DET NORSKE VERITAS™

Final Report

Task 3.4 – Input to Report: Implications for Recommendation P-09-1

Pipeline and Hazardous Materials Safety Administration
U.S. Department of Transportation
Washington, DC

Report No./DNV Reg No.: TAOUS811CSEAN (PP017533)
July 15, 2013

Task 3.4 – Input to Report: Implications for Recommendation P-09-1	DET NORSKE VERITAS (U.S.A.), INC. Materials & Corrosion Technology Center 5777 Frantz Road Dublin, OH 43017-1886, United States Tel: (614) 761-1214 Fax: (614) 761-1633 http://www.dnv.com http://www.dnvusa.com
For: U.S. Department of Transportation Pipeline and Hazardous Materials Safety Admin. East Building, 2nd Floor 1200 New Jersey Avenue, SE Washington, DC 20590	
Account Ref.:	

Date of First Issue:	June 28, 2013	Project No.	PP017533-3
Report No.:		Organization Unit:	Materials & Corrosion Technology Ctr.
Revision No.:		Subject Group:	
Summary:			

Please see Executive Summary.

Prepared by:	Sean Brossia, Ph.D. Director – Technology Development	*Signature*
Verified by:	John Beavers, Ph.D. Director – Failure Analysis	*Signature*
Approved by:	Oliver C. Moghissi, Ph.D. Director, Materials & Corrosion Technology Center	*Signature*

☐	No distribution without permission from the client or responsible organizational unit (however, free distribution for internal use within DNV after 3 years)		
☐	No distribution without permission from the client or responsible organizational unit	Key Words	
☐	Strictly confidential		
☑	Unrestricted distribution		

Rev. No. / Date:	Reason for Issue:	Prepared by:	Approved by:	Verified by

Executive Summary

Over the past few years, a number of high profile pipeline failures have occurred wherein fracture initiated at the longitudinal seam welds in early generation electric resistance welded (ERW) pipe. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In some cases, it appears that seam-integrity assessments, in-line inspection (ILI), and/or mill hydrotesting did not detect the presence of significant seam weld defects.

ERW seam defects can exist due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication (long seam welding) process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate or skelp. The plate or skelp also may contain planar inclusions that result in hook cracks in the welded pipe. These pre-existing seam weld defects can grow in service by pressure cycle fatigue.

Selective seam weld corrosion (SSWC) is another mechanism by which defects can be introduced at the seam weld. The research summarized in this report consisted of three main parts: a literature review of SSWC, development of a reliable field-deployable SSWC susceptibility test method, and an examination of the effectiveness of cathodic protection (CP) on mitigating SSWC.

Based on the available literature, the notion that sulfur enrichment and sulfide inclusions lead to localized corrosion in the weldment seems to have the greatest merit and the largest body of supporting evidence. In addition to controlling the level of sulfur and inclusion shape and composition, the overall steel composition and microstructure, welded heat input, and post-weld seam or full pipe body heat treatment are important considerations to minimizing SSWC susceptibility.

An approached based on making polarization resistance measurements was developed and tested as a way to quantify SSWC susceptibility. This new method utilized a barnacle cell to conduct polarization resistance (PR) measurements on small, selected areas of the pipe (e.g., the weldment and base metal). The method is relatively simple and can be utilized in the field without significant difficulty. Using this approach, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is suggested in order to incorporate it into existing standards or to develop a new standard.

Based on the work conducted, CP appears to be at least partially effective in reducing the corrosion rate of SSWC susceptible pipe. Application of more negative cathodic polarization than the -850 mV off potential or the 100 mV minimum cathodic polarization may be necessary to achieve effective protection for SSWC susceptible pipe. As there are many variables that can

affect CP effectiveness on actual operating pipelines, the results of this study should only be used as guidance and additional investigation should be conducted prior to defining a specific set of protection criteria that could be universally applied to all SSWC susceptible pipelines. Furthermore, caution must be exercised to ensure that increased CP levels (more negative polarization) do not introduce other additional integrity risks such as hydrogen embrittlement.

Table of Contents

List of Figures

1.0 BACKGROUND

Over the past few years, a number of high profile pipeline failures have occurred wherein fracture initiated at the longitudinal seam welds in early generation electric resistance welded (ERW) pipe. These include failure of a liquid propane pipeline operated by Dixie Pipeline Company in Carmichael, Mississippi in 2007. In some cases, it appears that seam-integrity assessments, in-line inspection (ILI), and/or mill hydrotesting did not detect the presence of significant seam weld defects. As a result of these observations, the National Transportation Safety Board (NTSB) recommended[1] that the U.S. Department of Transportation (DOT) Pipeline and Hazardous Materials Safety Administration (PHMSA) conduct a comprehensive study to identify actions that can be used by operators to eliminate catastrophic longitudinal seam failures in pipelines.

ERW seam defects can exist from a variety of causes. Lack of fusion weld defects can originate during the initial pipe fabrication process typically resulting from a loss of electrical contact between the runners and the parent steel plate, lack of proper plate edge preparation, and lack of sufficient gap closing force exerted on the plate or skelp. The plate or skelp also may contain planar inclusion that result in hook cracks in the welded pipe. Pre-existing defects at or near the seam weld can grow in service by pressure cycle fatigue.

Selective seam weld corrosion (SSWC) is another mechanism by which defects can grow at the seam weld. SSWC is a form of corrosion attack that preferentially occurs along the weld bond line/fusion zone (FZ) of line pipe and often has the appearance of a wedge shaped groove (leading to the term grooving corrosion). The mechanism of SSWC has been the subject of several studies in order to determine viable methods to mitigate and minimize its occurrence.[2-26] Sulfide inclusions have been recognized as preferential sites for localized corrosion of steels since the 1910's.[11] As a result, this well-known phenomenon has been cited as the primary cause of SSWC.[2, 5, 12-16] Regardless of the mechanism, because sulfide inclusions are known to induce rapid localized corrosion, it is logical to expect them, if present in the FZ and HAZ, to play a role in SSWC as well. The influence of sulfur can be mitigated through several different approaches including reducing the steel sulfur concentration, alloy chemistry modifications in order to control the size, shape and composition of the inclusions, and post-weld heat treatment. Each of these has shown, to varying degrees, to aid in mitigating the detrimental influence of inclusions on corrosion of steel.

To characterize the relative corrosion rate of SSWC compared to the corrosion rate and associated overall metal loss of the base metal, the grooving factor is sometimes used, as given by:

$$\alpha = \frac{d_1}{d_2} = 1 + \frac{a}{d_2}$$

where α is the grooving factor, a is the depth of the weld groove on the corroded surface, d_1 is the distance from the original metal surface prior to the onset of corrosion to the depth of the weld groove, and d_2 quantifies overall metal loss of the material.[26] These parameters are shown schematically in Figure 1. Thus, a grooving factor of 1.0 would indicate that no SSWC had occurred and that all metal loss was general and uniform across the surface. Grooving factor values greater than 2 (that is the seam weld is corroding at a rate that is twice that of the rest of the surface) are typically considered to indicate susceptibility and the threat of SSWC.[26]

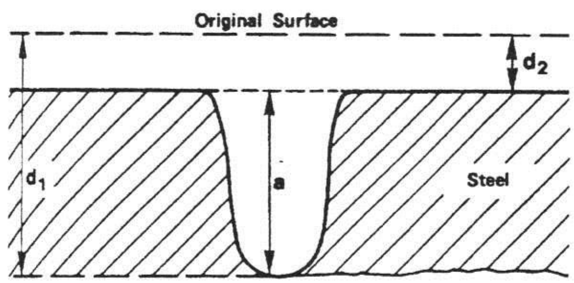

Figure 1. Schematic illustration of SSWC and the parameters used to calculate the grooving factor.[26]

Based on the information obtained from the literature, work was then performed to develop a reliable field-deployable method for detecting SSWC susceptibility and to evaluate the effectiveness of cathodic protection (CP) on SSWC susceptible pipe steel. In the following sections, a summary of the research performed is presented. A more complete discussion of the results from this work can be found elsewhere.[27, 28]

2.0 APPROACH

2.1 SSWC Susceptibility Test Method Development

The approach that was developed is based on comparing the polarization resistance values of the weldment and base metal. The polarization resistance technique is well recognized and widely used by the industry. Polarization resistance is a method in which the electrochemical response of a corroding metal is investigated near its corrosion potential. The primary limitation that needed to be overcome was how to introduce the environment (soil or liquid electrolyte) in a small region that would correspond to just the weldment. Obtaining measurements on the base metal is much easier because there is a much larger area from which to select a testing location. Based on past experience,[29] it was decided that polarization resistance measurements made using a barnacle cell might enable testing of limited areas such as the weldment.

A schematic illustration of a plan view of the barnacle cell is shown in Figure 2 and a side-cut view illustrating how measurements would be made on the weldment of a pipeline is shown in Figure 3. The barnacle cell consists of two electrodes: a stainless steel ring that acts as a counter electrode and a stainless steel wire that serves as a pseudo reference electrode. The working electrode for the polarization resistance measurement is the pipeline. The stainless steel ring and wire are embedded in epoxy in such a way that they are not shorted together. To conduct the polarization resistance measurement, a wetted sponge is used as the electrolyte and the barnacle cell is held against the pipeline.

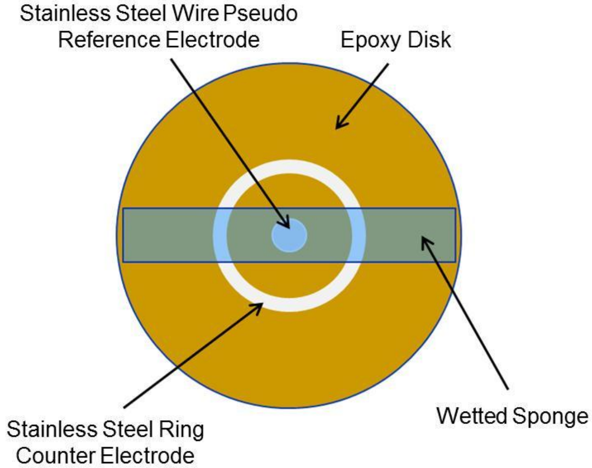

Figure 2. Schematic illustration of barnacle cell (plan view).

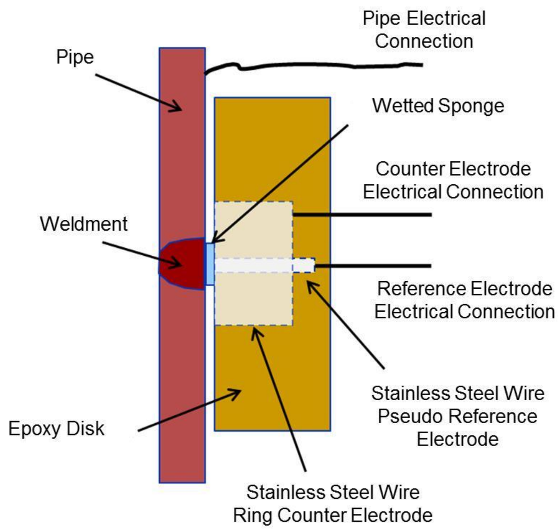

Figure 3. Schematic illustration of barnacle cell (cross section view) and its use in making polarization resistance measurements.

2.2 SSWC Cathodic Protection Effectiveness Testing

To evaluate the effectiveness of CP on SSWC susceptible pipe material, a set of soil boxes was created. In total, three steels were selected for evaluation: one steel that was not SSWC susceptible and two steels that were susceptible to SSWC with grooving factors between 4 and 5. The testing was performed in one soil from Dublin, Ohio. In order to isolate the corrosion behavior of the base metal, heat affected zone (HAZ), and weldment, a series of segmented electrodes was created, as shown in Figure 4. The segmented electrodes were constructed by machining separate blocks of material to represent the weldment, HAZ, and base metal. Independent electrical connection to each segment was achieved from the backside of the electrode by spot welding a wire. If a steel is not susceptible to SSWC, the base metal, HAZ, and weldment segments in the electrode would be expected to show the same corrosion rate. In contrast, if a steel is susceptible to SSWC, then the HAZ and weldment would be expected to show higher corrosion rates than that of the base metal.

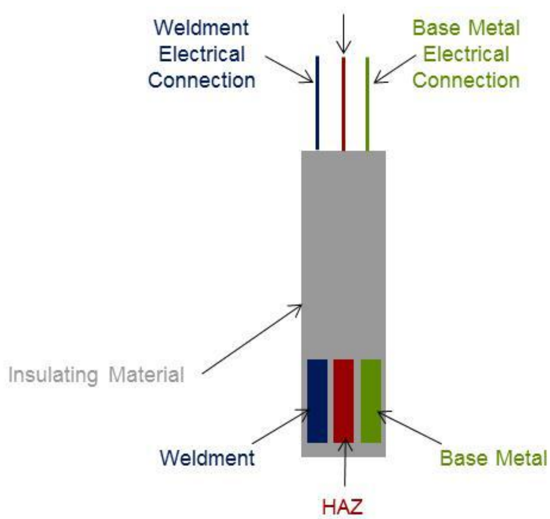

Figure 4. Schematic diagram of segmented electrode used to study SSWC.

In each soil box, the testing system consisted of the segmented electrode and a 4 inch × 6 inch section of pipe steel to serve as a surrogate for a pipeline. This pipe steel material did not contain any weldment and was taken from the same base material for each soil box. CP was applied to the pipe steel surrogate and the segmented electrode using a DC power supply connected to a mixed metal oxide (MMO) anode. The intent of the pipeline surrogate was to provide a reasonably large steel surface area such that the soil conditions and chemistry in proximity to the steel would change due to the effects of CP.

In each soil box, a separate steel material-CP level combination was tested. The electrochemical impedance spectroscopy (EIS) method was utilized to determine the polarization resistance of each segment over time. The EIS method was used to address issues with soil resistance and its change over time in the tests. The polarization resistance is inversely proportional to the corrosion rate and provides an indication of the effect of environmental polarization that results from the soil environment changing over time due to the applied CP. By performing the EIS tests on each isolated segment (base metal, HAZ, and weldment) separately, an indication of the effects of CP for each steel microstructure can be estimated. The polarization resistance measurements do not take credit for potential polarization, which will further decrease the estimated corrosion rate, so the results are conservative.

In addition to conducting EIS tests, CP effectiveness was also evaluated by estimating the corrosion rate of each segment by measuring the amount of metal loss on each electrode during the exposure period.

3.0 RESULTS AND DISCUSSION

3.1 SSWC Susceptibility Test Method Development

To verify that the polarization resistance measurements conducted using the barnacle cell would provide valid indications of SSWC susceptibility, barnacle cell results were compared to the results obtained from pre-screening tests using the test method developed by Masamura and Matsushima [9]. Based on the approach of Masamura and Matsushima,[9] Steels A, B, and C were all found to be susceptible to SSWC; whereas, Steel D was not susceptible. The comparison of barnacle cell polarization resistance results to the results from Masamura and Matsushima[9] are shown in Figure 5. Very good agreement was observed and, as a result, additional steels were tested using the barnacle cell approach.

The relative ratios of the average base metal and weldment polarization resistances for seven steels are shown in Figure 6. From these results, it is clear that Steels A, B, C, and E are susceptible to SSWC. If the same criteria used by Duran et al.,[26] wherein a difference of 2x in corrosion rate for the weldment and base metal is indicative of susceptibility to SSWC, then a clear delineation between the steels can be seen. All of the non-susceptible steels (D, F, and G) have base metal polarization resistance to weldment polarization resistance ratios near unity. All of the SSWC susceptible materials show ratios greater than 3.5. That is, the average polarization resistance of the base metal was at least 3.5X greater than the average weldment polarization resistance. Based on the good correlation to long-term SSWC testing results for Steels A, B, C, and D, it seems evident that the barnacle cell approach can distinguish between SSWC susceptible and non-susceptible pipe.

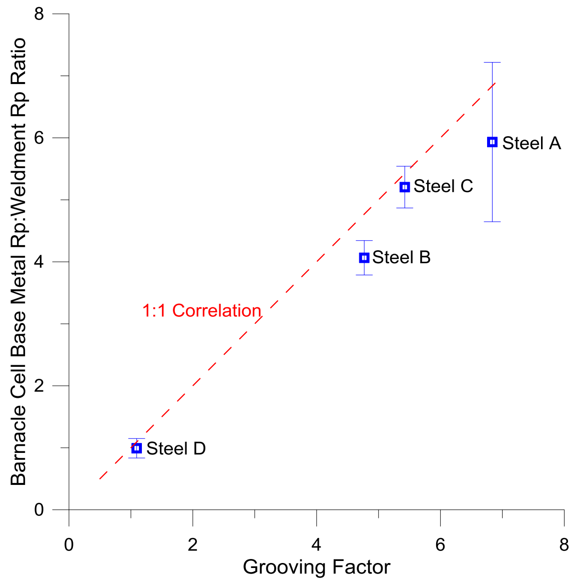

Figure 5. Comparison of the base metal polarization resistance (Rp) to weldment polarization resistance (Rp) ratio from the barnacle cell to the grooving factor measured using the approach of Masamura and Matsushima.[9]

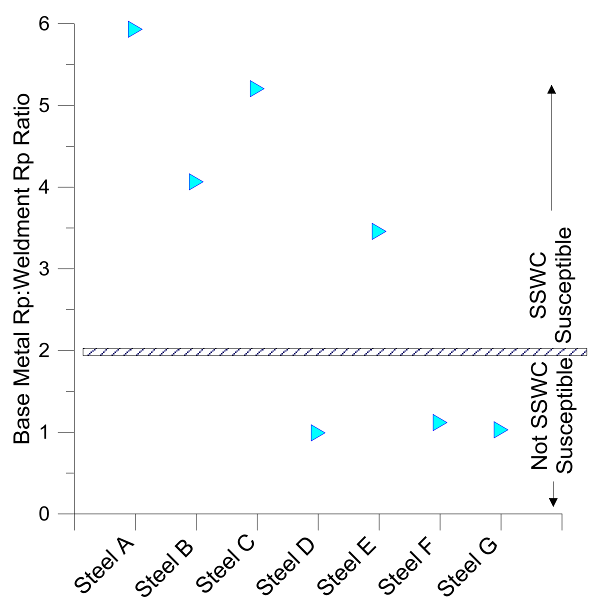

Figure 6. Base metal polarization resistance (Rp) to weldment polarization resistance (Rp) ratio for 7 different steels investigated. High ratio values indicate susceptibility to SSWC.

3.2 Cathodic Protection Effectiveness Testing

Long-term (13-month) soil box testing was conducted on one non-SSWC susceptible and two SSWC steels in one soil. Two CP criteria were evaluated; a negative polarized potential of at least 850 mV relative to a saturated copper/copper sulfate reference electrode (-850 mV off potential) and a minimum of 100 mV of cathodic polarization (100 mV polarization).

The testing results showed that the corrosion rates of SSWC susceptible pipe material decreased to some degree with applied CP, but effective protection was not achieved. However, in the testing of the -850 mV off-potential criterion, the criterion was initially achieved, but off potentials more negative than -850 mV were not maintained throughout the testing period. On potentials more negative than -850 mV were achieved in this testing. Similarly, in the testing of the 100 mV polarization criterion, that level of polarization was not consistently achieved.

Testing of the non-SSWC susceptible pipe material showed that the application of CP resulted in significant increases in the environmental polarization (i.e., lower corrosion rate) of the weldment, HAZ, and base metal. All three steel microstructures achieved comparable polarization resistance values. Post-test examination of metal loss on the segmented electrode coupons also corroborated the observation that the base metal, HAZ, and weldment exhibited comparable, low, corrosion rates during testing, as shown in Figure 7.

Testing of the SSWC susceptible pipe material showed that the application of CP had some influence on increasing the environmental polarization (i.e., a reduction in corrosion rate) for the weldment, HAZ, and base metal, as shown in Figure 8. However, CP was not capable of eliminating SSWC susceptibility, as the polarization resistance of the weldment and HAZ were consistently lower than the polarization resistance of the base metal. Post-test examination of metal loss also showed that the weldment and HAZ consistently had higher corrosion rates than the base metal, as shown in Figure 7. If CP were fully effective in eliminating SSWC, low corrosion rates for the three steel microstructures would have occurred.

Therefore, the results of the testing indicate that CP levels, while not meeting criterion, were partially effective in reducing the corrosion rate of SSWC susceptible pipe. These tests did not establish whether the -850 mV off-potential criterion or the 100 mV polarization criterion are adequate for this particular soil; but, given the fact that most off-potentials in the tests of the -850 mV off-potential criterion were near -850 mV, it is likely that even higher levels of CP are required for SSWC steels.

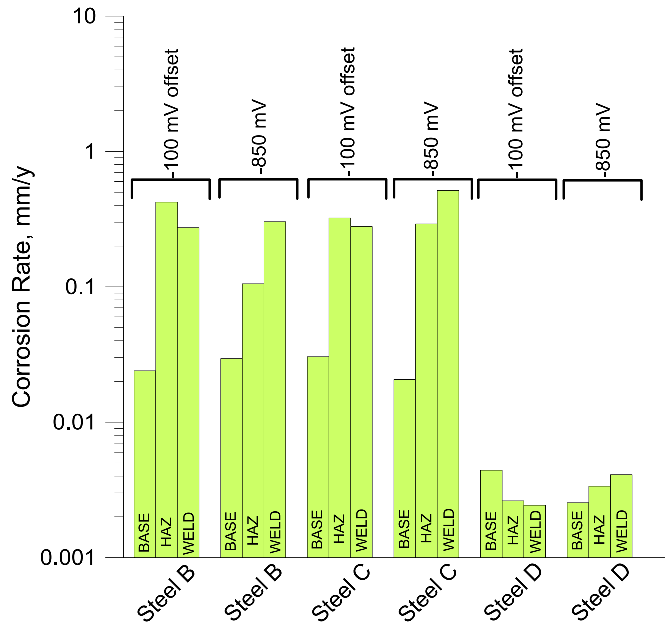

Figure 7. Corrosion rate estimates for segment electrodes during 13-month CP effectiveness evaluation tests.

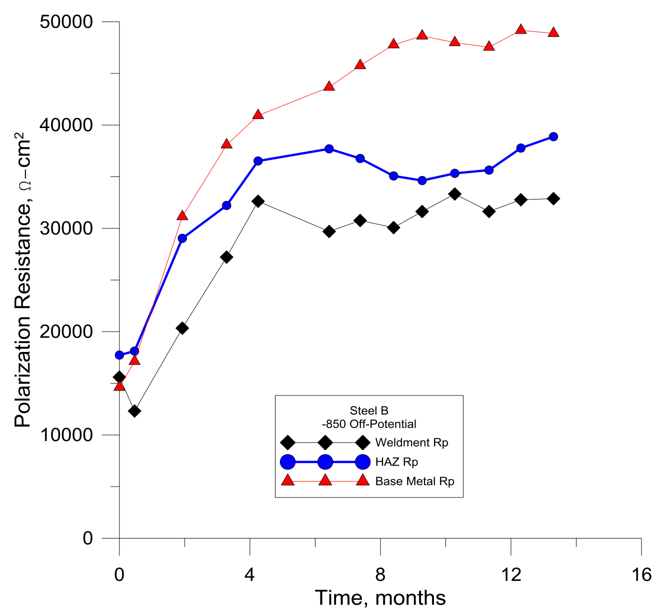

Figure 8. Polarization resistance values for Steel B weldment, HAZ, and base metal in the test of the -850mV off-potential criterion.

The research findings in Task 3.2 of this project (Selective Seam Weld Corrosion Test Method Development) found that the primary cause of SSWC is higher kinetics for corrosion of the seam weld microstructures as opposed to a galvanic effect between the base metal and the seam weld. Grooving factors greater than five were observed, indicating that the corrosion rate at the seam weld was five times faster than that of the base metal. Assuming that an off potential of -850 mV is adequate for the base metal, and that the Tafel slope for the anodic (corrosion) kinetics is between 150 and 200 mV, which is a typical range for soils, an additional 100 mV to 140 mV of polarization would be required to provide the same level of protection for the seam weld.

As there are many variables that can affect CP effectiveness on actual operating pipelines, the results presented should only be used as guidance and additional investigation would be needed. Furthermore, caution must be exercised to ensure that, at higher applied levels of CP, no additional integrity risks (e.g., hydrogen embrittlement) are created.

4.0 SUMMARY AND CONCLUSIONS

Based on the available literature, it is evident that SSWC is an integrity threat for ERW welded pipe. Research efforts have assisted in developing a better understanding of the possible mechanisms and key factors the lead to SSWC. Of the mechanisms posed, the notion that sulfur enrichment and sulfide inclusions lead to localized corrosion in the weldment seem to have the greatest merit. There is ample phenomenological evidence as well as fundamental science that provide a basis for linking inclusions to localized corrosion, though sulfide inclusions are not the sole cause of SSWC. Regardless of the mechanisms involved, it is evident that limiting the sulfur content, modifying sulfide composition, and shape-control by adjusting steel chemistry are important to minimize the risk of SSWC.

An approached based on making polarization resistance measurements was developed and tested as a way to quantify SSWC susceptibility. This new method utilized a barnacle cell to conduct the polarization resistance measurements on small, selected areas of the pipe (e.g., the weldment and base metal). The method is relatively simple and can be utilized in the field without significant difficulty. Using this approach, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is suggested in order to incorporate it into existing standards or to develop a new standard.

The effectiveness of cathodic protection in mitigating SSWC was also investigated. Based on the work conducted, CP appears to be at least partially effective in reducing the corrosion rate of SSWC susceptible pipe. Application of more negative cathodic polarization than the -850 mV off-potential or the 100 mV polarization criteria may be necessary to achieve more effective protection for SSWC susceptible pipe. The research findings in Task 3.2 of this project suggest that an additional 100 mV to 140 mV of polarization, over that provided by the standard criteria, may be required to provide the same level of protection for the seam weld.

As there are many variables that can affect CP effectiveness on actual operating pipelines, the results of this study should only be used as guidance and additional investigation should be conducted prior to defining a specific set of protection criteria that could be universally applied to all SSWC susceptible pipelines. Furthermore, caution must be exercised to ensure that increased CP levels (more negative polarization) do not introduce other additional integrity risks such as hydrogen embrittlement.

5.0 REFERENCES

1. http://www.ntsb.gov/publictn/2009/PAR0901.htm. *NTSB/PAR-09/01, PB2009-916501, Notation 7979A.* 2009.
2. C. Kato, Y. Otoguro, S. Kado, and Y. Hisamatsu, *Corrosion Science*, vol 18, p. 61 (1978).
3. I. Matsushima, in Uhlig's Corrosion Handbook, p. 561, R.W. Revie, Editor, John Wiley and Sons (2000).
4. K. Katoh, N. Kosuge, S. Itoh, A. Miyasaka, S. Tanioka, H. Kihira, and T. Murata, *Nippon Steel Technical Report*, vol. 39/40, p. 15 (1989).
5. M. Sephton and P.C. Pistorius, *Corrosion*, vol. 56, p. 1272 (2000).
6. A. N. Rothwell, *Corrosion Prevention and Control*, p. 113, October (1992).
7. T. Hemmingsen, H. Hovdan, P. Sanni, and N.O. Aagones, *Electrochimica Acta*, vol. 47, p. 3949 (2002).
8. A. G. Howell, "Under-deposit corrosion at weld seams in carbon steel piping," Paper No. 447, **Corrosion97**, NACE International (1997).
9. K. Masamura and I. Matsushima, "Grooving Corrosion of Electric Resistance Welded Steel Pipe in Water – Case Histories and Effects of Alloying Elements," Paper No. 75, **Corrosion81**, NACE International (1981).
10. R. Wong, *Corrosion*, in press (2012).
11. J. E. Stead, *J. Iron and Steel Institute*, vol. 11, p. 5 (1916).
12. T. P. Groeneveld, G.O. Davis, and D.N. Williams, Susceptibility of Resistance Welded, Flash Welded, and Induction Welded PipE to Selective Seam-Weld Corrosion, NG-18 Report No. 199, Pipeline Research Council International (1991).
13. E. Rasanen and K. Relander, *Scandinavian Journal of Metallurgy*, vol. 7, p. 11 (1978).
14. D. G. Atteridge, V. A. Dikshit, and D. A. Jones, "Investigation of Environmentally Enhanced Degradation of ERW Seam Welded Steel Linepipe," Paper No. 36, 1st International Symposium on Process Industry Piping, NACE International (1993).

15. T. P. Groeneveld, G. O. Davis, and D. N. Williams, "Evaluations of the susceptibilities of electric-welded pipe to selective seam-weld corrosion," Paper No. 14, Proceedings of Eighth Biennial Joint Technical Peeting on Line Pipe Research, European Pipeline Research Group, (1991).

16. W. E. Heitmann, P. D. Sothwick, and F. Pausic, "ERW Linepipe: The Effect of Welding and Annealing Upon the Properties, Microstructure, and Corrosion Resistance," p. 957 in International Conferene on Technology and Application of HSLA Steels, ASM International (1984).

17. G. Wranglen, in Sulfide Inclusions in Steel, *p. 361*, ASM International (1975).

18. Z. Szklarska-Smialowska, Pitting and Crevice Corrosion, NACE International (2005).

19. C. S. Brossia and R. G. Kelly, *Corrosion Science*, vol. 40, p. 1851 (1998).

20. G. Wranglen, *Corrosion Science*, vol. 14, p. 331 (1974).

21. P. Sury, *Corrosion Science*, vol. 16, p. 879 (1976).

22. P. Marcus, *J. Chim. Phys.*, vol. 88, p. 1697 (1991).

23. C. S. Brossia and R. G. Kelly, *Corrosion*, vol. 54, p. 145 (1998).

24. G.S. Eklund, *J. Electrochem. Soc.*, vol. 121, p. 467 (1974).

25. S.E. Lott and R.C. Alkire, J. Electrochem. Soc., vol. 136, p. 973 (1989).

26. C. Duran, E. Treiss, G. Herbsleb, *Materials Performance*, p. 41, September (1986).

27. C. S. Brossia, Selective Seam Weld Corrosion Test Method Development, Final Report, PHMSA (2013).

28. C.S. Brossia, Selective Seam Weld Corrosion Effectiveness of Cathodic Protection, Final Report, PHMSA (2013).

29. C. S. Brossia, M. Yunovich, D. Hill, K. M. Lawson, R. Denzine, J. T. Schmidt, E. Klechka, E. Schindelholz, E. Nordgren, D. Krop, R. Baboian, H. Hack, J. D. Flessas, D. C. Cook, "Corrosion condition assessment, mitigation, and preservation of USS Monitor artifacts," NACE Corrosion2007, Paper No. 07239 (2007).

Det Norske Veritas

DNV is a global provider of knowledge for managing risk. Today, safe and responsible business conduct is both a license to operate and a competitive advantage. Our core competence is to identify, assess, and advise on risk management, and so turn risks into rewards for our customers. From our leading position in certification, classification, verification, and training, we develop and apply standards and best practices. This helps our customers to safely and responsibly improve their business performance.

Our technology expertise, industry knowledge, and risk management approach, has been used to successfully manage numerous high-profile projects around the world.

DNV is an independent organization with dedicated risk professionals in more than 100 countries. Our purpose is to safeguard life, property, and the environment. DNV serves a range of industries, with a special focus on the maritime and energy sectors. Since 1864, DNV has balanced the needs of business and society based on our independence and integrity. Today, we have a global presence with a network of 300 offices in 100 countries, with headquarters in Oslo, Norway.

Global Impact for a Safe and Sustainable Future

Learn more on www.dnv.com