High-pH and near-neutral pH SCC of pipelines: challenges in susceptibility modelling

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External SCC is a challenge facing the industry on a global scale, particularly as pipeline infrastructure ages and becomes more vulnerable to failure. SCC and integrity management are essential to finding a solution, with both relying on the use of modelling.

Since the first reports of external stress corrosion cracking (SCC) in the US in the 1960s, the problem has turned into a global industry challenge with cases of SCC in Australasia, the Middle East, Europe and South America. As SCC is a time-dependent process, original construction practices and ageing pipelines would suggest that the industry could see increasing numbers of pipeline failures due to SCC, unless effective integrity management strategies are implemented.

Such strategies rely to varying degrees on the use of SCC susceptibility models. However, despite the establishment of a comprehensive knowledge base of external SCC mechanisms, there remains an inherent uncertainty in susceptibility analysis, which impacts the overall effectiveness of the process.

MANAGEMENT AND ANALYSIS

Nowadays, SCC susceptibility modelling forms an integral part of current pipeline industry practices[1, 2, 3] in managing the challenge of external SCC. The requirement of susceptibility modelling activities for pipelines deemed unpiggable comes to our engineering minds more naturally, as it provides a more systematic and consistent approach to the identification of cracking 'hot spot' locations and thus of necessary direct examination activities to infer pipeline condition.

The overall approach for unpiggable pipelines is well captured in the NACE SCC Direct Assessment (DA) SP0204[1] and CEPA SCC Recommended Practice.[2] Similarly, even in the case of piggable pipelines, susceptibility methodologies have been extensively integrated with crack management programs over recent years.

The combination of using SCC susceptibility analysis assessments and inline inspection (ILI) information as part of SCC integrity management programs has offered the industry a number of benefits, including the ability to:

» prioritise direct inspections (ILI or excavations) as a function of susceptibility and risk, which is important in the case of a large pipeline network system
» optimise further findings from ILIs by discriminating SCC features from other defect types
» prevent unnecessary costly field excavations, where SCC is actually not present
» provide the most representative picture of the pipeline condition in order to conduct appropriate integrity assessments and develop adequate repair and integrity management plans
» calibrate and optimise SCC susceptibility tools on a field-by-field basis.

CHALLENGES IN SUSCEPTIBILITY MODELLING

Most of the available industry SCC susceptibility models have been developed to reflect the knowledge and key industry trends[4, 5] associated with the manifestation of external SCC on pipeline infrastructure. These commonly integrate parameters have been identified as major contributors to the likelihood of SCC, such as coating type, proximity to compressors, operating stress, temperature, pressure cycles, soil type, soil resistivity and more.

Despite the advances in the understanding of the SCC mechanism, there remains a degree of uncertainty in SCC susceptibility analysis. Lack of accuracy or availability of input data is one common cause of uncertainty[6], but there are other, more fundamental processes contributing to uncertainty in SCC susceptibility analysis.

Invalid use of methods and measurements

One example is the common use of pipe-to-soil (P/S) potentials, as monitored by close-interval potential surveys (CIPS), in the susceptibility models. The level of pipe polarisation provides indications of the likelihood for external SCC.

For the realisation of high-pH SCC, the presence of polarisation to levels more positive than the standard cathodic protection (CP) criteria of $-850\ \mathrm{mV}_{\mathrm{Cu/CuSO4\ (CSE)}}$ is necessary; a range of potentials[A] of -600 to $-750\ \mathrm{mV}_{\mathrm{CSE}}$ [7] is often referred to as being critical. On the other hand, near-neutral pH SCC occurs at the free-corrosion potential (E_{corr}), which occurs when the pipeline is fully shielded from CP or when CP is not in place.

While the use of pipe-to-soil potentials therefore appears appropriate to assess SCC susceptibility, it is essential to note that the great

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[A] But note that this is dependent on temperature.

COATING DEFECT		ABILITY OF ABOVEGROUND TECHNIQUES TO DETECT COATING DEFECTS							
Type	**Severity***	**CPCR**	**DCVG**	**CC**	**CIPS**	**ACVG**	**CA**	**TS**	**EIS**
Disbondment and CP shielding	1	No	No	No	No	No	No	No	No
Holidays	2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Disbondment with passage of CP	3	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown
Blistering	4	Unknown	Unknown	No	No	No	No	No	No
Loss of adhesion	5	No	No	No	No	No	No	No	No
Loss of cohesion	6	No	No	No	No	No	No	No	No
Water permeation	7	Yes	Unknown	Unknown	Unknown	Unknown	Unknown	Unknown	Yes
Air permeation	8	No	No	No	No	No	No	No	No

CPCR: CP Current Requirements; DCVG: Direct Current Voltage Gradient; CC: Current ACVG: Alternating Current Voltage Gradient; CA: Current Attenuation; TS: Transwave System; EIS: Electrochemical Impedance Spectroscopy

**Severity: 1 is the worst case*

TABLE 1: Ability of aboveground surveys to detect coating type defects.

majority[B] of occurrences of high-pH and near-neutral pH SCC on buried pipelines are found at locations of coating disbondment (which leads to partial or full CP shielding). However, CIPS are ineffective when it comes to measuring the true pipe polarisation levels under a disbonded coating and this means that the use of P/S potentials (as recorded by CIPS) requires caution when interpreting the susceptibility of a pipeline to SCC.

Figure 1 shows a pipeline for which ILI and excavations revealed multiple locations of SCC colonies across the pipeline length, despite the CP levels having been reported by CIPS as compliant with the protection criteria. The pipeline was designed with a coating that is now known to be susceptible to disbondment and hence gives rise to CP shielding.

Ignoring potentially influential parameters

Some parameters known to influence SCC susceptibility are not considered in the models or, due to their general measurement complexity, are often not treated in sufficient detail and with adequate accuracy across the entire pipeline length. Some examples are given below.

Coating disbondment

As mentioned earlier, one of the most critical parameters associated with the occurrence of SCC relates to the presence of coating disbondment. Currently, no aboveground survey technologies are available to identify such coating-type defects (Table 1)[8]. While certain technologies[9] have been developed to address this challenge, there is certainly room for further technological advances and analysis improvements on measuring coating disbondment.

Soil characteristics

Yet another example of important SCC parameters not necessarily easily available across the entire pipeline length are actual soil characteristics (e.g. type, water drainage characteristics, etc.) at pipe crown level. The availability of digital geological maps could provide a general characterisation of burial conditions at pipe depth and is certainly a good starting point.

In the UK, for example, such data is provided by the British Geological Survey. However, local surveys or soil core sampling are often required to obtain more accurate data (e.g. soil resistivity, redox potential, anaerobic bacteria activity, etc.) and to improve the granularity in the model outputs.

When looking at soil characteristics such as water retention, it is essential to incorporate the influence of seasonal variations in these parameters into the modelling approach.

MATERIALS AND REALISATION OF SCC

Pipeline material characteristics are not necessarily well addressed in SCC models. This is partly due to the difficulty of having the necessary information available, but also because of the

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[B] The failure of a coating system is a primary factor in the initiation and propagation of SCC, and most, if not all, SCC failures were reported under disbonded coating. While it is acknowledged that the great majority of external SCC failures occurred on pipelines with coating and CP, there have been a few cases of SCC failures on bare pipelines of 9 to 16 years of age with no CP and 1 to 17 years with CP. It is believed such failures were associated with near-neutral pH SCC in high resistivity soils. Similarly, there are a few rare occasions of cracks found under sections of coatings that did not appear to have disbonded. In such cases, ground water may have penetrated through microscopic pores in the coating.

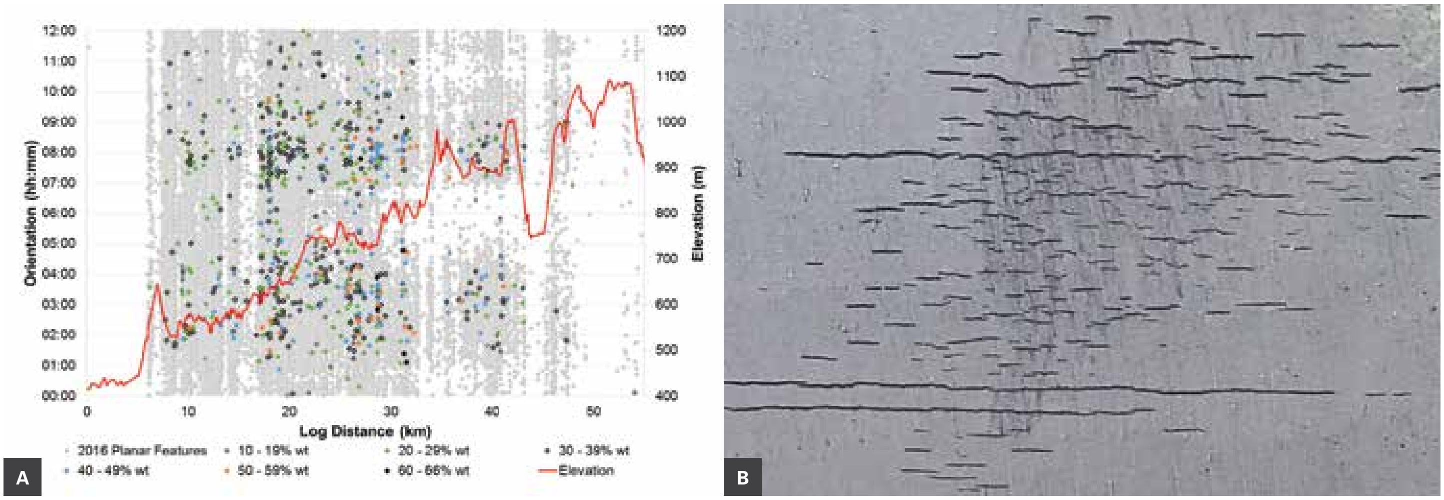

FIGURE 1: SCC identified on a pipeline with adequate CP levels as reported by CIPS – (a) crack features reported by ILI; (b) SCC colonies confirmed during dig verification.

uncertainty between the relationship of steel microstructure and mechanical properties with high-pH and near-neutral pH SCC susceptibilities.

SCC is a complex phenomenon whose realisation is dependent on its sensitivity to the triangle of environment-materials-stress. While the environmental and stress criteria are essential components, they are not completely sufficient for the realisation of SCC.

The complexity of SCC is augmented by its relationship with the materials. When the influence of metallurgy on SCC is being investigated, one has to look to the materials chemistry and microstructure, which generally includes, but is not limited to:

- general material alloying composition
- chemistry at grain boundaries
- nature of phases and distribution in space
- grain morphology and texture, and grain sizes
- inclusion chemistry and inclusion density.

One way to discuss the role of chemistry and microstructure in SCC is through their influence on the occurrence of intergranular (i.g.) and transgranular (t.g.) SCC[10], although many of the material parameters could contribute to both i.g. and t.g. cracking.

Intergranular SCC

For example[10], intergranular cracking generally relies on an active dissolution path at, or adjacent to, the grain boundaries or intergranular corrosion, while the overall material bulk is mainly within a passive state or sees much lower dissolution rates in comparison with the grain boundaries.

Ideal conditions for this usually occur when the alloy bulk chemistry is favourable to the formation of a stable and protective surface film while the grain boundaries remain locally exposed to the corrosive environment.
The preferential activity at the grain boundaries is generally maintained by the segregation of impurities such as sulphur or phosphorus at the grain boundaries, which contribute to the precipitation of weaker or more unstable films that generally offer insufficient protection.

The precipitation of secondary metallic phases at the grain boundary, whose electrochemical potentials are different from that of the grain matrix, could also contribute to the formation of a local galvanic cell generating preferential corrosion along the grain boundaries.

Transgranular SCC

On the other hand, t.g. SCC is, by definition, associated with cracks propagating through grains. The main parameters for the occurrence of t.g. SCC could thus be related to those material properties[10] that could offer preferential conditions for localised corrosion activation within grain bulk – if an anodically assisted SCC is considered – and easy passage to the crack growth across grains, like (i) phase chemical composition and crystal structure, (ii) grain morphology and size, (iii) phase mechanical properties (yield strength, hardness) and (iv) crystal stacking-fault energy.

In the case of near-neutral pH SCC, there remain disagreements within the research community as to whether the mechanism is a pure anodically dissolution-assisted mechanism or a hydrogen-related mechanism involving the entry of hydrogen into the lattice of the metal and its concentration at crack tips and other stress raisers, and bond breaking, or a combination of both.

It is nevertheless common for hydrogen-related mechanisms to work in concert with other crack-initiation mechanisms such as corrosion pits or fatigue.[11] For hydrogen-related mechanisms, the properties of the materials microstructure in allowing hydrogen adsorption and absorption, its diffusion, collection at susceptible points and the potential formation of hydrides are important aspects of SCC susceptibility.

Clearly, there is a requirement to understand the fundamentals of the SCC susceptibility relation with the steel microstructure, macro- and micro-chemistry, and its mechanical properties (yield strength and toughness). Several studies have been conducted to develop a satisfactory model, but no general trends have been observed to date.[11, 12, 13, 14]

SCC and steel grades

SCC has been found to occur in a wide range of pipeline grades, compositions, diameters, wall thicknesses, manufacturers and joining techniques, and so on with no strong correlations with SCC susceptibilities. Attempts to develop an SCC-resistant steel have so far proved elusive.

One particular feature, which merits being highlighted, is the uncertainty regarding the relationship of SCC susceptibility with steel grades. In one example,[15] Danielson and Jones showed that for high-pH SCC the intensity factor for SCC (K_{ISCC}) for more modern steels (X65, X70, X80) could be lower than that of older steels (X52).

At the same time, X65 and X70 have shown a similar steady-state crack propagation rate as X52, but higher than X80. One would have

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expected 'cleaner' modern steels (with less impurities that might segregate at the grain boundaries) to be less susceptible to high-pH SCC.

This observation might suggest that the grain boundary chemistry is not a primary factor in controlling the intergranular process; however, this does not detract from the fact that certain batches have been found more susceptible than other batches with similar compositions and microstructures[16]. The situation appears to be similarly ambiguous in the case of near-neutral pH SCC.

Near-neutral and hydrogen

As mentioned above, there are discussions suggesting the role of hydrogen in the near-neutral pH SCC mechanism, which indicates that one would expect the crack growth rate in such cases to increase with the steel yield strength, since it is a common pattern for hydrogen embrittlement mechanisms (e.g. sulphide-stress corrosion cracking). There is at present no strong evidence this is the case[12]; there are no laboratory or field data indicating that one particular microstructure or grade of steel is significantly more resistant to near-neutral pH SCC.[11]

Some research[17] shows that the susceptibility with lower grade steels (X52) and with higher strength steels (X80) indicates a similar SCC susceptibility under cyclic loading and at higher applied stresses. One has to consider that under cyclic loading, acceleration in crack growth as a result of hydrogen absorption can occur in all steels, from the lower yield strength of older existing pipeline systems (42–65 ksi) to the higher strengths of new pipelines (70–120 ksi).

Nevertheless, a definite lesson from industry experience demonstrates that the occurrence of near-neutral pH SCC is frequently associated with discontinuous features such as corrosion pits, dents, scratches and welds.

CONCLUSION

SCC susceptibility modelling plays a key role in the development and implementation of crack management programs. Unfortunately, we still face challenges that compromise the reliability of predictions made through modelling.

More specifically, some of these limits relate to the fact that:

1. Parameters, however critical to SCC likelihood, cannot be effectively measured by currently available industry methods; examples include the presence of coating disbondment and true pipe polarisation in areas affected by disbonded coating.
2. The reliability and the granularity of the model outputs could be affected as some key parameters, e.g. soil characteristics at pipe crown level, cannot be practically made available across the entire pipeline length. For the soil characteristics, it is essential to reflect on the influence of seasonal variations and how this is addressed in the modelling.
3. Although pipeline materials – grade, chemical composition, grain boundary chemistry, mechanical properties, etc – are an essential aspect of SCC likelihood, they have not been well integrated in the models, as no strong correlations with SCC susceptibilities have yet been established. Until clear trends are established, it is important that pipe manufacturers and steel heats (batches) are clearly recorded according to pipe joints.

REFERENCES

[1] National Association Of Corrosion Engineers Standard Recommended Practice SP0204-08, Stress Corrosion Cracking (SCC) Direct Assessment Methodology, NACE, 2008.

[2] CEPA Stress Corrosion Cracking Recommended Practices, 3rd Edition.

[3] ASME 31.8S, Managing System Integrity of Gas Pipelines.

[4] Integrity Management of Stress Corrosion Cracking in High Consequence Areas. R. R. Fessler; A. D. Batte; M. Hereth, ASME STP-PT-011, ASME, October 2008.

[5] Essential Elements of An Effective SCC Direct Assessment Program, IPC-2012, Paper No. 90238, S. C. Rapp; J. E. Marr; F. H. Martinez; G. Verkade; A. D. Batte, 2012.

[6] Management of Pipeline External Stress Corrosion Cracking: A Time Story, 3R International Journal, Special 01 2018, Daniel Sandana, April 2018.

[7] Near Neutral pH and High pH SCC - Industry Good Practice Guide, UKOPA/GP/009, UK Onshore Pipeline Operator's Association (UKOPA).

[8] Aboveground techniques for monitoring external pipeline coatings, MP, S. Papavinasam, M. Attard, R. W. Revie, April 2010.

[9] EMAT, Pipe Coatings, Corrosion Control, and Cathodic Protection Shielding, R. Norsworthy, J. Grillenberger, S. Brockhaus, M. Ginten, NACE/Corrosion 2013, Paper 2378.

[10] Stress-Corrosion Cracking: Materials Performance and Evaluation, ASM International, R.H. Jones, 1992.

[11] Mechanisms Of High pH And Near-Neutral-pH SCC Of Underground Pipelines, J. Beavers, B. A. Harle, IPC 1996-1860, 1996.

[12] OPS TTO8 – Stress Corrosion Cracking Study, ChallengeUs, 2004.

[13] Materials Factors influencing the initiation of Near-Neutral pH SCC on underground pipelines, J. Beavers, T. Johnson, R. L. Sutherby, IPC2000-221, 2000.

[14] Effect of microstructure and microchemistry on the SCC behaviour of pipeline steels in a High-pH environment, M.J. Danielson, R.H. Jones, K. Krist, NACE/Corrosion 2000, Paper 0359, 2000.

[15] Effect of microstructure and microchemistry on the SCC behaviour of archival and modern pipeline steels in a High-pH environment, M.J. Danielson, R.H. Jones, K. Krist, NACE/Corrosion 2001, Paper 01211, 2001.

[16] Stress Corrosion Cracking Model, NACE/Corrosion 2004, Paper 4189, J. Beavers, W. Harper, 2004.

[17] Near-Neutral pH SCC properties of pipeline steels of Grade X80 and X52, NACE/Corrosion 2011, Paper 11286, M. Sawaruma, H. Asahi, T. Omura, H. Kishikawa, N. Ishikawa, M. Kimura, 2011.