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Monitoring Cathodic Protection Effectiveness at Trenchless Crossings

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ABSTRACT

Trenchless technologies are increasingly used to install pipelines at crossings with environmentally sensitive features, highways, etc. For deep crossings installed in rock via horizontal directional drilling (HDD), there has been concern within the pipeline industry about the effectiveness of conventional monitoring and cathodic protection techniques.

This paper summarizes the results of research sponsored by the Pipeline Research Council International. Field testing was conducted at a long crossing installed in rock where an array of monitoring and cathodic protection equipment had been installed, and recommendations were developed.

The testing indicated that deep sections of the pipeline in drilling mud required low currents to polarize. The installation of deep coupons in an environment similar to the pipeline's is recommended. Only small differences were observed between the efficiency and effectiveness of local shallow and deep groundbeds.

Keywords: cathodic protection design, deep coupons, horizontal directional drilling (HDD), monitoring, trenchless crossing.

INTRODUCTION

Pipeline construction has increasingly relied on trenchless technologies such as horizontal directional drilling (HDD) and track boring. These techniques are used to cross features such as environmentally sensitive areas, roads, rivers and other pipelines. Unlike open-trench installation methods, the coating cannot be inspected prior to carefully backfilling the pipe because trenchless techniques rely on pushing or pulling the pipe through the ground.

The Pipeline Research Council International (PRCI)[(1)] has sponsored a series of research projects on the installation and monitoring practices used to determine the effectiveness of cathodic protection (CP) at trenchless crossings. The subject program addresses concerns with current distribution and measurement efficacy for deep HDD crossings in rock.

The project was coordinated with the installation of a more than 1 km-long, 60 m-deep HDD located in a limestone/shale formation. A CP and monitoring system were designed to provide enhanced short-term testing capabilities in addition to providing long-term protection, with project-specific enhancements funded by PRCI.

The project tasks were: gathering information about the state-of-the-art coatings and CP monitoring for HDDs; designing, manufacturing, and installing the enhanced monitoring system; field testing and reporting. This paper outlines the major findings of the report; for further information and detailed results, refer to the publicly-available project report, which can be downloaded from the PRCI store[(2)].

SYSTEM DESCRIPTION

The subject HDD was required for a long water crossing. The pre-existing upstream and downstream sections of the pipeline are protected primarily by sacrificial magnesium anodes, with some influence from an adjacent impressed current CP system. However, the crossing was isolated from these sections using monolithic isolating joints (MIJ) to provide the most operational flexibility for the CP system. The design details for the crossing are shown in Table 1.

Table 1
Crossing Details

Parameter	Value
Pipe diameter	0.219 m (NPS 8)
Coating type	Fusion bonded epoxy with abrasion resistant overcoat
Length of crossing pipe (arc length)	1196 m
Maximum depth	60 m

Site access was limited on the entrance side of the crossing due to landowner concerns, so most of the testing was conducted on the exit side of the crossing.

Soil resistivities were measured using pin spacings up to 50 m using the 4-pin Wenner technique. The results, which were inverted using W-GeoSoft's WinSev software[†], indicated the bedrock resistivity was in the range of 800 to 1000 Ω·m. The overburden was up to 3 m thick with a resistivity of 20 to 100 Ω·m.

Cathodic Protection System

A dedicated CP system consisting of two groundbeds, one shallow horizontal groundbed installed in the overburden and one deep vertical groundbed installed in rock, was designed to protect the crossing. As the groundbed installation would occur during the HDD construction, it was necessary to design the groundbeds ahead of time (i.e. prior to installation of the HDD). For current requirements, the coating damage was conservatively assumed to be 1% bare and the design current density was chosen as 10 mA/m^2. Due to the MIJs, the CP requirements for the adjacent pipeline sections was not expected to have a significant impact on the CP system sizing. This differs from a typical targeted installation,

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(1) Pipeline Research Council International (PRCI), 15059 Conference Center Drive, Suite #130, Chantilly, VA USA 20151
(2) https://www.prci.org/Research/Corrosion/CORRProjects/EC-8-4/4219/141117.aspx
† Trade name.

where the efficiency of a local installation is less than 100%; that is, a groundbed with a 1 A output will supply less than 1 A to the HDD itself.

The shallow groundbed consisted of three packaged high-silicon cast iron in a 2 m-deep trench and was powered by a 20 V, 5 A rectifier. The deep groundbed consisted of a 15 m-long custom NPS 8 bare steel pipe anode installed to a maximum depth of 60 m and was powered by a 48 V, 1 A rectifier.

Monitoring System

The monitoring consisted of coupon assemblies and reference electrodes installed at various depths on the two sides of the crossing. The coupon assemblies consisted of two integrated coupon/reference units (ICR) and one stationary $Cu/CuSO_4$ reference electrode (CSE), as shown in Figure 1. The two ICRs have areas of 10 cm^2 and 25 cm^2 and each has an internal zinc reference electrode.

Figure 1: Coupon assembly consisting of a 10 cm^2 ICR, a stationary CSE and a 25 cm^2 ICR

Deep coupon assemblies were installed in vertical boreholes that were subsequently filled with drilling mud to within a few metres of the overburden and capped with concrete to act as an electrical seal. This configuration was chosen for its similarity to the pipeline installed via HDD, which is encapsulated in a very long column of drilling mud. The drilling mud had a resistivity of 3.6 Ω·m.

On the exit side, coupon assemblies are installed at 20 m, 40 m and 60 m depth in three separate boreholes. On the entry side, a coupon assembly is installed at 60 m depth. On both sides, protection levels in the overburden are monitored using two ICRs installed along with the pipe using open-trench techniques.

To supplement this monitoring, two zinc references were pulled into the HDD along with the pipeline to assess protection levels measured directly in the annulus. Based on the location along the pipeline, it is estimated that these references sit at around 30 m deep.

The monitoring provisions, except for the two zinc references, were installed after the actual HDD crossing for logistical reasons.

TESTING RESULTS AND ANALYSIS

Coupon Resistance

The resistance of the coupons on the exit side were measured using the fall-of-potential method relying on remote electrodes so that the 62% rule applies.[1] The resistance of the coupons at each depth was measured together (i.e., the 10 cm^2 and 25 cm^2 were bonded together). The applicability of the 62% rule was confirmed by varying the placement of the electrode near the 62% position and the change in measured resistance was less than 1%. The results are given in Table 2. The implied resistivity is calculated assuming that each coupon is a circular disk in uniform soil.

Table 2
Measured Coupon Resistances

Coupon Location	Measured Resistance (Ω)	Implied Uniform Resistivity (Ω·m)
Surface	75.5	13.9
20 m deep	52.3	9.6
40 m deep	28.8	5.3
60 m deep	32.1	5.9

Although the soil at the surface has a much lower resistivity than the bedrock, the deep coupons, which were backfilled in drilling mud, had lower measured resistances than the surface coupons. This is attributed to the low resistivity drilling mud, which this testing showed was counteracted by the effect of the high resistance bedrock. Therefore, for holidays encased in a column of drilling mud, the defect resistance is reasonably low.

Coating Quality

The coating quality was tested immediately after completing the HDD and prior to welding the pipe to upstream or downstream sections using the technique developed in the report PR-262-9738 and updated in the report PR-444-13602.[2,3] The test arrangement and schematic are shown in Figure 2. The calculated percentage bare was 0.019% and there was minimal visible damage to the lead end of the pipe, resulting in a classification of “Suitable for Monitoring”. This percentage bare was much less than the conservative design parameter (i.e. 1% bare) chosen for designing the CP system, indicating the design was oversized as compared to the actual required capacity. Note that other than designing the groundbed after the HDD crossing has been tested, this over-design problem is largely unavoidable.

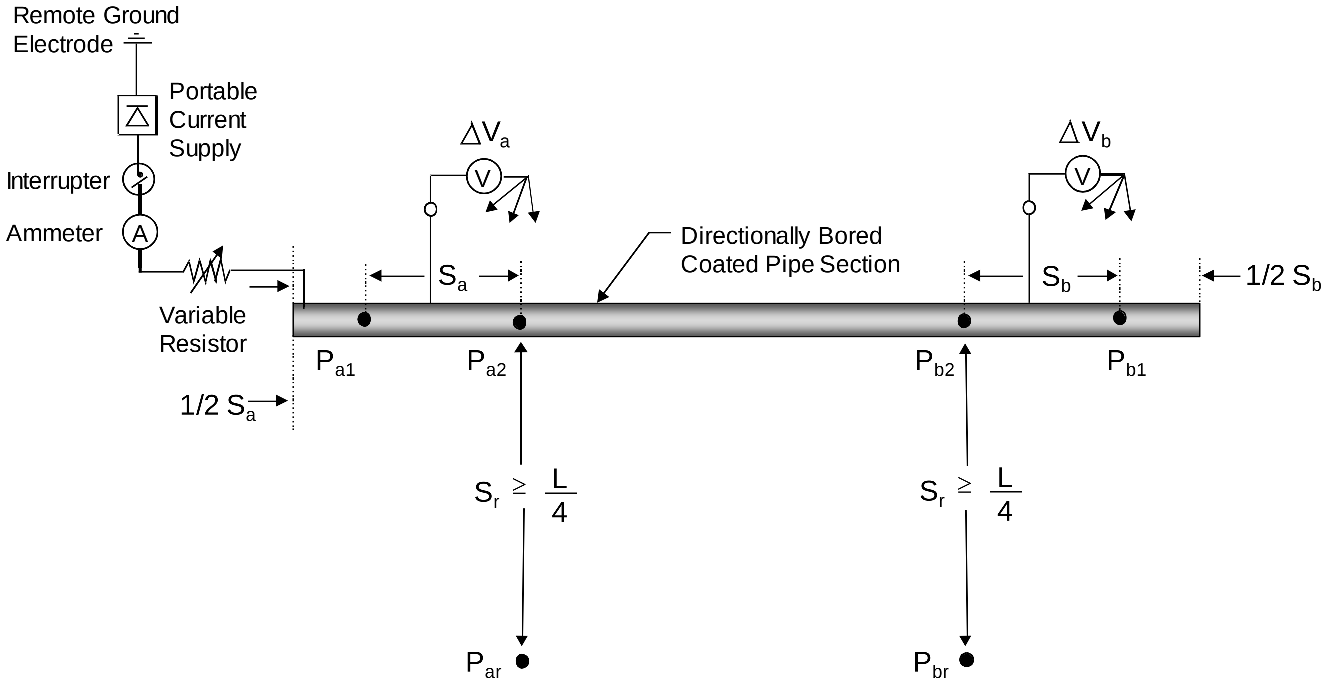

Figure 2: Arrangement of test equipment and testing schematic

There has been concern expressed in the industry that the potentials measured at grade do not reflect what is happening to the pipe deep underground. Since the HDD crossing was equipped with MIJs, it was possible to re-test the coating quality with coupons connected and with coupons disconnected. Results from the conventional and follow-up tests are shown in Table 3.

Table 3
Results from Coating Conductance Tests

		Conventional test			Follow-up test with coupons connected			Follow-up test with coupons disconnected		
		ON	OFF	Δ	ON	OFF	Δ	ON	OFF	Δ
Measured potential (mV_{CSE})	Entry 1	-1047	-962	85	-1395	-1311	84	-1418	-1329	89
	Entry 2	-1048	-925	123	*	*	*	*	*	*
	Entry remote	-1072	-965	107	-1311	-1231	80	-1329	-1236	93
	Exit 1	-1157	-945	212	-1468	-1362	106	-1482	-1379	103
	Exit 2	-1189	-987	202	-1459	-1366	93	-1400	-1304	96
	Exit remote	-1142	-971	171	*	*	*	*	*	*
Current (mA)		29			35			28		
Calculated % bare		0.019%			0.068%			0.039%		

*Landowner concerns or datalogger failure prevented measurement

The measured potentials ("entry 1", "entry remote", etc.) were recorded at the locations chosen based on the PRCI test procedure as illustrated in Figure 2, with "a" corresponding to the exit side and "b" corresponding to the entry side and P_{ar} and P_{br} referring to remote measurement locations.[3] Note that in practical terms, it is not always possible to locate the references as shown, but that the remoteness of the references is critical to obtaining accurate test results, as shown below.

The highly electronegative instant-OFF potentials as measured during the follow-up tests are thermodynamically difficult to achieve for steel, and the most common cause for this type of error is residual CP current. In this case, the unique test configuration ruled out residual CP current and the very electronegative potentials could instead be due to the very high current densities in deaerated soil or possibly measurement problems. Since the conductance test relies on the voltage drop produced by a known test current, the results are still considered reliable.

The results from the conventional test indicated a large difference between the potentials measured on the entry and exit sides. Although the groundbed was placed approximately 25 m away from the bore exit and was energized by only 29 mA, the higher gradients on the exit side are attributed to the groundbed gradient. If this data were removed from consideration, the calculated % bare would increase to 0.032%. This would not have changed the bore's status of Suitable for Monitoring and closely matches the results of the follow-up testing with coupons disconnected. Nevertheless, the difference observed here highlights the importance of installing the groundbed as remote as practical.

Also, worth noting is the relatively large difference in calculated percent bare between the follow-up tests with coupons connected and coupons disconnected. Although the bare surface area changed by only 0.002%, the calculated difference in bare area changed by 0.02%. The original testing performed for PR-262-9738 that formed the basis for this calculation relied on results from a relatively short piece of pipe with strips of steel simulating much higher degrees of coating damage, and this calculation has provided very accessible and practical results indicating a range of coating damage from minimal to extensive. The calculated percentage bare should continue to be relied on primarily as an indicator of degree of coating damage rather than assuming it translates exactly to a precise bare area. In addition, as the amount of coating damage increases, it matches more closely the results of the original testing for PRCI.

Note that if deep coupons and references are installed prior to conducting the coating conductance test, references close to coupons must not be relied upon to measure the coating conductance if the coupons are connected; such references would observe lower shifts due to being electrically close to the coupons.[4]

Current Distribution Testing

Current distribution testing was conducted to compare the effectiveness of different current sources on the current distribution, particularly for deep coupons. To understand the implications for other pipelines, the most important comparisons were:

- close deep groundbed versus a close shallow groundbed
- close groundbed versus remote groundbed/anodes

Four different current sources were tested as part of the current distribution testing: the dedicated close shallow groundbed; the dedicated close deep groundbed; remote magnesium anodes; and a remote shallow groundbed plus remote magnesium anodes. Since most HDDs are not isolated from the upstream and downstream piping, a temporary bond was also installed across the south monolithic isolating joint to determine the impact on the protection levels of the HDD. The existing line is protected by direct-connected magnesium anodes, so whenever the bond was activated, these anodes were made continuous with the HDD. A temporary remote groundbed, a culvert located 9 km south of the HDD beside the existing pipeline, was also energized to act as a remote impressed current source.

Three levels of net current output were tested: low, medium and high. The low output was the net current from the dedicated groundbeds, as selected during commissioning of the system. This had resulted in a well-protected condition, with coupon potentials ranging from -1150 mV_{CSE} to -1250 mV_{CSE}. The medium output was chosen to be about five times higher than the low output, and the high output was chosen to be about five times higher than the medium output. These relatively high outputs were selected to facilitate measurement of the small coupon currents and to emphasize differences between the test configurations.

As an example, the test configurations for the medium output setting are shown in

Table 4. The output currents for each of the medium output test configurations are shown in Table 5. Also shown is the net current protecting the HDD and coupons (i.e., the output from the deep and shallow groundbeds plus the current supplied to the HDD across the bond), which can be used to normalize the current on each coupon. Similar configurations exist for the low and high outputs, except that the high output bond configuration was not tested due to difficulty in attaining enough current from a temporary remote source.

Table 4
Medium Output Test Configurations

Test configuration	Shallow rectifier	Deep rectifier	Bond across MIJ	Remote rectifier
Medium bond			Y	Y
Medium shallow	Y			
Medium shallow bond	Y		Y	
Medium deep		Y		
Medium deep bond		Y	Y	

Table 5
Currents for Medium Output Test Configurations

	Current (mA)			
Test configuration	Close deep groundbed current	Close shallow groundbed current	Bond current (positive picked up on HDD)	Net current on HDD and coupons
Medium bond	0	1	83	84
Medium shallow	0	135	0	135
Medium shallow bond	0	137	-45	92
Medium deep	131	0	0	131
Medium deep bond	132	1	-40	93

Local Shallow Groundbed vs. Local Deep Groundbed

The efficiency of a local shallow groundbed was compared to that of the local deep groundbed in terms of percentage of the net current picked up by a deep coupon.

Figure 3 shows the variation in percentage of net current picked up by the 25 cm^2 60 m-deep coupon versus net current on the HDD for the two groundbed configurations and corresponds to results from the low, medium and high output configurations.

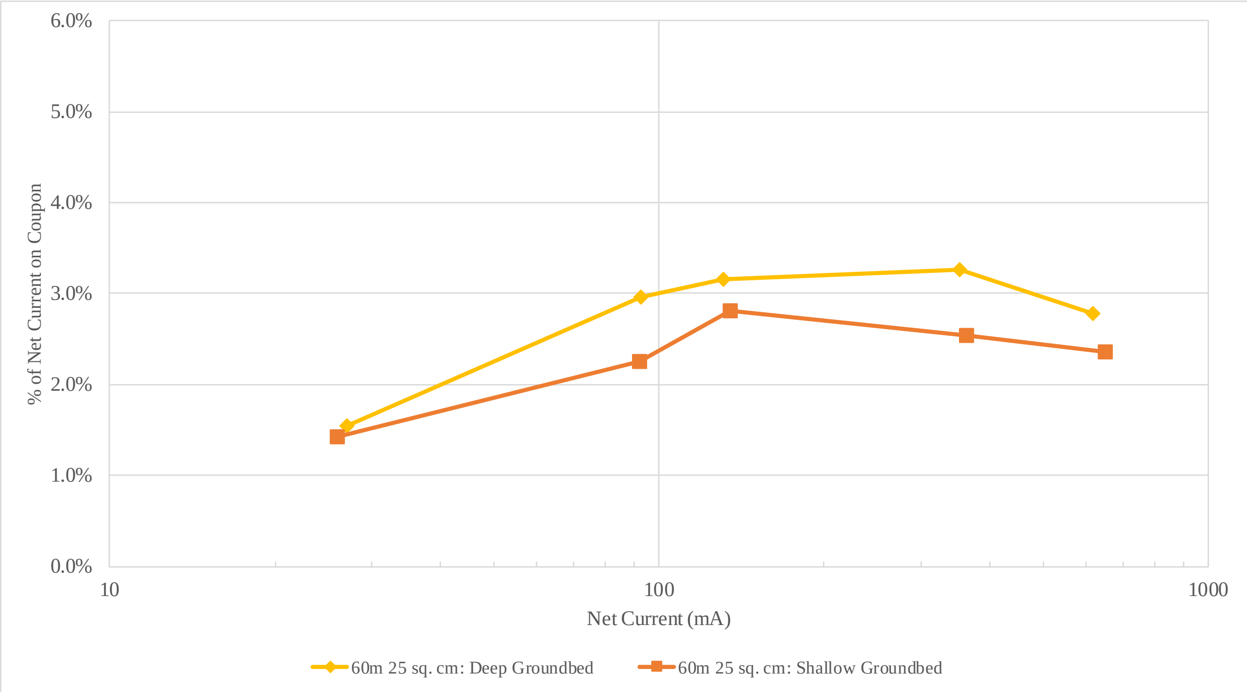

Figure 3: Effect of local shallow and deep groundbeds on a deep coupon

As expected, the coupon picked up more current from the deep groundbed, but the difference was less than 1% of the total net current, with both the pipeline and all the coupons fully protected. In terms of difference between percentages of the net current, the current resulting from the deep groundbed was 10-20% higher than the current resulting from the shallow groundbed at the higher outputs.

Thus, the testing showed that for this specific HDD both the local shallow and deep groundbed options were effective at protecting the deep coupons. This also indicates the deep sections of the pipeline in drilling mud received enough protection current. This may not prove true for all cases, particularly when the coating damage is more severe or in contact with electrolyte other than the drilling mud. Deep coupons in suitable backfill would help provide the information required to make this determination.

Remote Shallow Groundbed vs. Local Deep Groundbed

Figure 4 shows the variation in percentage of net current picked up by the 25 cm^2 60 m-deep coupon versus net current on the HDD for the remote shallow and local deep groundbeds.

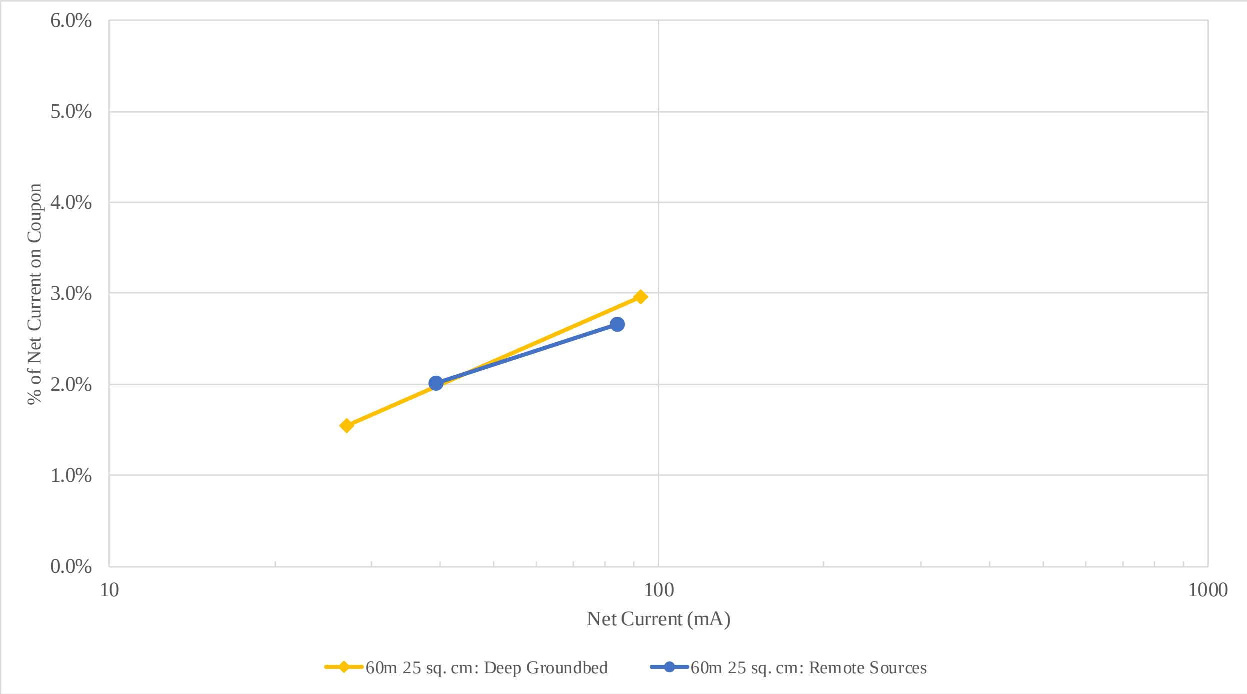

Figure 4: Effect of remote shallow and local deep groundbeds on a deep coupon

The results point to very small differences in percentage of net current picked up (i.e., being passed to the HDD); however, the actual efficiency, meaning percentage of groundbed output to current picked up from a remote groundbed, would depend on the coating quality along the remaining sections of the pipeline. For HDDs associated with new pipelines and those similar to this specific one, a remote groundbed appears to be a realistic solution. However, for HDDs associated with modifications on old pipelines or pipelines with electrically continuous stations, a dedicated local groundbed might be required.

Polarization Testing

The polarization characteristics were measured in October 2017 using a potentiostat programmed to step from the open-circuit potential to a potential of at least -1100 mV_{CSE} in steps of 25 mV to capture the oxygen plateau and tail at hydrogen evolution. At each step, the potential was allowed to stabilize so that the change in current was less than 10% per minute, with the change less than 5% per minute for all the steps except the first step to -932 mV_{CSE}. Those steps with slower changes were held for up to 1000 seconds. This is much slower than the rate normally chosen for a polarization scan conducted in a liquid as the polarization mechanisms are expected to be slower in soil. The test was performed on the 20 m-deep, 25cm^2 coupon as the results from this coupon were generally representative of the deep coupons.

A Gamry 1000E† was used to apply the potential steps and monitor the applied current. In addition to responding to the potential steps, the current exhibited random fluctuations, generally about 5-10% of the applied current, throughout the test. After extensive consultation with the manufacturer, it appears that the long reference electrode and working electrode (coupon) cables were interacting with the instrument. As the general trend matched expectations, this instability in the current was compensated by using short-term averages for all current measurements.

† Trade name.

Prior to the test, the coupons were disconnected from each other and from the CP system for almost two months. However, the depolarization was very slow and the open-circuit potential of the 20 m-deep, 25 cm^2 coupon under test was -886 mV_{CSE}. As a result, the oxygen plateau was not evident, likely because the environment remained deaerated even after this extended period. The results of the stepped polarization test are shown in Table 6 and in Figure 5 as current density versus applied potential. The data is also presented in Figure 6 using the more typical polarization curve format.

Table 6
Stepped Polarization Results

Voltage (mV_{CSE})	Current (µA)	Current Density (mA/m^2)
-886	0.0	0.0
-932	6.6	2.6
-957	12.3	4.9
-982	18.3	7.3
-1007	26.4	10.6
-1032	37.7	15.1
-1057	53.9	21.5
-1082	81.4	32.5
-1107	127.9	51.2

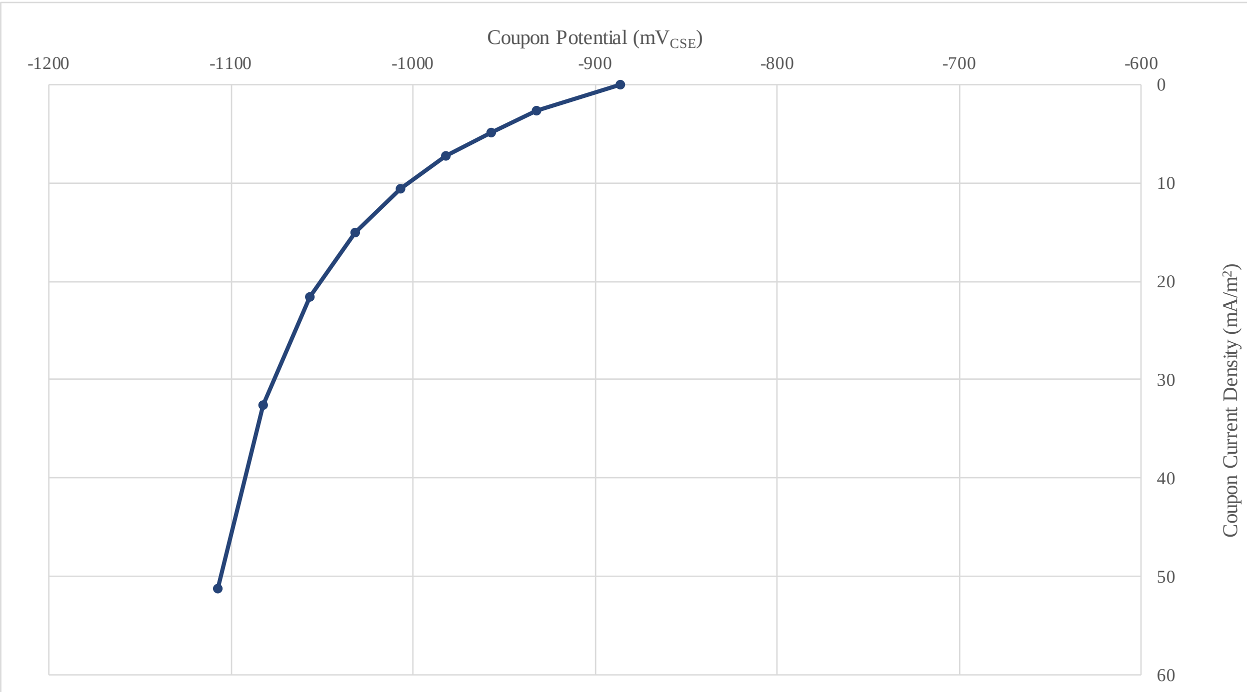

Figure 5: Current density vs. coupon potential

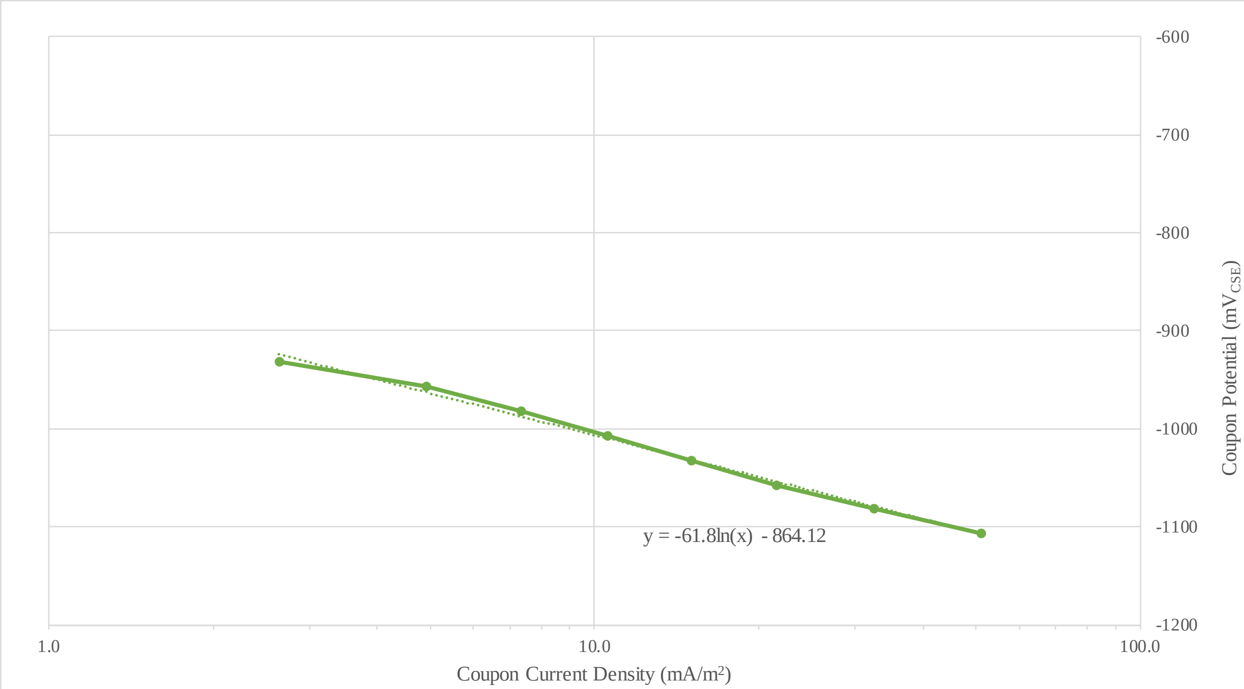

Figure 6: Polarization curve of coupon in drilling mud

The current required to polarize to the target -1100 mV$_{CSE}$ was relatively low. This result and the slope of the polarization curve were consistent with the polarization of steel in a deaerated environment. The low current requirement is also a result of the highly electronegative open-circuit potential, which is the starting point of current application. This near-static potential was so electronegative that it already satisfied the NACE -850 mV$_{CSE}$ protection criterion, effectively indicating that no current would be required for protection.[5] However, the initial static potentials on the deep coupons were also very electronegative, around -820 mV$_{CSE}$, so the current requirements to provide protection would have been very low.

After the oxygen entrained during the HDD installation is consumed, there is expected to be limited availability of oxygen along the deep sections of an HDD both due to depth and drilling mud. Therefore, a similar polarization slope would be expected for most HDD pipelines, because in a deaerated environment the potential is controlled by hydrogen evolution. This may be less true for slip bores.

However, corrosion has been reported on deep HDD pipelines where sufficient CP levels were measured at the two ends of the HDD. If the deaerated condition remains true, as expected, then there are at least two possible explanations: less electronegative open-circuit potentials and higher spread resistances. Both could result from differences in the environment, and these could vary along the HDD.

Less electronegative open-circuit potentials could result in much higher required current densities. Higher spread resistances could make achieving these current densities more difficult.

The environmental factors that would be expected to impact the open-circuit potential of bare areas on HDDs are drilling mud composition, drilling mud mixing water, entrainment and type of native soil/rock, and contact with native soil/rock along the HDD. As the coupons were installed in straight drilling mud, as opposed to the mix of drilling mud and native soil/rock drill cuttings that the HDD itself is installed in, the results may not be totally representative of the conditions along the HDD itself.

Coating defects surrounded by low resistivity drilling mud will have a much lower spread resistance than coating defects directly in contact with high resistivity rock (or a very thin layer of drilling mud). If this results in wide variations in current density requirements, protecting certain coating defects may be very difficult. In addition, coupons in pure drilling mud would not effectively capture this effect.

For future installations, it may be beneficial to sample the pH and resistivity of the drilling mud/cuttings mix as the HDD bore is progressing, and possibly perform polarization tests. This would give insight into the likely polarization characteristic of coating defects along the bore. This information could also be leveraged to modify the backfill used for the installation of deep coupons to more closely represent the most severe conditions along the HDD.

Part of the goal of this project was to record data to facilitate modelling/computer simulation. The fast polarization that was observed supports the use of unaerated conditions for modelling the polarization. The steady-state open circuit potential would ideally be measured for multiple locations along the HDD, but additional work in this area is required.

The model should also account for local variations in soil resistivity, particularly with respect to some defects being directly in contact with the rock versus other defects surrounded by drilling mud. The open-circuit potentials at such locations could also vary significantly.

For modelling purposes, the coupons should be installed prior to performing the conductance test. These measurements could then be fed into a blind study to confirm the accuracy of the model. With the accuracy verified, the soil resistivity could then be varied to determine the impact on protection levels of remote or local CP installations.

FUTURE WORK AND RECOMMENDATIONS

Future work should be focused in the areas of coupon backfill and modelling.

In the present work, drilling mud was used around the deep coupons to represent the electrolyte surrounding the HDD pipeline. However, the native soil/rock may influence the composition of the drilling mud in the HDD and some coating defects on the pipeline may be in contact with the rock rather than the drilling mud. Therefore, for the coupons to represent the most severe conditions along the HDD pipeline, further investigation is required.

In the future, it would be very beneficial to conduct measurements at another deep HDD location outfitted with deep coupons but in a location with higher resistivity bedrock to validate the findings of this study.

In the area of modelling, it will be critical to prove the accuracy and effectiveness of the techniques that have been developed. One possible approach will be to conduct a blind approach, where data typically accessible in the field is used to develop a model, which is then validated against additional field measurements.

With further developments in these areas, operators will gain additional confidence in judging the effectiveness of their CP systems at critical bore locations.

CONCLUSIONS

This project examined techniques for monitoring and cathodically protecting long, deep HDD pipelines. There are several clear conclusions from the field data:

- The PRCI coating conductance and current requirement test was confirmed to be an effective measure of coating quality on newly-installed HDDs.

- The deep sections of the HDD in drilling mud behaved as a deaerated environment, requiring low currents to polarize to highly electronegative levels. This conclusion is based not only on the coupons but also on the reference installed in the actual bore measured with respect to the pipe itself and is also apparent in the polarization curves.
- To achieve similar environmental conditions to those experienced by the HDD pipeline, deep coupons are strongly recommended, with additional work required to determine the most suitable backfill(s).
- Only small differences were observed between the efficiency and effectiveness of local shallow and deep groundbeds.

Caution is recommended extending the conclusion about low current requirements to all HDDs, especially due to reported corrosion. Therefore, additional testing on other environments (e.g. granite) is strongly recommended.

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