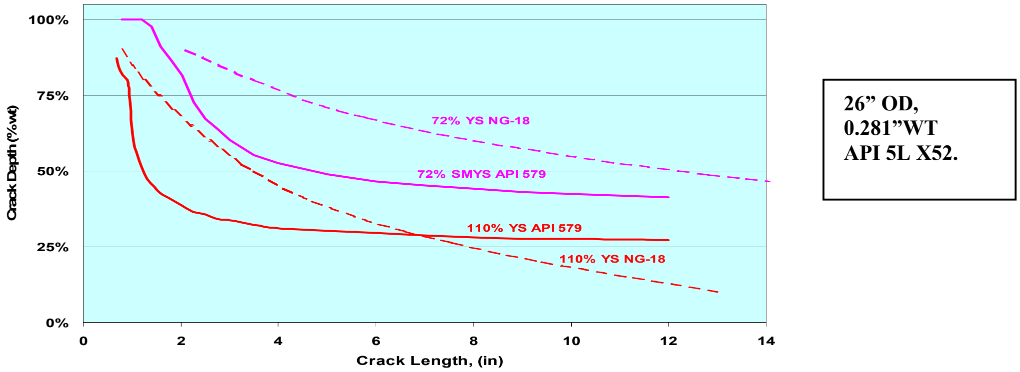

Figure 6: A Comparison of critical crack size prediction between API 579 FAD and NG-18 methods,

4 SUMMARY

A critical review of the benefits and limitations of crack detection tools (USCD) and hydrostatic testing for SCC evaluation suggests that ILI inspection is the more appropriate integrity management methodology for piggable pipelines. ILI inspection with a good probability of detection basis, followed by an appropriate fracture mechanics analysis could result in a comprehensive pipeline management plans. Limited experience in crack assessments using elastic-plastic fracture mechanics methods suggests that the two-criteria FAD approach is more appropriate than NG-18 method. Industry standards API 579 and BS 7910 approach provides conservative but consistent results for FFP. This approach also provides opportunities for more accurate high level FAD assessment using material specific and finite element analysis (FEA) input data to meet various engineering purposes.

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