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Final Report

Task 3.3 – Selective Seam Weld Corrosion Cathodic Protection Effectiveness Evaluation

Pipeline and Hazardous Materials Safety Administration
U.S. Department of Transportation
Washington, DC 20590

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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 defects can exist due to a variety of reasons and causes. Lack of fusion weld defects can originate during the initial pipe fabrication (long seal 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, the effectiveness of cathodic protection in mitigating SSWC was investigated using three steels and one soil. Based on previous testing (Task 3.2 of this project), one steel was known to not be susceptible to SSWC (i.e., the corrosion rate of the weldment and base metal were comparable); whereas, two had been shown to be susceptible to SSWC (i.e., the corrosion rate of the weldment was significantly greater than the base metal). Long-term soil box testing was conducted evaluating the effectiveness of two cathodic protection criteria (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) in mitigating SSWC.

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 periods. On potentials, more negative than -850 mV, were maintained in this testing. Similarly, in the testing of the 100 mV polarization criterion, that level of polarization was not consistently achieved.

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. To achieve adequate protection, SSWC susceptible pipe needs to have higher levels of CP applied. 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. The research findings in Task 3.2 of this project (Selective Seam Weld Corrosion Test Method Development) found that the 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 in 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 mV 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 and predictions 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.

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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 seam weld 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 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 defects 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). To characterize the relative corrosion rate of the seam weld 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, 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.[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, the tests used to evaluate the effectiveness of standard cathodic protection (CP) levels are presented and discussed. The objective of this effort was to determine if the standard CP protection criteria listed in NACE SP0169-2007[3]; a negative polarized potential of at least

850 mV relative to a saturated copper/copper sulfate reference electrode (-850 mV off-potential) or a minimum of 100 mV of cathodic polarization (100 mV polarization) are effective in mitigation SSWC on susceptible pipe steel material.

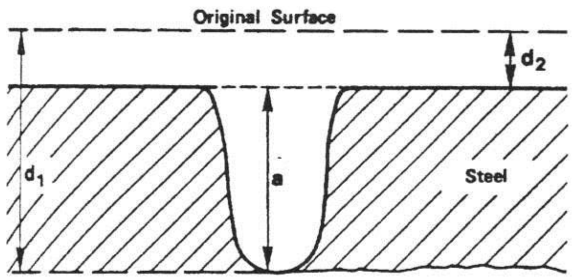

Figure 1. Schematic illustration of SSWC and the parameters used to calculate the grooving factor.[2]

2.0 APPROACH

To evaluate the effectiveness of CP on SSWC susceptible pipe material, a set of soil boxes was created. The dimensions of the boxes were approximately 2 feet × 1 foot × 1 foot. A schematic of the electrodes in the soil boxes is shown in Figure 2. In total, six soil boxes were constructed. The steels were chosen based on previous work conducted to develop a field-applicable method to determine SSWC susceptibility. Based on that work,[4] three pipe steels were selected for long-term CP effectiveness testing. Two steels (labeled B and C in[4] and also labeled B and C in this report to maintain consistency) were observed to be susceptible to SSWC and had grooving factors of 4.8 and 5.4 based on long-term testing. One steel, (labeled D in [4] and also in this report to maintain consistency) was observed to not be susceptible to SSWC and had a grooving factor of 1.0 based on long-term testing.

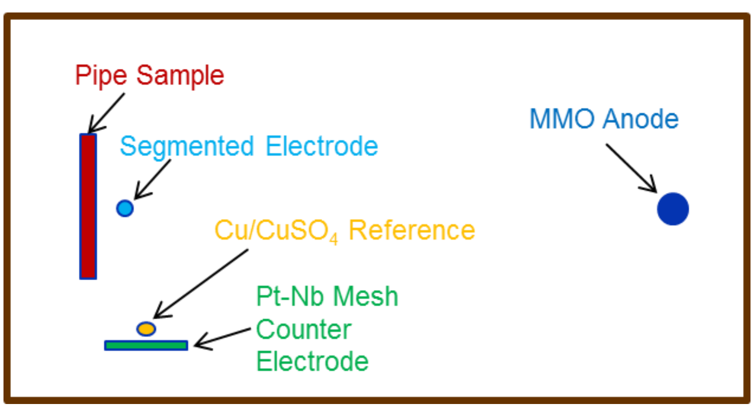

Figure 2. Schematic diagram of soil box used for CP testing.

The soil boxes were filled with Dublin, Ohio, USA soil to which water was added on a weekly basis to maintain a roughly constant conductivity over time. The soil pH was near 7.1 and the soil resistivity was measured to be between 830 to 1045 Ω-cm. In each soil box, the testing system consisted of 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 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.

All potentials were measured using copper-copper sulfate reference electrodes and a NIST calibrated Fluke Model 289 digital voltmeter equipped with a calibrated CC Technologies EI-120 electrochemical interface. The electrochemical interface was used to increase the input impedance of the multimeter and minimize any polarization effects on the test samples during the measurements. The copper/copper sulfate reference electrodes were newly purchased MC Miller RE-375 pencil electrodes. The new reference electrodes were compared to our NIST traceable calibrated RE-375 pencil electrode and confirmed to be within calibration (± 10 mV).

To study the effect of CP on SSWC, a series of segmented electrodes was created, as shown in Figure 3. 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 14 AWG solid copper wire. A coating (3M 323 epoxy) was used to mask off each spot weld. All samples and wires were encapsulated in an Epon™ material with the exception of the exposed steel test surfaces, which were polished to an 800 grit finish. The insulated copper wire ends protruded outside of the Epon™ for connecting to the CP circuit.

The steel segments were electrically isolated from each other for electrochemically determining corrosion rates for the weldment, HAZ, and base metal separately. After assembly of the segmented electrodes, resistance measurements were conducted between each segment to ensure that the segments were not shorted together and were in fact isolated. By having the base metal, HAZ, and weldment isolated, the corrosion rate or polarization resistance of each could be independently measured and then compared. Thus, if a steel were 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 were susceptible to SSWC, then the HAZ and weldment would be expected to show higher corrosion rates than that of the base metal.

While exposing the segmented electrode to CP, all three segments of the electrode were coupled together and were also coupled to the pipeline surrogate sample. The segmented electrode was positioned in close proximity to the surrogate pipe sample in order to aid in exposing the segments to changes in the soil conditions resulting from the application of CP. This segmented electrode approach was critical in order to ascertain CP effectiveness for the SSWC susceptible weldments because the weldments typically constitute a small fraction of the overall pipeline area. Fabrication of a sample in which the weldments, HAZ, and base metal were together would produce results that reflected the relative areas of the regions.

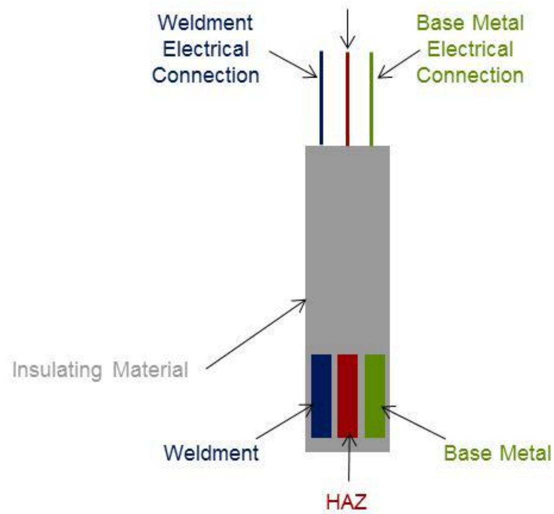

Figure 3. Schematic diagram of segmented electrode used to study SSWC.

In each soil box, a separate steel material-CP level combination was tested. To determine the polarization resistance of each segment over time, electrochemical impedance spectroscopy (EIS) was utilized. Because determination of accurate polarization resistance values in high resistance environments can be challenging using linear polarization resistance, EIS is a widely known methodology used to obtain polarization resistance values under these conditions. In traditional EIS testing, a small amplitude AC voltage sine wave of 10 mV is imposed on the sample of interest over a range of frequencies and the resultant current response is then measured. For this measurement, a reference electrode is used for the potential and a counter electrode (in this case a Pt-Nb mesh) is used to supply and measure current. The potential sine wave is centered at the corrosion potential. In the present case, just prior to EIS testing the instant-off potential for the individual electrode segments was measured by interrupting the connection to the CP system. The second displayed potential on the Fluke digital voltmeter was recorded as the off-potential. After depolarizing the segment of interest, EIS was then conducted to obtain the polarization resistance. This measurement provides an indication of the effect of environmental polarization that results from the soil environment changing over time due to the applied CP. Observation of the environmental polarization increasing is an indication of a decrease in the corrosion rate. 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. 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 during the exposure period. The maximum metal loss (maximum depth) was measured using 3-D optical profilometry and the corrosion rate was calculated using the entire testing time and assuming that corrosion occurred at a uniform, constant rate during the entire exposure.

3.0 RESULTS AND DISCUSSION

Over the course of approximately 13 months, sets of segmented electrodes constructed from different line pipe steels was buried in soil boxes and CP was applied following the two criteria. The experimental results for this effort are summarized in Figure 4 to Figure 22. In these figures, the measured polarization resistance of the weldment, HAZ, and base metal for three different steels are presented along with post-test photo documentation of the appearance of the samples and estimated corrosion rates. The polarization resistance values from EIS measurements can be used to calculate the corrosion rate (in the same fashion as linear polarization measurements) if the proportionality constant, B, is known or if the anodic and cathodic Tafel slopes are known. In order to remove any possible ambiguity and uncertainty associated with assuming different values for the Tafel slopes, the polarization resistance measured was used as the metric for comparison instead of calculating a corrosion rate. Recall that the corrosion rate is inversely proportional to the polarization resistance. Thus, low polarization resistance values indicate higher corrosion rates; whereas, high polarization resistance values indicate lower corrosion rates.

As described above, the corrosion rates estimated from EIS measurements only account for the environmental component of CP; that is, the effect of the change in the environment at the pipe surface as a result of the CP on the corrosion rate at the new corrosion potential associated with the environmental change. The other component of CP, potential polarization, is not accounted for in the EIS measurements. Therefore, the results of this analysis are conservative. On the other hand, the metal loss measurements consider both forms of polarization.

The results presented below are organized by the three materials studied. The corrosion rate estimates based on metal loss measurements for the three steels are presented together in Section 3.4.

3.1 Linepipe Steel D – Non-SSWC Susceptible

The results from long-term soil box testing to study the effectiveness of CP on non-SSWC susceptible Linepipe Steel D are presented in Figure 4 –Figure 9. This material was chosen as a baseline control material for the tests to ensure that the approach was effective and did not induce or create any bias. In Figure 4 the measured instant-off potentials for the weldment, HAZ, and base metal with applied CP in the test to evaluate the 100 mV polarization criteria are shown. The initial measured corrosion potentials in the soil prior to the application of CP are also presented in Figure 4 as the data at zero time. Also presented are the on-potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -690 to -700 mV vs. copper/copper sulfate. After some initial changes in potential in the first two months, the on-potential was stabilized to values near -800 mV vs. copper/copper sulfate. The measured off-potentials also tended to stabilize after the first two months with values typically ranging between -770 and -790 mV, indicating that 100 mV of polarization from the original corrosion potential was not consistently achieved.

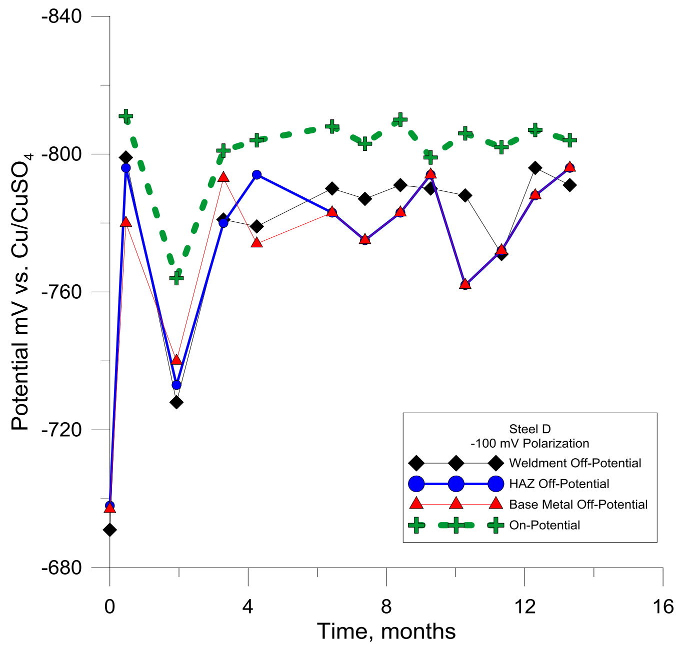

Figure 4. Instant-off and on potentials for Steel D in the tests of the 100 mV polarization criterion.

In Figure 5, the measured instant-off potentials for the weldment, HAZ, and base metal with applied CP in the test of the -850 mV off-potential criteria are shown. The initial measured corrosion potentials in the soil prior to the application of CP are also presented in Figure 5 as the data at zero time. Also presented are the on potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -690 to -720 mV vs. copper/copper sulfate. The on potentials were generally stable at values more negative than -850 mV with a few noted occasions. The measured off-potentials were typically stable, ranging between -805 and -840 mV depending on the on potential. The off-potential measurements indicate that the stated -850 mV criteria was initially achieved but, over time, the potentials drift down. Even though the off-potentials drifted down, they were still within 10-20 mV of -850 mV.

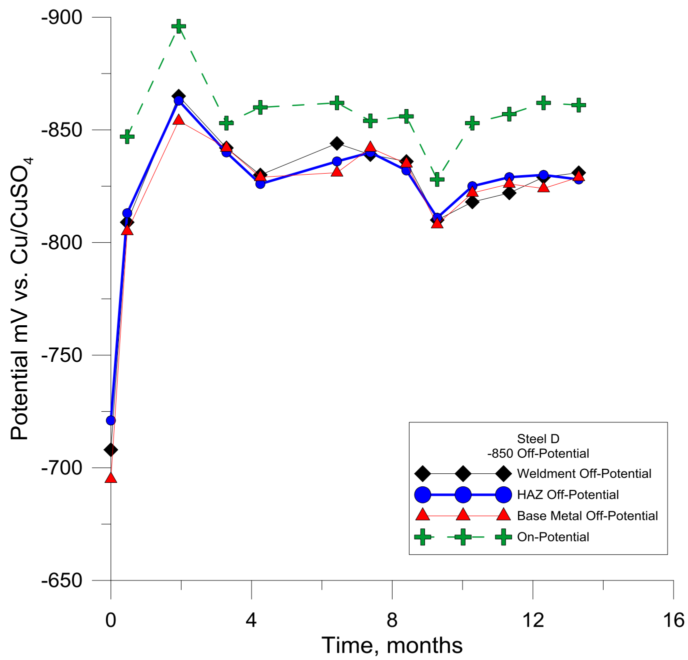

Figure 5. Instant-off and on potentials for Steel D in the tests of the -850 mV off-potential criterion.

In Figure 6, the measured polarization resistance for the weldment, HAZ, and base metal for Steel D in the test of the 100 mV polarization criterion are presented. The initial polarization resistance values prior to the application of CP were approximately 15-18 kΩ-cm^2 for the three steel microstructures.

After the application of CP, the depolarized polarization resistance values did not change immediately. However, after two months, the polarization resistance values measured had significantly increased to values greater than 42 kΩ-cm^2, which would indicate an approximately 2X decrease in corrosion rate. Over longer time periods, the polarization resistance values trended higher attaining values in excess of 90 kΩ-cm^2 (which would roughly correspond to a 6-fold decrease in corrosion rate). This decrease is smaller than the ideal case of a 10-fold decrease or better. However, these measurements do not take credit for potential polarization, which will further decrease the corrosion rate. As can be seen, there was no appreciable differences in the measured polarization resistance values for the three steel microstructures for this material. This is expected because this linepipe steel was not found to be susceptible to SSWC. These results also indicate that the approach used is valid.

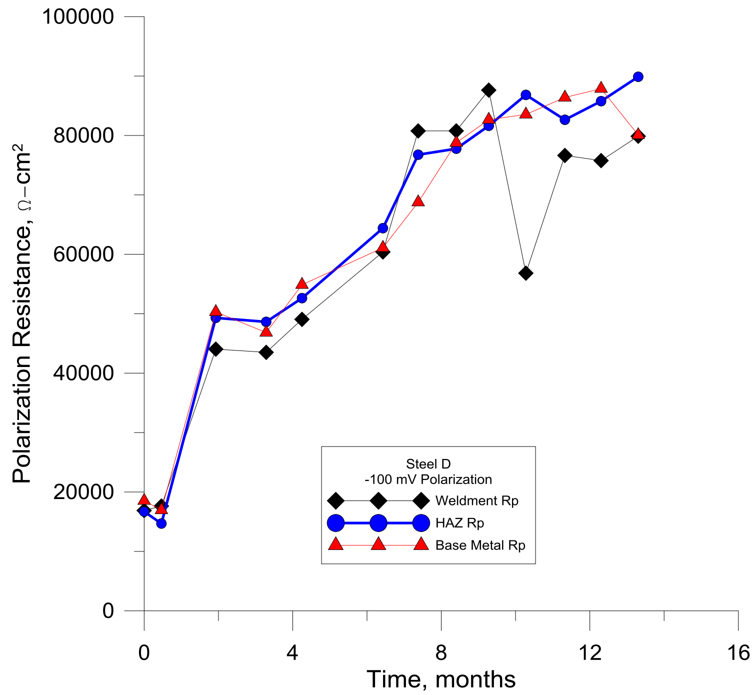

Figure 6. Polarization resistance values for Steel D weldment, HAZ, and base metal in the tests of the 100 mV polarization criterion.

In Figure 7, the measured polarization resistance for the weldment, HAZ, and base metal for Steel D in the test of the -850 mV off-potential criteria are presented. The initial polarization resistance values prior to the application of CP were approximately 10-17 kΩ-cm^2 for the three steel microstructures. After the application of CP, the polarization resistance values did not change immediately. After two months, the polarization resistance values measured had significantly increased to values approximately 90 kΩ-cm^2. Over longer time periods, the polarization resistance values did not seem to increase and generally stayed at values between 90 and 98 kΩ-cm^2. As was seen for the samples in the 100 mV polarization tests, there were no appreciable differences in the measured polarization resistance values for the three steel microstructures.

The post-test appearances of the samples are shown in Figure 8 and Figure 9. Though it appears that significant corrosion has taken place, post-test cleaning and examination of the samples revealed only limited metal loss (see Section 3.4).

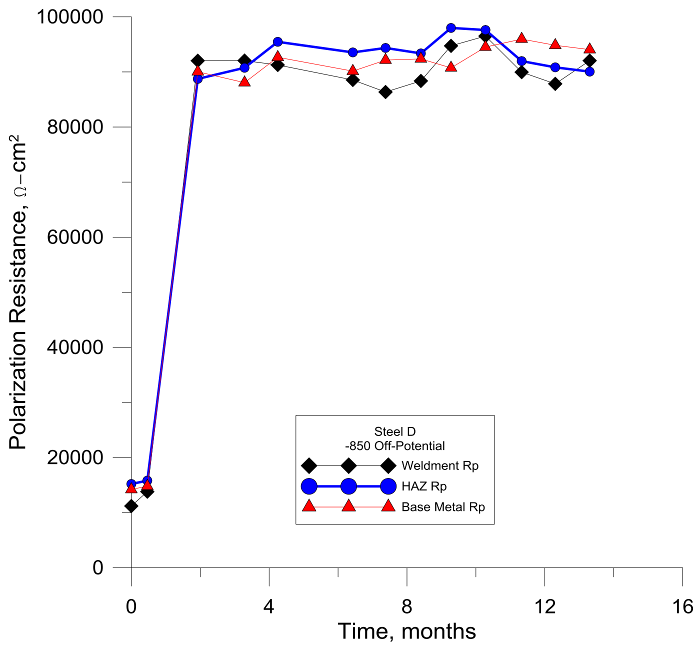

Figure 7. Polarization resistance values for Steel D weldment, HAZ, and base metal in the tests of the -850 mV off-potential criterion.

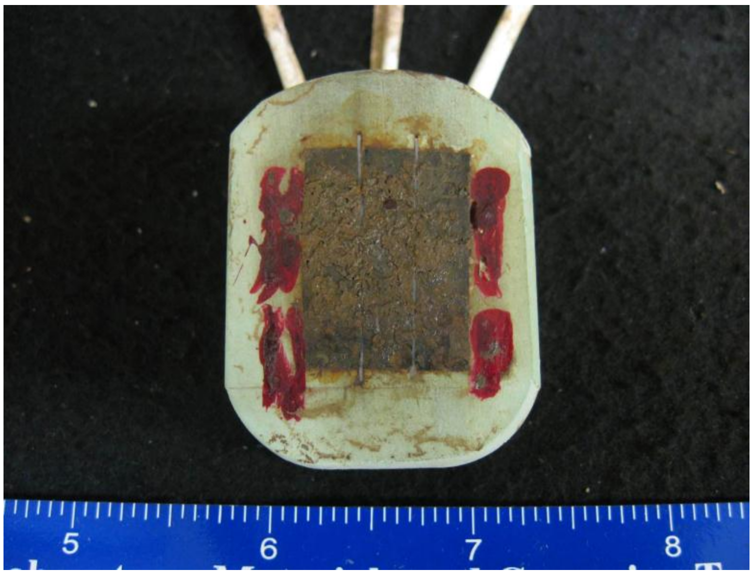

Figure 8. Post-test appearance of Steel D segment electrode after 13 months in the tests of the100 mV polarization criterion.

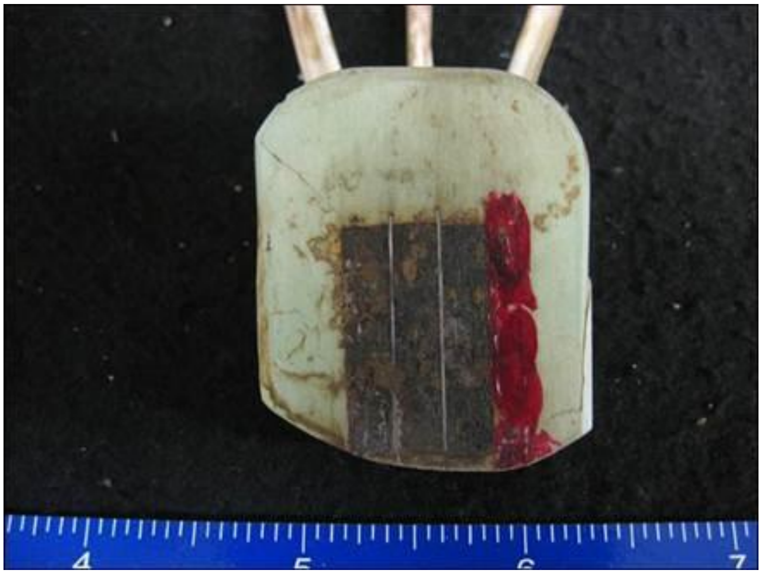

Figure 9. Post-test appearance of Steel D segment electrode after 13 months in the tests of the -850 mV off-potential criterion.

3.2 Linepipe Steel B – SSWC Susceptible

The results from long-term soil box testing to study the effectiveness of CP for SSWC susceptible Linepipe Steel B are presented in Figure 10 – Figure 15. This material was selected for testing because it showed susceptibility to SSWC. In Figure 10, the measured instant-off potentials for the weldment, HAZ, and base metal are shown for the test of the 100 mV polarization criterion. The initial measured corrosion potentials in the soil prior to the application of CP are also shown as the data at zero time. Also presented are the on potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -690 to -715 mV vs. copper/copper sulfate. After the initial application of CP, the off-potentials trended to more negative values eventually steadying at values near -780 mV for all three steel microstructures, indicating that 100 mV of polarization from the original Ecor was not consistently achieved. The on-potentials are also shown and were typically between -790 and -820 mV.

In Figure 11, the measured instant-off potentials for the weldment, HAZ, and base metal with applied CP in the test of the -850 mV off-potential criterion are shown. The initial measured corrosion potentials in the soil prior to the application of CP are also presented as the data at zero time. Also presented are the on potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -690 to -695 mV vs. copper/copper sulfate. The on potentials were generally stable at values more negative than -850 mV. The off potentials initially were more negative than -850 mV but drifted down to less negative values over time.

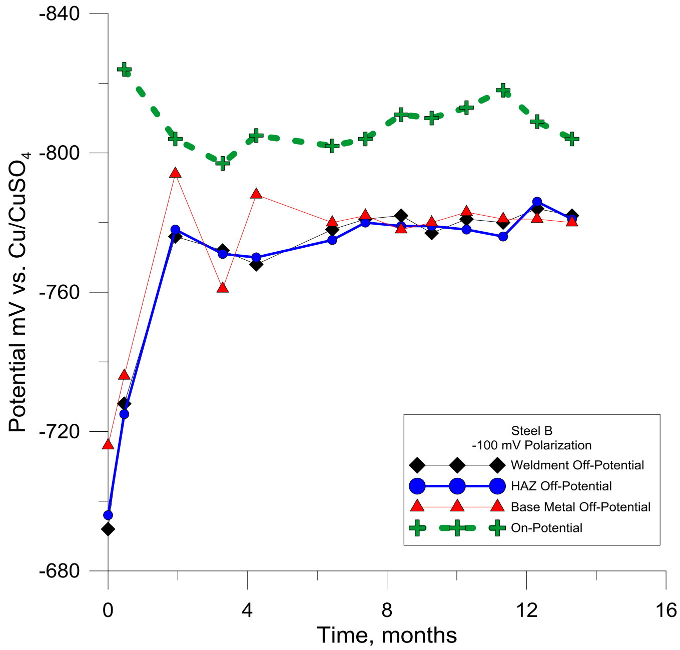

Figure 10. Instant-off and on potentials for Steel B in the tests of the 100 mV polarization criterion.

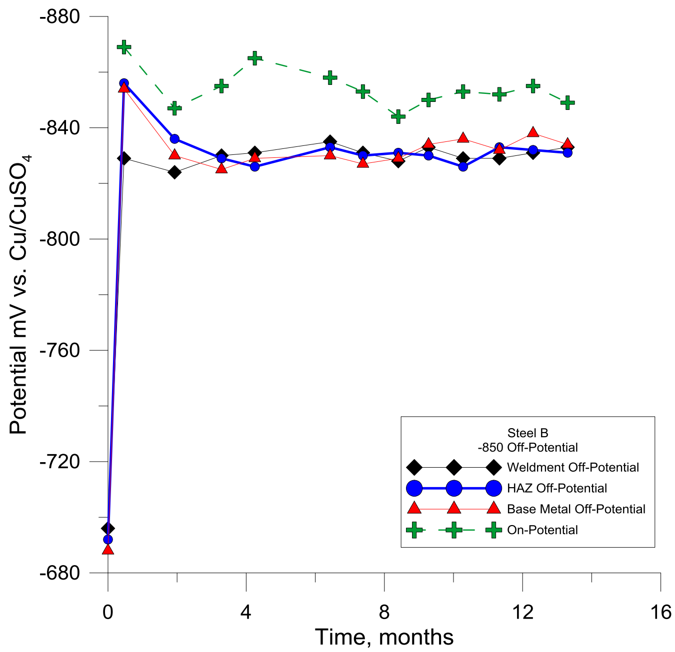

Figure 11. Instant-off and on potentials for Steel B in the tests of the -850 mV off- criterion.

In Figure 12, the measured polarization resistance values for the weldment, HAZ, and base metal for Steel B in the test of the 100 mV polarization criterion are presented. The initial polarization resistance values prior to the application of CP were approximately 9.5-20 kΩ-cm^2 for the three steel microstructures. These values are similar, if perhaps a little lower, than those measured for the non-SSWC steel (Steel D). After the application of CP, the polarization resistance values did not change immediately but generally increased over time. After approximately eight months, nominally steady state values for the polarization resistance were measured. As opposed to Steel D, where all three microstructures had similar polarization resistance values, the different microstructures for Steel B exhibited different polarization resistance values. The weldment showed the lowest polarization resistance, only attaining a steady state value near 22 kΩ-cm^2 after 13 months of polarization. The HAZ had a higher polarization resistance of around 35 kΩ-cm^2; whereas, the base metal polarization resistance was near 48 kΩ-cm^2. It is evident that, for this SSWC susceptible steel, the weldment and HAZ appear to be less protected than the base metal. It should also be noted that the Steel B base metal had polarization resistance values about half of that observed for the Steel D base metal. The observed increase in polarization resistance over time indicates that the application of CP provides some benefit in reducing the corrosion rate by continuing to alter the environment at the pipe surface in a beneficial way.

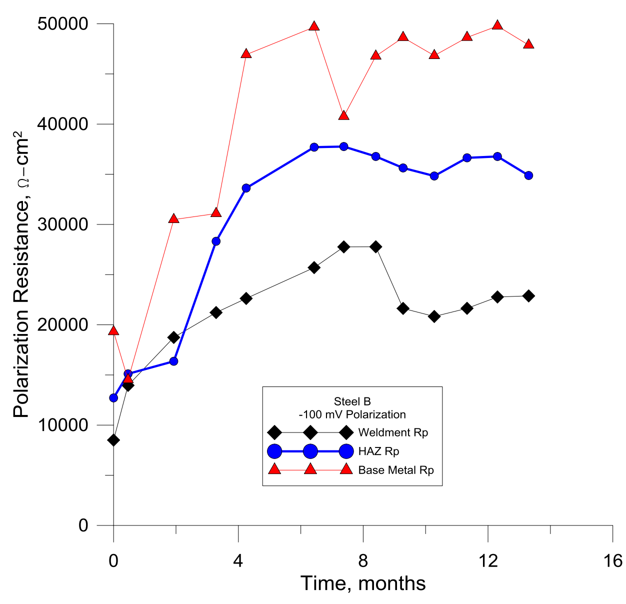

Figure 12. Polarization resistance values for Steel B weldment, HAZ, and base metal in the test of the 100 mV polarization criterion.

In Figure 13 the measured polarization resistance for the weldment, HAZ, and base metal for Steel B in the test of the -850 mV off-potential criterion are presented. The initial polarization resistance values prior to the application of CP were approximately 14-18 kΩ-cm^2 for the three steel microstructures. After the application of CP, the polarization resistance values steadily increased over the first 4-9 months and then reached nominally steady values. As was seen for the sample in the test of the 100 mV polarization criterion, the three steel microstructures did not achieve the same level of polarization resistance. The weldment showed the lowest values of approximately 32 kΩ-cm^2; whereas, the HAZ and base metal had values of approximately 38 and 49 kΩ-cm^2. Though there appears to be some difference in the attained polarization resistance values for the weldment and the HAZ, the difference between these values is relatively small and it is likely that these two microstructures showed similar performance. From this test, it is clear that, the level of CP achieved in the test was less effective for the weld and the HAZ compared to the base metal. It should be noted, however, that the application of CP was effective in increasing the polarization resistance (and thus decreasing the corrosion rate) of all three steel microstructures. Furthermore, these data suggest that the higher levels of polarization achieved in the test of the -850 mV off-potential criterion, compared to those achieved in the tests of the 100 mV polarization criterion, were more effective based on the higher polarization resistance values measured for all three steels. Caution should be exercised, however, since these results only represent a single set of long-term tests conducted in the laboratory and are not likely to represent all situations and conditions experienced by operating pipelines.

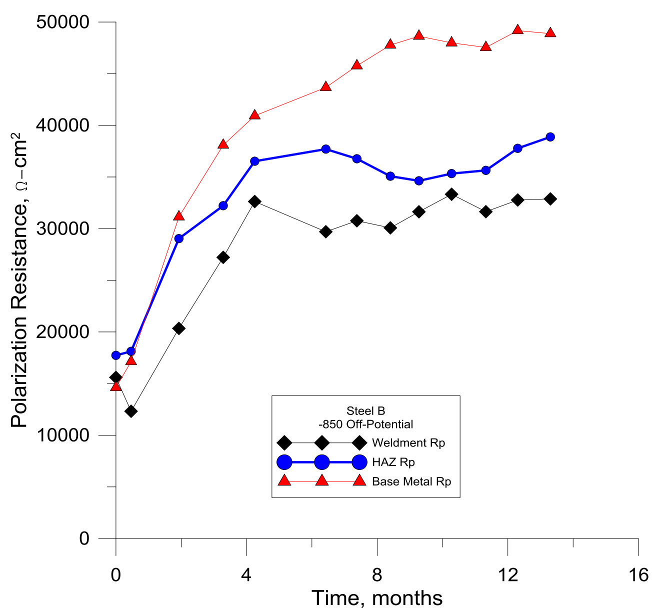

Figure 13. Polarization resistance values for Steel B weldment, HAZ, and base metal in the test of the -850mV off-potential criterion.

The post-test appearances of the samples are shown in Figure 14 and Figure 15. Though it appears that significant corrosion has taken place, post-test cleaning and examination of the samples revealed only limited metal loss (see Section 3.4).

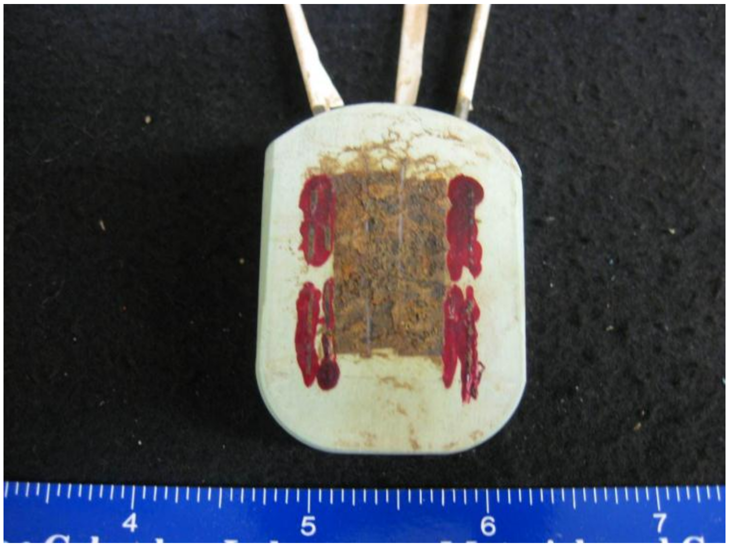

Figure 14. Post-test appearance of Steel B segment electrode after 13 months in the test of the 100 mV polarization criterion.

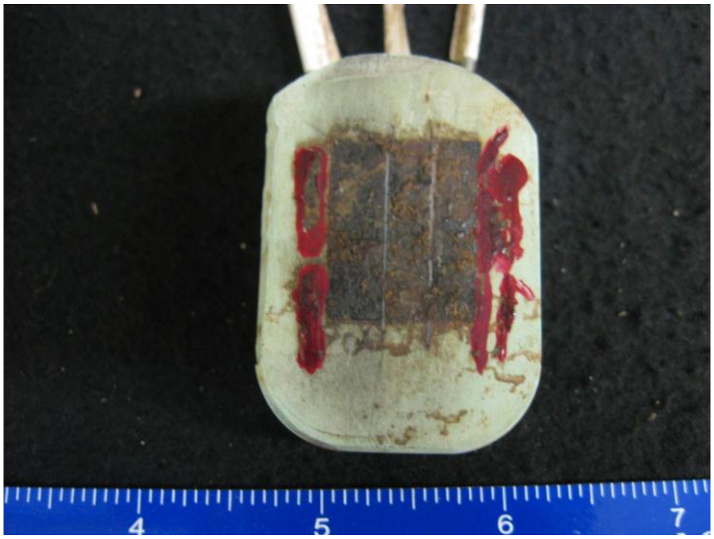

Figure 15. Post-test appearance of Steel B segment electrode after 13 months in the tests of the -850 mV off-potential criterion.

3.3 Linepipe Steel C – SSWC Susceptible

The results from long-term soil box testing to study the effectiveness of CP for SSWC susceptible Linepipe Steel C are presented in Figure 16 – Figure 21. This material was selected for testing because, like Steel B, it showed susceptibility to SSWC. In Figure 16, the measured instant-off potentials for the weldment, HAZ, and base metal with applied CP in the test of the 100 mV polarization criterion are shown. The initial measured corrosion potentials in the soil prior to the application of CP are also shown as the data at zero time. Also presented are the on potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -705 to -715 mV vs. copper/copper sulfate. After the initial application of CP, the off potentials trended to more negative values, reaching as low as -820 mV before eventually settling at values between -770 and -785 mV. Therefore, 100 mV of polarization from the original Ecor was not consistently achieved. The on potentials are also shown and were typically around -820 mV for the duration of the experiment with the exception of Month 4 where an on potential of approximately -835 mV was recorded.

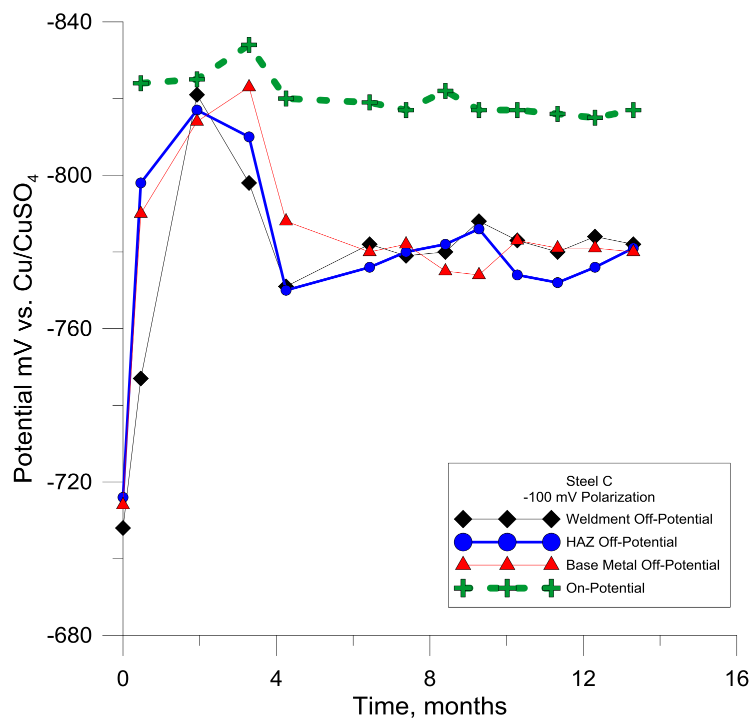

Figure 16. Instant-off and on potentials for Steel C in the tests of the 100 mV polarization criterion.

In Figure 17, the measured instant-off potentials for the weldment, HAZ, and base metal with applied CP in the test of the -850 mV off-potential criterion are shown. The initial measured corrosion potentials in the soil prior to the application of CP are also presented as the data located at zero time. Also presented are the on potentials applied to the samples. The initial corrosion potential values for the weldment, HAZ, and base metal were all in close proximity and approximately -665 to -685 mV vs. copper/copper sulfate. The on potential was generally stable at values near -860 mV. The measured off potentials initially achieved the -850 mV criteria but then drifted to less negative values (but within ~10-15 mV of -850 mV) over time.

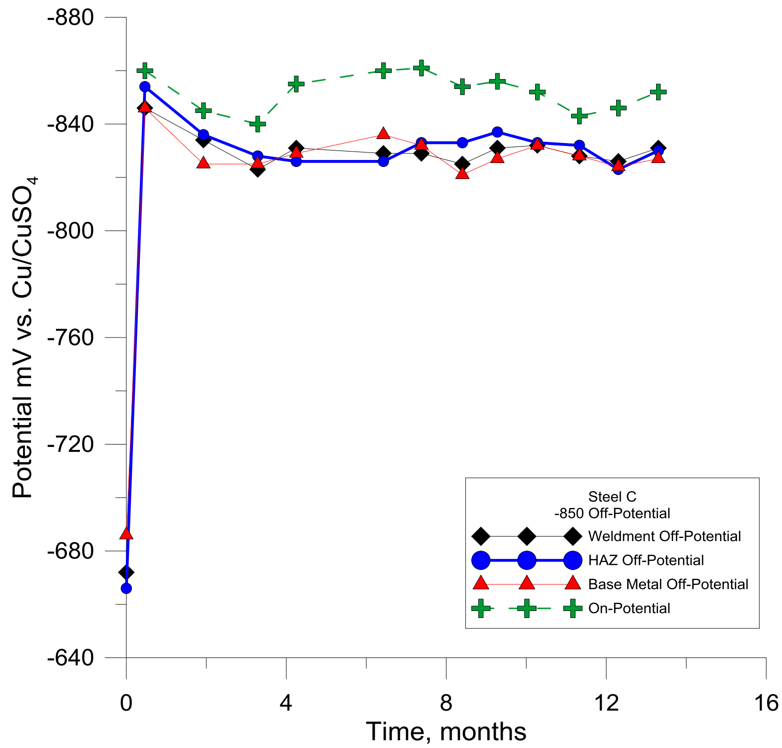

Figure 17. Instant-off and on-potentials for Steel C in the tests of the -850mV off-potential criterion.

In Figure 18, the measured polarization resistance values for the weldment, HAZ, and base metal for Steel C in the tests to evaluate the 100 mV polarization criterion are presented. The initial polarization resistance values, prior to the application of CP, were approximately 13-15.5 kΩ-cm^2 for the three steel microstructures. These values are similar to those measured for Steel B and are again perhaps a little lower than those measured for Steel D. After the application of CP, the polarization resistance values did not change immediately but did tend to trend to higher values over time. After approximately four months, nominally steady state values for the polarization resistance were measured. As was also seen for Steel B, the different microstructures for Steel C exhibited different polarization resistance values. The weldment showed the lowest polarization resistance only attaining a steady state value near 26 kΩ-cm^2 after 13 months of polarization. The HAZ had nearly the same steady state polarization resistance at around 32 kΩ-cm^2; whereas, the base metal polarization resistance was 45 kΩ-cm^2. These values for the polarization resistance are similar to those measured for Steel B. The observed increase in polarization resistance over time indicates that the application of CP provided some benefit in reducing the corrosion rate, but the increases were relatively small. As noted previously, the base metal for Steel C had polarization resistance values about half of that observed for the base metal of Steel D.

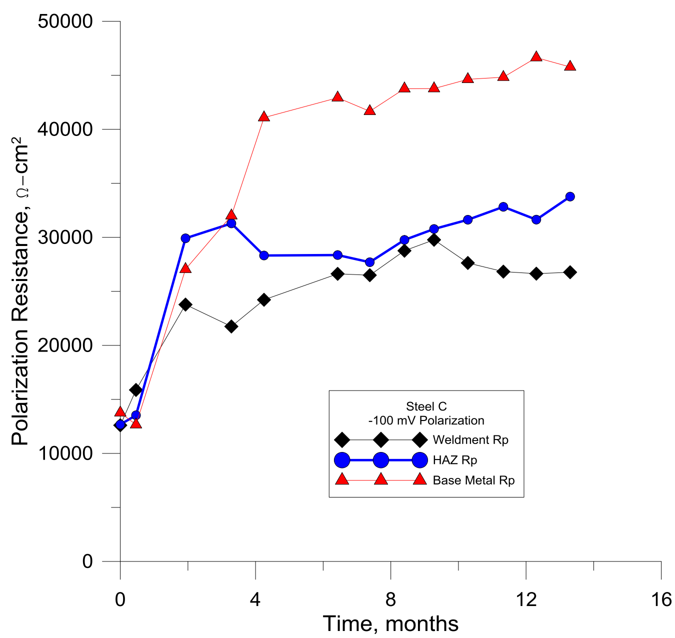

Figure 18. Polarization resistance values for Steel C weldment, HAZ, and base metal in the tests of the100 mV polarization criterion.

In Figure 19, the measured polarization resistance values for the weldment, HAZ, and base metal for Steel C in the test of the -850 mV off-potential criteria are presented. The initial polarization resistance values prior to the application of CP were approximately 12.5-17 kΩ-cm^2 for the three steel microstructures. After the application of CP, the polarization resistance values steadily increased over the first four months and then reached nominally steady values. As was seen for the sample in the test of the 100 mV polarization criterion, the three steel microstructures did not achieve the same level of polarization resistance, though they were much closer together than was observed for Steel B. The weldment still showed the lowest value of approximately 36 kΩ-cm^2; whereas, the HAZ and base metal had values of approximately 38 and 43 kΩ-cm^2. As was seen for Steel B, the CP was less effective for the weld and the HAZ compared to the base metal.

It should be noted, however, that the application of CP was still effective in increasing the polarization resistance (indicating that some benefit in decreasing the corrosion rate occurred.) of all three steel microstructures over time. Furthermore, as was seen for Steel B, the polarization resistance values for all three steel microstructures were higher in the tests of the -850 mV off-potential criterion in comparison with the tests of the 100 mV polarization criterion. Again, caution is needed since these results only represent a single set of long-term tests conducted in the laboratory and are not likely to fully represent all situations and conditions experienced by operating pipelines.

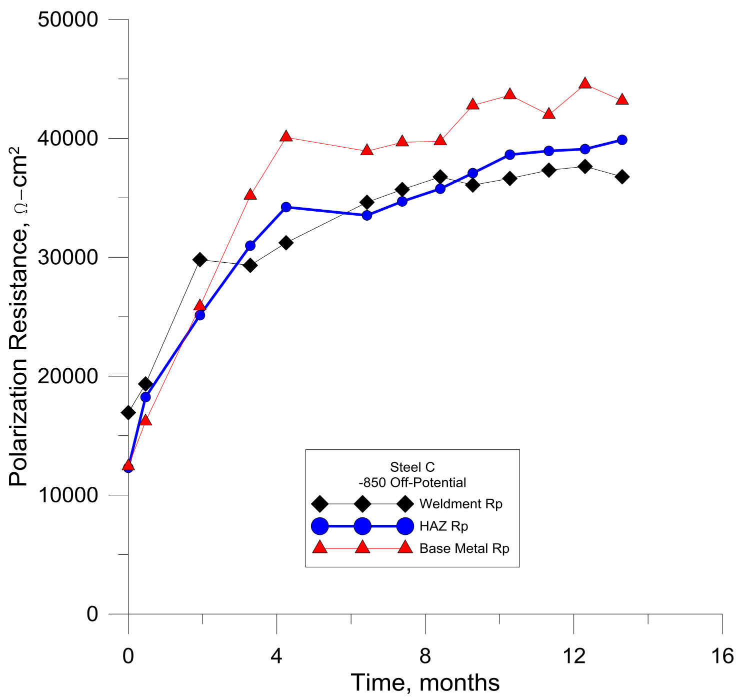

Figure 19. Polarization resistance values for Steel C weldment, HAZ, and base metal in the tests of the -850mV off-potential criterion.

The post-test appearances of the samples are shown in Figure 20 and Figure 21. Though it appears that significant corrosion has taken place, post-test cleaning and examination of the samples revealed only limited metal loss (see Section 3.4).

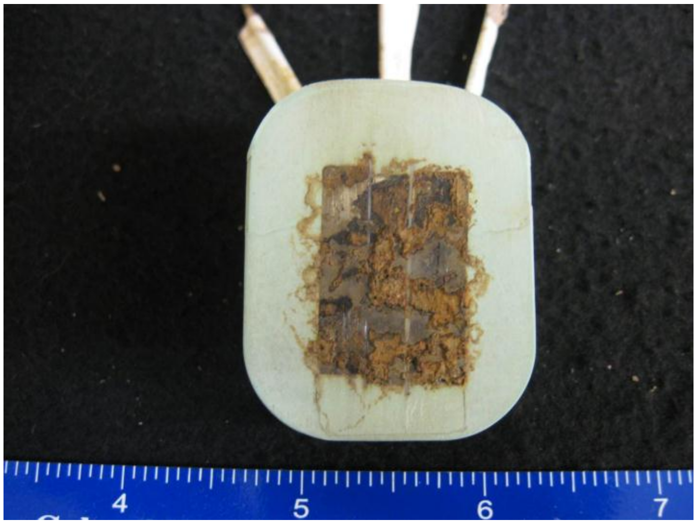

Figure 20. Post-test appearance of Steel C segment electrode after 13 months in the tests of the 100 mV polarization criterion.

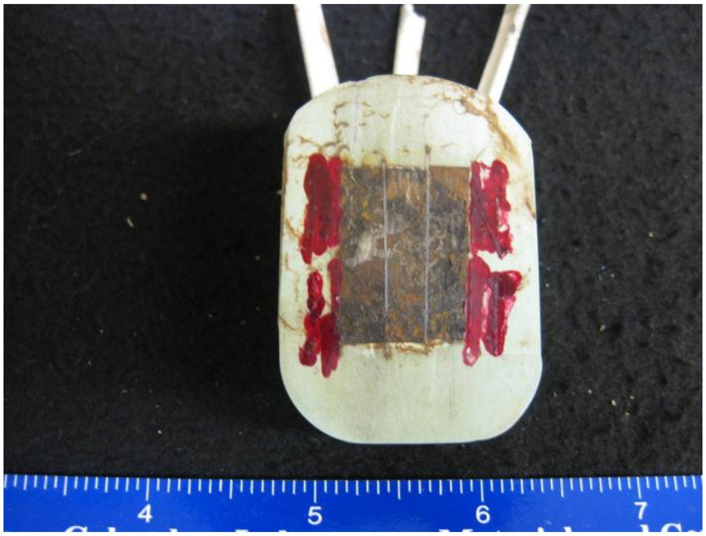

Figure 21. Post-test appearance of Steel C segment electrode after 13 months in the tests of the -850 mV off-potential criterion.

3.4 Post-Test Examination and Corrosion Rate Estimate

Upon completion of the long-term tests, the segment electrodes were cleaned and analyzed to determine the amount of metal loss that occurred during the testing, using 3-D optical profilometry. The maximum metal loss determined was used along with the test duration period to calculate a corrosion rate for each segment electrode. The results of this analysis are summarized in Figure 22. As can be seen, the base metal, HAZ, and weldment of the SSWC susceptible steels (B and C) exhibited higher corrosion rates than did these microstructures in the non-SSWC susceptible steel (D). The base metal corrosion rates for the SSWC susceptible steels were approximately 0.02 to 0.03 mm/y during the CP tests; whereas, the HAZ and weldments for these steels showed corrosion rates approaching 0.1 to 0.5 mm/yr. For these steels, the high corrosion rates for the weldment compared to the base metal results in grooving factors that range from 3.5 to 25. There did not appear to be any effect of the CP criterion tested on the corrosion rates, although neither CP criterion was consistently achieved in these tests. The non-SSWC susceptible steel, in contrast, showed comparable corrosion rates for the base metal, HAZ, and weldment. The estimated corrosion rates were on the order of 0.002 to 0.004 mm/y. From these results, it is evident that SSWC was not eliminated for the two susceptible steels in either test.

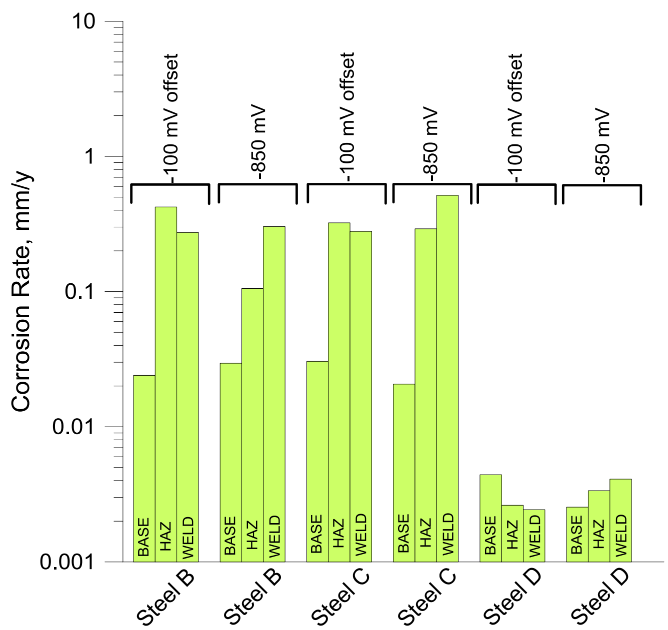

Figure 22. Corrosion rate estimates for segment electrodes during 13-month CP effectiveness evaluation tests.

4.0 SUMMARY AND CONCLUSIONS

In this work, the effectiveness of cathodic protection in mitigating SSWC was investigated. This was accomplished by constructing a set of segmented electrodes that consisted of weldment, HAZ, and base metal for three steels. One steel was known not to be susceptible to SSWC; whereas, two had been shown to be susceptible to SSWC. Long-term soil box testing was conducted in one soil evaluating two CP criterion; 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.

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. 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. If CP was fully effective in eliminating SSWC, comparable, 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 test 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.

The research findings in Task 3.2 of this project (Selective Seam Weld Corrosion Test Method Development) found that the 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 mV and 200 mV, which is a typical range for soils[5], 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.

5.0 REFERENCES

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