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RISK MANAGEMENT OF STRESS CORROSION CRACKING OF BURIED PIPELINES

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Abstract

In this work a framework for risk management of stress corrosion cracking of buried pipelines is presented. It is demonstrated that for a robust risk based management plan a collaborative approach is required that formally incorporates consideration of susceptibility to cracking, critical defect dimensions, a thorough understanding of the cause of the failure, appropriate inspection technology, rehabilitation actions and risk assessment. We visualize this as a framework of interconnected elements, and use parametric susceptibility analyses to aid inspection data evaluations, focusing on those locations of highest susceptibility and overall risk, which then evolve into risk analyses used to select appropriate rehabilitative, preventative and mitigation measures. The paper will explore in detail how influential parameters are used as diagnostic assumptions and subsequently tested and refined iteratively through in-line and subsequent infield inspections.

1. Introduction

For many pipeline operators, their first significant experience of Stress Corrosion Cracking (SCC) is dealing with the aftermath of an unexpected failure. At this point the priority of the operator is to repair or replace the affected section and return the pipeline to full service. However, experience shows that SCC rarely occurs in isolation, which places substantial uncertainty upon the feasibility of continued safe and economic operation. In some cases, this uncertainty has resulted in operators having to accept significant reductions in operating pressure for extended periods and even permanently. Hence, a return to full service is contingent upon the operator being able to demonstrate that the pipeline is fit for service and any residual risk is within tolerable limits.

1.1. Stress Corrosion Cracking of Line Pipes

In general, it is now well established that SCC is an environmentally assisted cracking mechanism caused by the combined action of stress (tensile) and a corrosive environment. Over the last few decades, SCC on the soil side of high pressure transmission pipelines has occurred in several countries. The first documented occurrence (FPC, 1965) and majority of reported incidents involved intergranular cracking mechanism (also refered to as high pH SCC), whilst cases of trans-granular cracking (now recognized as low or near-neutral pH SCC) have been reported more recently. In 2002 the European Gas Incident data Group (EGIG) reported that failures from SCC constituted 1% of failures related to external corrosion (EGIG, 2002); by 2015, that proportion had increased (EGIG, 2015) to 8%, indicating the increasing prevalence of this threat. Reflecting on a number of reviews (PARKINS, 1996; YUNOVICH et al, 1998; XIE et al, 2010; SONG, 2009) and guiding documents(NACE, 2015; CEPA, 2007; UKOPA 2015) it is apparent that apart from cracking morphology, there are a number of differences which differentiate these two mechanisms. In the case of high pH SCC, high risk areas are associated with pipeline sections within 20 km downstream from a compressor stations, mainly as a consequence of higher stresses and temperature that accelerates coating degradation; interestingly, no temperature dependence has been observed for the near neutral pH SCC. Whilst there is enough evidence to suggest that both types of cracking are more likely to occur in poorly drained soils, e.g. clays and silts, it is also argued that concentration of CO_2 in the soil environment may be of importance for both mechanisms. Other contributing factors include pipelines' age; coating type, e.g. asphalt and polyethylene tape; additional stresses; cathodic protection (CP), i.e.

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CP shielding; topography etc. For most cases of SCC the corrosive environment is a result of coating disbondment, and ineffective, or shielded cathodic protection.

High pH SCC is now relatively well understood (PARKINS, 2000), with a repetitive (periodic) process of film rupture and slip dissolution generally accepted as the cracking mechanism; here the crack walls are passive, whilst the crack tip is subject to film rupture and subsequent dissolution. By contrast, the situation for near-neutral pH SCC is more complicated[Error! Reference source not found.]. In general, it may be argued that whilst cracks may appear dormant (shallow, blunt and containing corrosion products), it is the extent of anodic activity and absorption of atomic hydrogen into to the metal ahead of crack tip (hydrogen embrittlement) which control crack propagation; at present, the mechanism of hydrogen embrittlement is not fully understood. There is a growing body of evidence(PARKINS, 1996; PARKINS 2000, SMITH et al, 2016, Liu et al, 2008) suggesting that transgranular SCC indeed involves anodic dissolution and hydrogen entry to the steel, with the sufficient hydrogen concentration being critical (XIE et al, 2010) for the susceptibility of pipeline steel to this form of SCC. However, transgranular cracks can also be induced in pipeline steel at different pH values (6-8) and more importantly, transgranular cracking was observed under cathodic conditions (potentials) where anodic dissolution can be considered negligible (BUENO et al 2009; GABETA et al, 2001). Hence, the process can be controlled by (i) anodic dissolution and hydrogen embrittlement at potentials close to free corrosion conditions, but (ii) at cathodic potentials (e.g. cathodic overprotection) hydrogen embrittlement would dominate the mechanisms. Hence, the name near-neutral (low) pH SCC, normally used for transgranular external cracking of buried pipelines may be inappropriate, as it may lead to misunderstandings(GABETA et al, 2001).

This basic, but important, information can provide an indication of susceptibility; however, experience has shown that deviations from these basic conditions often occur, i.e. cracks are found in sections that would not automatically be considered as susceptible according to common parameters. To improve the adjudication on susceptibility, a robust and iterative process of data gathering and analysis is required that identifies locally influential parameters.

2. Stress Corrosion Cracking Management Framework

Once SCC is discovered in a pipeline system, industry based practice (ASME, 2016) requires scheduling of either: (i) hydrostatic testing, (ii) inline inspection, or (iii) direct assessment. Hydrostatic testing becomes a mandatory requirement following failure of the pipeline and is often regarded as the safest method, the rationale being that any cracks close to failure will do so under test conditions (UKOPA, 2016). Whilst this rationale may hold true, hydrostatic testing often requires significant downtime which is impractical for many operators and naturally raises the question of reasonable practicality[1]. Since hydrostatic testing has become the received wisdom, to supplant this routine requires something equally as effective, or more reasonably practicable. A framework containing a range of multi-disciplinary elements was developed to effectively manage SCC and other cracking mechanisms. A flowchart for the developed SCC framework is presented in

Figure 1, with the risk based elements highlighted in red boxes and subject of our attention in the current work.

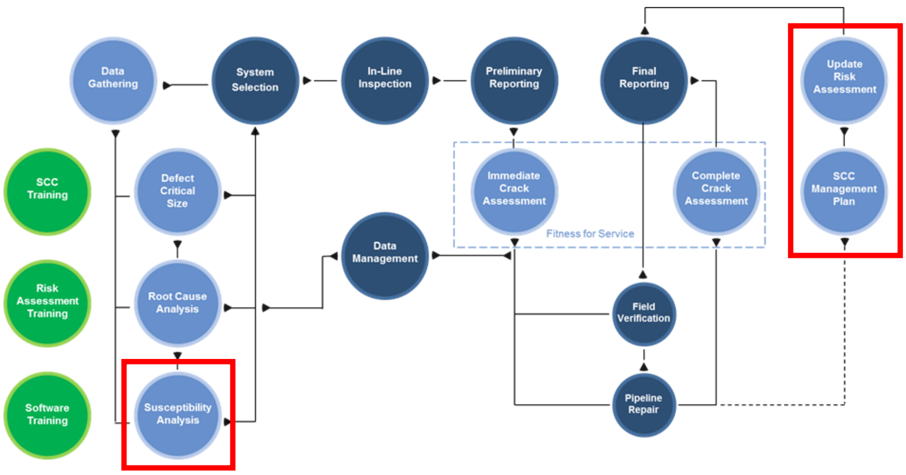

Figure 1: Stress corrosion cracking management framework.

[1] The test of ‘reasonably practicable’ involves weighing a risk against the trouble, time and money needed to control it

2.1. Stress Corrosion Cracking Susceptibility Analysis

In general, SCC represents a complex corrosion phenomena and as already indicated there are often unique characteristics or scenarios which may exist for different systems. The parametric analysis uses the following base algorithm to organize data and estimate susceptibility (WRIGHT et al, 2015). The algorithm allows parameters to remain independent variables that increase or decrease the likelihood of failure (Eq. 1):

$$FF = FF_H \prod \frac{S_n}{1-(1-M_1I_1)\dots(M_nI_n)} \quad (1)$$

Where: FF is the calculated failure frequency, FF_H is the historic failure frequency of the system, S is the threat severity based on a range of mechanistic and operational conditions, M is the quality of mitigation measures and I is the effect of mitigation measures.

Conceptually, the model assesses the severity of a threat by identifying and segmenting the influential mechanistic, environmental and operational conditions along the length of the line and comparing them against the active and passive mitigations. The result is a highly detailed profile of FF values distributed around the historic rate (i.e. identifying which sections of the pipeline are more or less likely to fail than average and the estimated magnitude). An example output is displayed in Figure 2.

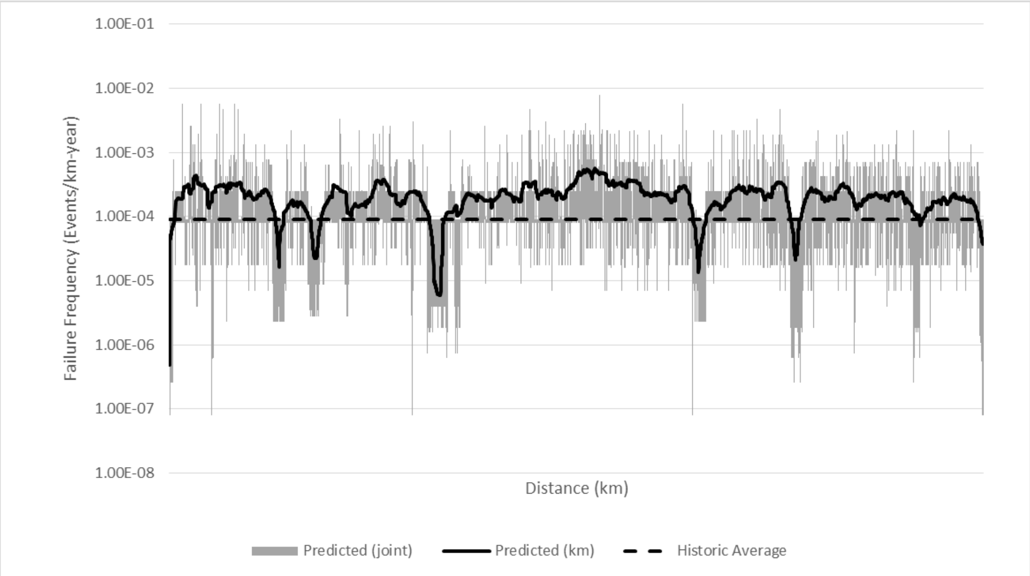

Figure 2: An example for susceptibility analysis.

At this stage the susceptibility analysis is a prediction, based upon the parametric analysis, of the sections more or less likely to fail than the historic average. Whilst the units used are a mathematical frequency, the frequency nor the probability of failure cannot be known with a quantifiable degree of certainty. Nonetheless, it is still anchored in a semblance of current reality by the historic rate. The key outcome at this stage is a ranking of the system in terms of the identified (known) parameters. The produced results have duel usage: (i) they act as a prioritization for inline inspection data analysts and allow site selection for detailed review; and (ii) as a prioritization for identifying sites for infield investigations. High quality inspection, analysis and infield verification hold the key to authenticating the assumptions about influential parameters; both the factual and counterfactual results need to be considered before confidence can be gained that the key aspects have been encapsulated i.e. evidence of cracking discovered as predicted and absence of cracking confirmed where not predicted.

In practice, it is not common to find an operator with a full set of detailed and relevant information. The algorithm and process was designed so that inputs remain as independent variables, i.e. data sets may be added, removed or interchanged at will without affecting incumbent parameters. Working assumptions or surrogate data sets can be incorporated on a temporary basis alongside what-if analyses to prioritize (and maximize) the potential value of further data collection and integration.

2.2. Risk Based Assessments

The role of risk assessment is to identify areas at high risk and by analyzing results, formulate targeted strategies to reduce it. Risk is always the product of likelihood and consequence and whilst there are multiple methodologies available for both, the rule of thumb is that the complexity or accuracy of the methodology should be commensurate with the anticipated risk. Risk based methods can provide a more refined prioritization of repairs as opposed to deterministic assessments as they contain additional consequence parameters which carry equal weight. However, there needs to be acceptance that a risk based method may prioritise a defect with low probability of failure in a high consequence area over a more significant defect in a low consequence area. This type of analysis can prove invaluable when deterministic assessments result in the requirement for multiple investigations and repairs, and operators are without unlimited resources.

2.3. Likelihood of Failure

The output of the susceptibility analysis is a profile of failure frequency, based upon a parametric analysis, which may be a direct feed into risk assessment as the likelihood of failure. However, at the parametric analysis stage, the results may be considered accurate on a relative basis only. By combining this output with the results of high quality in-line inspection (ILI) and infield investigations, the parametric results may be benchmarked and validated. For this to occur the findings of the ILI and infield investigations (reported anomalies and defects) need to be converted to a comparable metric – probability.

For each reported anomaly or defect, the Probability of Exceedance (PoE) can be calculated; this represents the likelihood of each flaw exceeding its critical dimensions; for an example refer to

Figure 3. PoE is calculated by considering some of the assessment inputs as random variables with a statistical distribution. For example, the reported length and depth may be treated as random variables, with distributions defined by the measurement uncertainty (tolerance) of the measurement tool e.g. ILI.

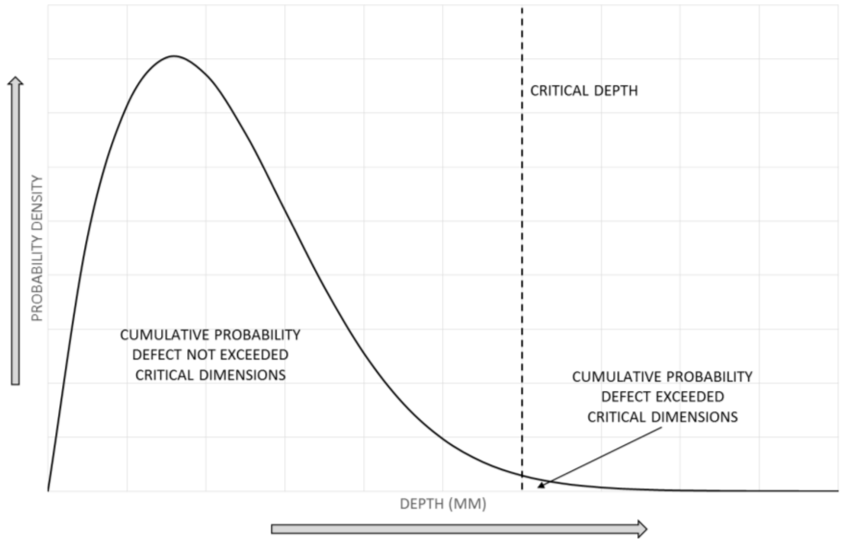

Figure 3: Probability of exceedance for defects (cracks) depth

For each section of the pipeline, the combined PoE is calculated based on all flaws therein. This results in a PoE profile along the pipeline which quantifies the likelihood of failure (failure and exceedance are assumed to be interchangeable). Comparison to the results of the susceptibility analysis is the feedback loop to assess the accuracy of results and should be closely correlated. Thereafter the methodology may be used to assess other pipelines in the system, in particular those without ILI. Furthermore, based on estimates of crack growth rates (and associated uncertainty), the anticipated future likelihood of failure can be projected into the future. The dates when the PoE (and any subsequent categorization) reaches an intolerable level can be identified.

2.4. Consequence of Failure

Geographic Information Systems (GIS) have been around in commercial form since the early 1980's, but recent advances have increased the ability to integrate various kinds of data using an explicit spatial location. The GIS environment provides the ideal platform to perform high resolution and detailed consequence analyses by allowing combinations of geographic and demographic data with established analytical techniques, such as fire models. An example for such a system (ROAIMS) developed at ROSEN is presented in Figure 4.

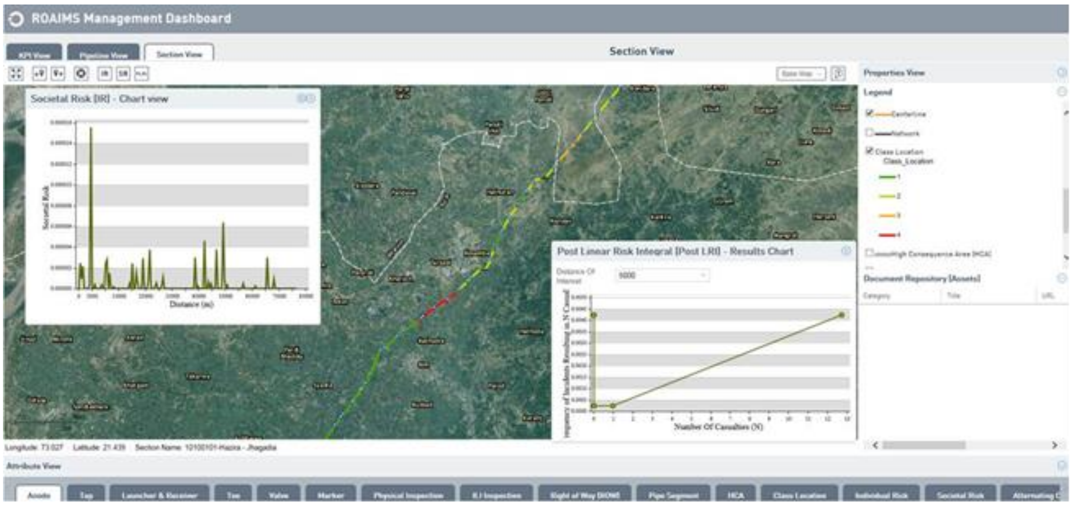

Figure 4: Geographic Information System environment and analytics

By constructing the pipeline in the digital environment and aligning with existing population and infrastructure data, a detailed picture of the pipeline can be built and analyzed to provide precise consequence scenarios. These routines mean operators can now align individual defects with the surrounding environment and create and visualize a true picture of the subsequent risk.

3. Risk Assessment and Development of Stress Corrosion Cracking Management Plan

Corporate or Enterprise risk management frameworks provide detailed acceptability criteria and clear guidance for appropriate action levels. The above assessments provide a range of flexible analytics which map to these frameworks, making selection of preventative and mitigation activities a robust and auditable trail.

The activities described thus far set a baseline only, as a time dependent threat, the key consideration is to use the information and assessments to set a robust management plan for future operation and maintenance of affected pipelines. The precise elements and details of the plan will differ on a case by case basis and there will undoubtedly be an evolution in understanding, available technology and methodologies across the elements. Whilst the importance of the technical elements of the plan cannot be understated, there should also be a large emphasis upon how the plan promotes this continuous learning and improvement. The technical elements of the plan should consider:

- Data management and control
- Susceptibility and risk methodologies
- Inspection technology and capability
- Infield investigation
- Defect assessment methods

- Repair methods
- Pipeline safe operating pressure
- Selection of preventative and mitigation activities
- Emergency response

All of the above are common elements in the majority of integrity management plans, albeit specialist components that focus on SCC are required. The effectiveness of the technical elements is critically dependent upon application and the ability of the system to deal with feedback and respond. This requires formal routines and protocols that actively promote and encourage behaviors.

- Performance management (key performance indicators)
- Intermediate and periodic reviews
- Management of change and well-defined triggers to re-evaluate
- Roles and responsibilities
- Training and knowledge sharing
- Communication and staff engagement

Creating this framework at the outset and setting the expectations will not only provide the best chance of managing SCC, but should also carry over into the best practice in the wider integrity management context.

4. Concluding Remarks

Experience has shown that pipelines affected by SCC cause a high level of uncertainty and unease for their operators. This can lead to acceptance of overly onerous mitigation actions to ensure that no failures due to SCC will occur. Whilst this strategy may be prudent in the immediate aftermath of a failure, a long term strategy should be focused on implementation and optimization of actions and necessary resources.

Condition and operation of pipelines affected by SCC can be successfully managed through a robust risk assessment and SCC management plan that identifies the necessary mitigation actions to ensure the risk of SCC remains low. A targeted approach to data gathering and an iterative refinement of the risk analysis ensures continued confidence in the long term integrity of such pipeline systems.

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