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Final Report

Task 3.2 – Selective Seam Weld Corrosion Test Method Development

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

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Task 3.2 – Selective Seam Weld Corrosion Test Method Development	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
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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 weld 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. In this work, two new possible field-deployable SSWC susceptibility test methods were developed and evaluated. The main purpose was to develop a robust, rapid, non-destructive, field-deployable SSWC susceptibility test methodology that can quantify SSWC susceptibility on operating pipelines.

Because differences in corrosion potential for the weldment and base metal have been cited as the cause for SSWC, initial tests were conducted to examine the possibility that differences in the measured corrosion potentials of the weldment and base metal might be large enough to distinguish between SSWC susceptible and non-susceptible pipe. However, testing showed that there is no significant difference in corrosion potential between the base metal and the weldment for pipe steels, in general, and for pipe steels that are susceptible to SSWC. This finding indicates that differences in the corrosion kinetics between the weldment and the base metal are the primary cause of SSWC. The second, alternative, method developed is based on this corrosion mechanism.

This alternative approach utilized a barnacle cell to conduct linear polarization resistance (LPR) 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. Several alternative solutions were evaluated to wet the sponge that acts as the electrolyte for conducting the LPR measurements. Based on the testing conducted, a simple salt solution (table salt + water, ~ 3.5% NaCl) is likely to give the best sensitivity to SSWC. Using the barnacle cell, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is recommended in order to incorporate it into existing standards or to develop a new standard. To accomplish the development of a standard, the number of tests for a given pipeline necessary to have high confidence (e.g., 95%) in assessing SSWC susceptibility would also have to be conducted.

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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) line 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 weld seam defects in the ERW line pipe. 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 weld defects can exist from a variety of 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. Pre-existing defects at or near the seam weld can grow in service by pressure cycle fatigue.

Selective seam weld corrosion is another mechanism by which defects can grow at the seam weld. Selective seam weld corrosion (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). To characterize the relative corrosion rate of SSWC compared to the corrosion rate and associated overall metal loss by 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, 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.[2] 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.[2]

In this report, a field-deployable methodology is described to assess susceptibility to SSWC. The purpose of this effort is to develop a rapid, reliable, and non-destructive method to determine if as-welded linepipe is susceptible to SSWC.

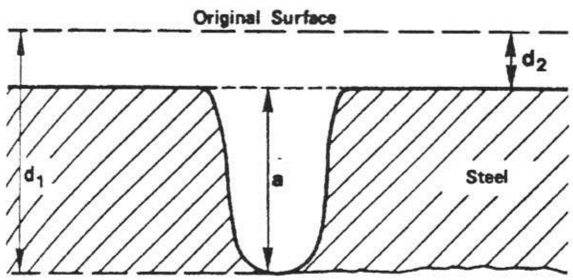

Figure 1. Schematic illustration of SSWC and the parameters used to calculate the grooving factor.[2]

2.0 APPROACH

The primary goal of this task of the PHMSA project was to determine susceptibility to SSWC in a rapid, reliable, and non-destructive way. Traditional corrosion testing that is conducted to determine SSWC susceptibility involves potentiostatic (constant potential) or galvanostatic (constant current) polarization in 3.5 wt% NaCl solutions for periods of several days to several weeks.[3] After testing using this traditional methodology, the samples are examined using optical microscopy and metallurgical cross sectioning in order to determine the relative metal loss depth for the base metal and weldment. Though the traditional method is effective, it is slow and destructive because samples must be cut from the pipeline.

For this effort, two different approaches were evaluated that are non-destructive and can be performed on an operating pipeline. The first approach utilized making local corrosion potential measurements in which the pipeline was connected to a high impedance voltmeter (or a digital voltmeter equipped with an electrometer) and a standard copper/copper sulfate reference electrode was pressed against a small wetted sponge that was then pressed against the pipeline. The size and shape of the sponge was such that, when potential measurements of the weldment were obtained, the sponge-wetted area on the pipeline was predominantly the weldment and heat affected zone (HAZ) of the weld, herein referred to as the weldment. That is, the sponge was small enough that very little base metal was underneath the sponge when weldment measurements were performed. The goal of this approach was to ascertain if significant differences in the corrosion potentials of the weldment and base metal for SSWC susceptible line pipe existed and could be measured.

The second approach that was evaluated was to conduct linear polarization resistance (LPR) measurements on the weldment and base metal. The LPR technique is well recognized and widely used by the corrosion industry. LPR is a method in which the electrochemical response of a corroding metal is investigated near its corrosion potential. Typically, this involves polarization of the pipe sample 10 to 30 mV below the corrosion potential followed by a slow increase of the potential to a comparable potential above the corrosion potential. Within this potential region, it is assumed that the relationship between potential and the log of the current is linear, thereby allowing the calculation of the corrosion rate via:

$$CR = C_1 \frac{i_{corr} EW}{\rho}$$

and

$$i_{corr} = 10^6 \frac{B}{R_p}$$

where:

CR is the corrosion rate, C_1 is a constant depending on the units of measure used, i_{corr}, is the corrosion current density, EW is the equivalent weight (g/equivalent), ρ is the metal density, B is the Stern-Geary coefficient, and R_p is the polarization resistance value obtained from the LPR test. R_p is the slope of the potential-current curve at zero over-potential.

The primary limitation that needed to be overcome compared to typical LPR measurements 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,[4] it was decided that LPR 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 LPR 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 LPR measurement, a wetted sponge is used as the electrolyte and the barnacle cell is held against the pipeline.

Lastly, the effect of sponge wetting liquid on the measured R_p values was also examined. The intent of these tests was to explore the sensitivity of the approach to different electrolyte compositions to ensure that the method is robust. Ideally, a field deployable methodology would not be dependent upon highly precise chemistries for wetting the sponge because reagent-grade chemicals and deionized water may not be readily available. Thus, a range of different electrolytes that might be readily available or easily obtained was studied.

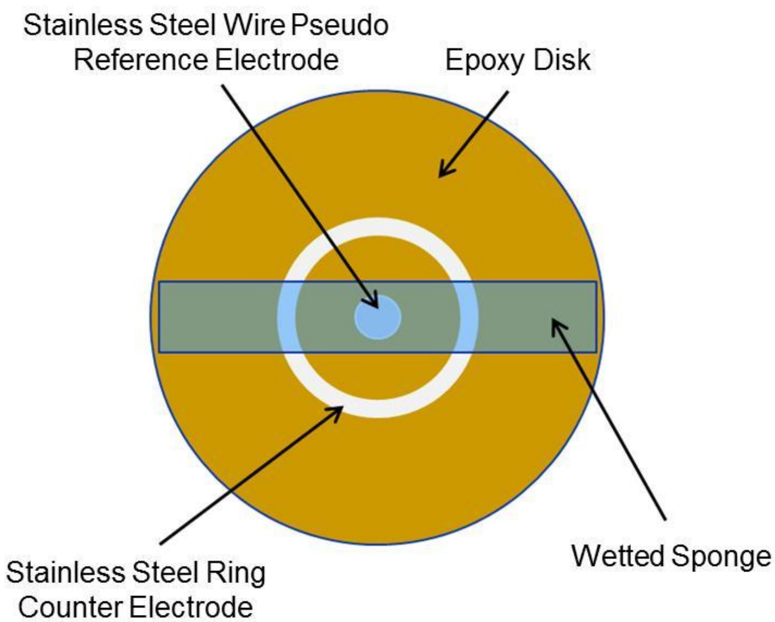

Figure 2. Schematic illustration of barnacle cell (plan view).

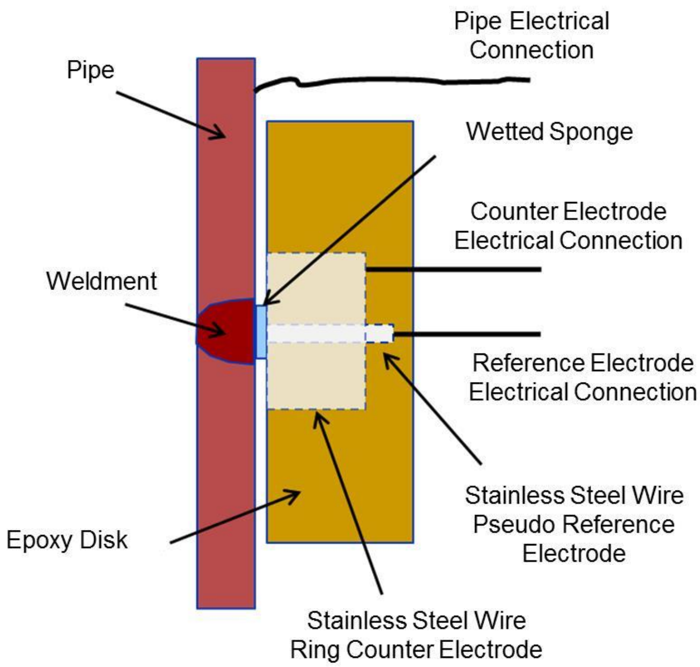

Figure 3. Schematic illustration of barnacle cell (cross section view) and its use in making LPR measurements.

3.0 RESULTS AND DISCUSSION

The purpose of this effort was to develop a robust, rapid, non-destructive, field-deployable method that can quantify SSWC susceptibility on operating pipelines. Tests were performed examining two possible approaches to accomplish this goal. The first approach was to make local corrosion potential measurements of the steel weldment and base metal to investigate if significant, reproducible differences in potential were evident. The second approach examined making LPR measurements using a barnacle cell with a wetted sponge as the electrolyte. These approaches are discussed below.

3.1 Potential Difference Measurements

The results of potential difference measurements for the weldment and base metal of four different steels are shown in Figure 4 and Figure 5. Tests were conducted using tapwater and 3.5% NaCl solution to wet the contact sponge. The data presented represent the average of 15 different potential measurements and the error bars show the standard deviation for each set. As can be seen, the measured corrosion potentials for the weldment and base metal, using either tapwater or NaCl, were nearly identical or, at a minimum, had overlapping data scatter bands. As will be discussed below, Steels A, B, and C are all susceptible to SSWC and Steel D is not susceptible. Examination of the corrosion potentials shows no significant difference between these materials. The typical scatter in the corrosion potential measurements was less than ± 30 mV in all cases, but because the average potentials were essentially the same, this approach does not seem capable of determining SSWC susceptibility.

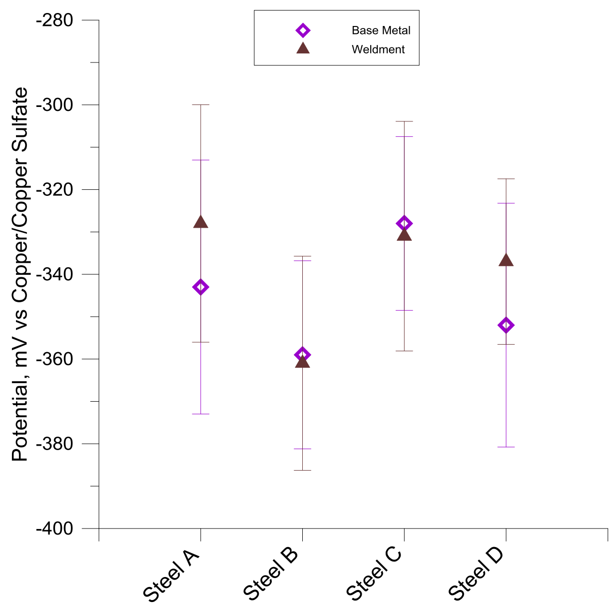

Figure 4. Measured corrosion potentials for the base metal and weldment of four different steels using a copper/copper sulfate reference electrode and a tapwater-wetted sponge.

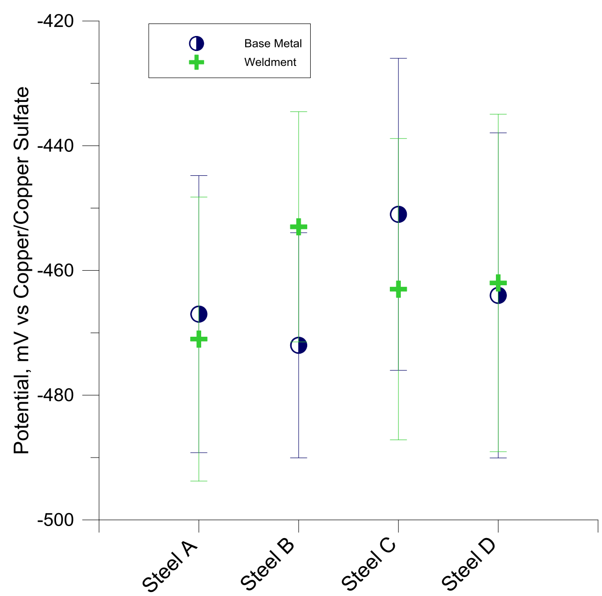

Figure 5. Measured corrosion potentials for the base metal and weldment of four different steels using a copper/copper sulfate reference electrode and a 3.5 wt% NaCl solution-wetted sponge.

3.2 Barnacle Cell LPR Measurements

To verify that the LPR measurements conducted using the barnacle cell would provide valid results, a series of evaluation tests was initially performed. In these tests, the polarization resistance (R_p) of the base metal of four steels was measured using the barnacle cell and compared against the R_p measured using a traditional electrochemical corrosion test cell. Tests were conducted using a 1,000 ppm sodium sulfate solution to wet the sponge and as the electrolyte for the test cell. The sodium sulfate solution was chosen because it was expected to provide sufficient conductivity to make LPR measurements while not being highly aggressive and causing significant general corrosion. In Figure 6, the average R_p measured from 5 replicate tests using the barnacle cell and 5 replicate R_p measurements using LPR with a traditional test cell are shown. The results indicate that a linear relationship exists between the two data sets, though a one-to-one correlation is not present. The barnacle cell R_p values are consistently greater than those measured using a traditional test cell, by a factor of approximately 1.34X. The cause of the deviation was not investigated but could be due to a higher effective solution resistance for a wetted sponge compared to a bulk liquid environment. The consequence of the barnacle cell giving higher R_p values is that the corrosion rate measured using this approach will tend to be non-conservative and underrepresent the actual corrosion rate. As a result, only the ratio of the polarization resistance of the base metal compared to the weldment was used instead of the actual corrosion rate. For SSWC susceptible pipe, the R_p measured for the weldment would be expected to be lower than that measured for the base metal. A typical difference of 2X or greater was used as a good indication of susceptibility, which would indicate that the corrosion rate of the weld metal is approximately twice as high as that of the base metal.

The results of the barnacle cell were also compared to the grooving factor determined from pre-screening tests using the test method developed by Masamura and Matsushima.[3] Steels A, B, and C were all found to be susceptible to SSWC, with grooving factors above 5 in the grooving corrosion tests, as shown in Figure 7. Steel D was found to not be susceptible to SSWC, with a grooving factor of one. In addition, Figure 7 shows that the results of the base metal R_p to weldment R_p ratio obtained using the barnacle cell correlated reasonably well with the grooving factor from the grooving corrosion tests. The barnacle cell tended to slightly under-predict the grooving factor from the deepest corrosion noted on the weldment. The magnitude of the under prediction, however, is relatively small and, in most cases, the range of values measured using the barnacle cell did coincide with a one-to-one correlation.

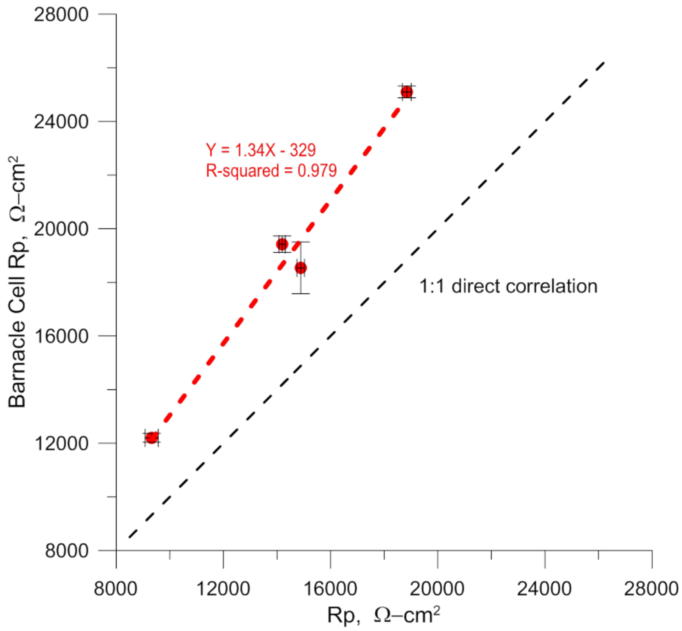

Figure 6. R_p measured using the barnacle cell compared to measurements made using LPR with an electrochemical corrosion test cell. Error bars show standard deviation from five replicate tests.

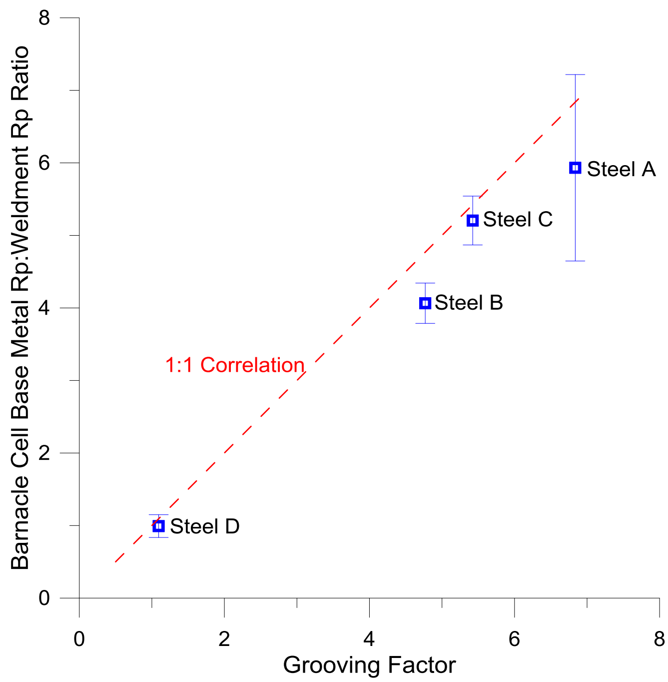

Figure 7. Comparison of the base metal R_p to weldment R_p ratio from the barnacle cell to the grooving factor measured using the approach of Masamura and Matsushima.[3]

The results of the LPR measurements of the weldments and base metals of seven different steels, using the barnacle cell, are shown in Figure 8 to Figure 11. In these tests, the barnacle cell was held against the material using a wetted sponge as the electrolyte. In Figure 8, the measured R_p using the barnacle cell with a tapwater-wetted sponge is shown. The data points represent the average of five measurements at different locations for each material phase. The error bars show the standard deviation for the five measurements. From an examination of the data, it can be noted that four of the seven steels investigated showed significant differences between the R_p measured for the base metal compared to the weldment (Steels A, B, C, and E). For one steel (F), the R_p of the weldment was less than, but close to, the value of that for the base metal. The remaining two steels (D and G) had weldment R_p values that were nominally the same as the base metal.

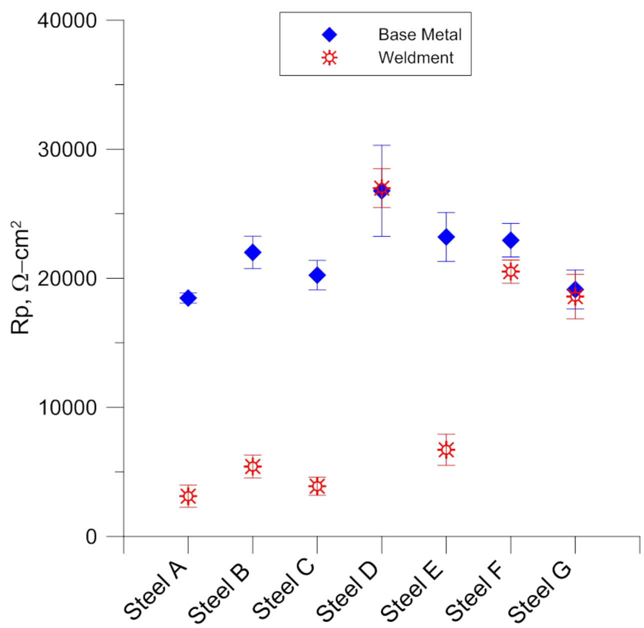

Figure 8. Polarization resistance of base metal and weldment for seven different steels using the barnacle cell with a tapwater-wetted sponge.

When the relative ratio of the average base metal and weldment R_p values are analyzed, it is clear that Steels A, B, C, and E are susceptible to SSWC (Figure 9). If the same criteria used by Duran et al.,[2] 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 R_p to weldment R_p ratios near unity. All of the susceptible materials show ratios greater than 3.5. That is, the average R_p of the base metal was at least 3.5X greater than the average weldment R_p. 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. The results from using barnacle cell method to characterize Steel E, corresponded to what was observed for this steel during pipeline service. That is, the pipeline fabricated using Steel E experienced SSWC in-service. Though not tested for SSWC susceptibility, Steels F and G are more modern steels and are not expected to be susceptible to SSWC because the ERW seams are usually normalized, result in weld zone microstructures that are similar to base metal microstructures.

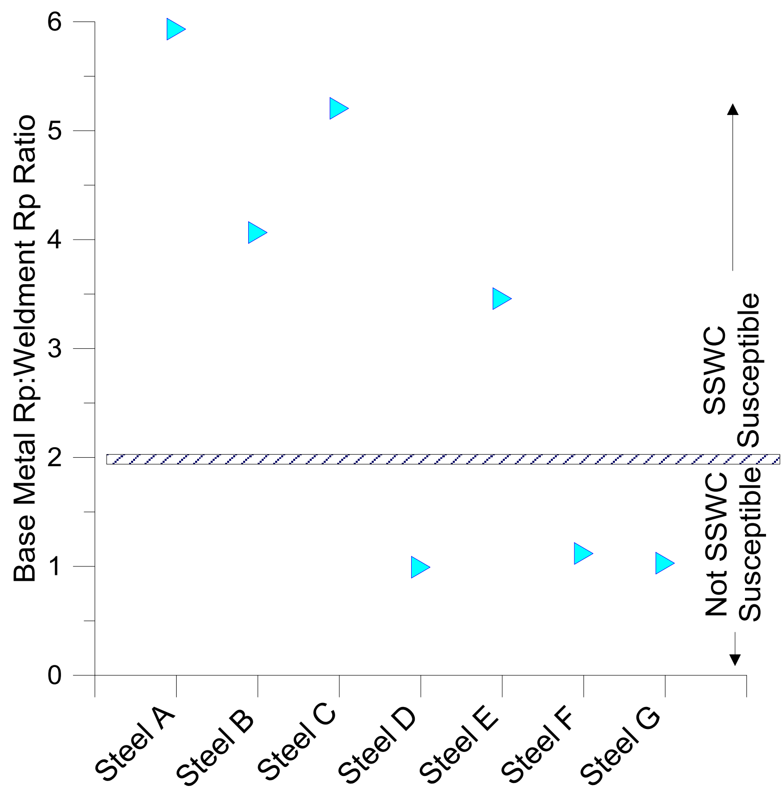

Figure 9. Base metal R_p to weldment R_p ratio for seven different steels investigated. High ratio values (>2) indicate susceptibility to SSWC.

To evaluate the sensitivity of the barnacle cell measurements to the sponge wetting solution, a series of tests on two SSWC susceptible pipe steels was conducted (Figure 10 and Figure 11). The sponge wetting solutions included a sodium chloride salt solution (3.5wt%), tapwater, a sodium sulfate salt solution (1000 ppm), and a sports drink. The sodium chloride and sodium sulfate solutions represent well-controlled and defined chemistries that are readily available in corrosion laboratories but are perhaps less than ideal for a field-deployable testing methodology, though using a tablespoon of table salt per quart of water should be easily achievable. As a result, tapwater and a sports drink were also tested. In Figure 10, the average and standard deviation of the ratio of the base metal R_p to the weldment R_p for Steel A is shown. The average and standard deviation were based on conducting five replicates for each sponge wetting solution. The average of the R_p ratio for the different solutions were nearly the same. The only exceptions might be that the sports drink showed slightly lower ratio values (meaning the R_p values for the base metal and weldment were closer together) and sodium chloride showed slightly higher ratio values (meaning the R_p values for the base metal and weldment were farther apart). Figure 11 shows the results for similar tests conducted on Steel B. The results for these two steels indicate that the sponge wetting solution may perhaps have a small influence on the results in terms of the relative values of the base metal and weldment R_p. However, in general, the differences were relatively small. Though not conclusively proven, these results seem to imply that nearly any wetting solution could be utilized for conducting the SSWC susceptibility field test. This leads to a significant amount of flexibility in the field test method as well as allowing some simplification of the test method.

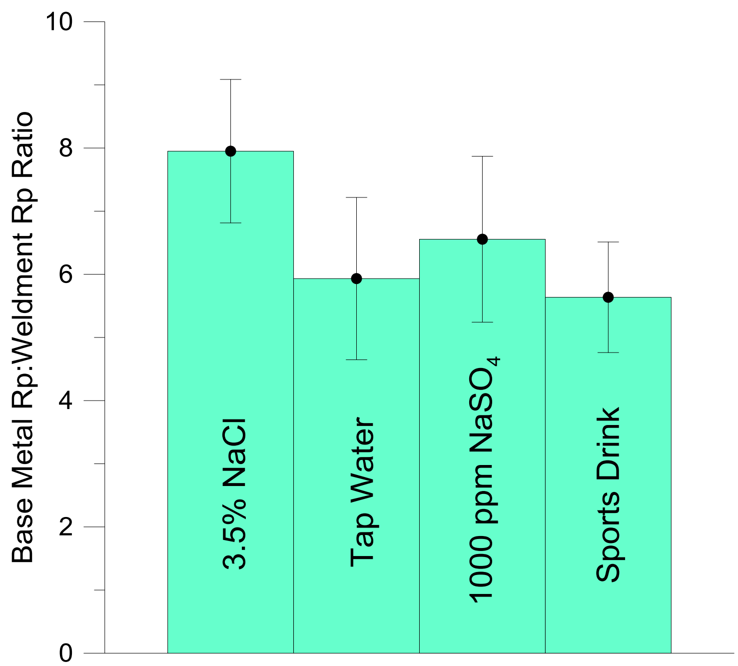

Figure 10. Base metal R_p to weldment R_p ratio for Steel A using different sponge solutions.

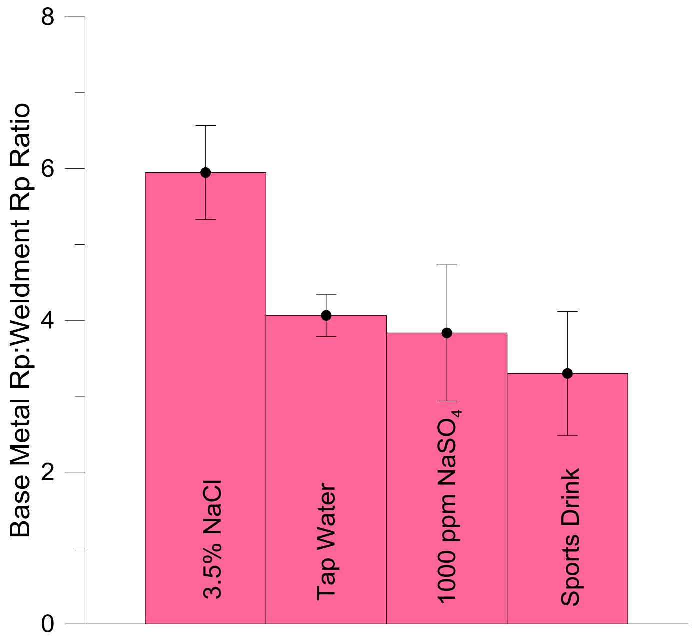

Figure 11. Base metal R_p to weldment R_p ratio for Steel B using different sponge solutions.

4.0 SUMMARY AND CONCLUSIONS

In the present work, the main purpose was to develop a robust, rapid, non-destructive, field-deployable SSWC susceptibility test methodology that can quantify SSWC susceptibility on operating pipelines. Because differences in corrosion potential for the weldment and base metal have been cited as the cause for SSWC, initial tests were conducted to examine the possibility that differences in the measured corrosion potentials of the weldment and base metal might be large enough to distinguish between SSWC susceptible and non-susceptible pipe. However, testing showed that there is no significant difference in corrosion potential between the base metal and the weldment for pipe steels, in general, and for pipe steels that are susceptible to SSWC. This finding indicates that differences in the corrosion kinetics between the weldment and the base metal are the primary cause of SSWC. The alternative method developed is based on this corrosion mechanism.

This new method utilized a barnacle cell to conduct LPR 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. Several alternative solutions were evaluated to wet the sponge that acts as the electrolyte for conducting the LPR measurements. Based on the testing conducted, a simple salt solution (table salt + water, ~ 3.5% NaCl) is likely to give the best sensitivity to SSWC. Using the barnacle cell, it was shown that SSWC susceptible and non-susceptible pipe could be easily distinguished. Further evaluation of this approach is recommended in order to incorporate it into existing standards or to develop a new standard. To accomplish the development of a standard, the number of tests for a given pipeline necessary to have high confidence (e.g., 95%) in assessing SSWC susceptibility would also have to be conducted.

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