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Cathodic Protection Coupon Interpretation

in Multiple Pipeline Corridors

Daniel Fingas
Corrosion Service Company Limited
9-280 Hillmount Road
Markham, Ontario, L6C 3A1
Canada

Len J. Krissa
Enbridge, Liquid Pipelines
Enbridge Centre
10175 101 Street NW
Edmonton, Alberta, T5J 0H3
Canada

ABSTRACT

Pipeline operators are becoming more dependent on coupons for demonstrating adequate cathodic protection as the use of multi-line corridors has increased. In such complex right-of-way configurations, the pipelines are often bonded together for cathodic protection purposes. The presence of widely varying coating qualities and current requirements means that protection levels measured during test post or close interval potential surveys are mixed potentials influenced by all the pipelines in the corridor. Targeted assessment of an individual pipeline therefore becomes much more complicated, particularly when a pipeline is newly constructed and is situated amongst legacy operating assets. To help account for this, coupons are heavily relied on to accurately assess protection levels on a specific pipeline.

Literature and the NACE standard SP0104 indicate that correct interpretation of coupon measurements may require the use of non-metallic soil-access tubes and/or a nearby stationary reference electrode. In practice, it is not always possible to install soil-access tubes along with the coupons due to factors such as land use, coupon depth, etc. This paper considers the theoretical and experimental basis for the need for a soil-access tube or a close-coupled reference. The interpretation of coupon data for new pipelines is examined in light of coupon data recorded on a new transmission pipeline that shares a corridor with several older pipelines. Recommendations are provided.

Key words: coupons, equalization currents, IR-drop, long-line currents, monitoring port, multiple pipelines, multi-line corridors, multi-line right-of-way, soil-access tube

INTRODUCTION

Coupons are used to represent small coating defects on the pipeline and are being increasingly relied on for assessing cathodic protection (CP) and corrosion. NACE Standard SP0104-2014[1], which provides guidance on the use of coupons for CP monitoring, recognizes the possibility of errors in instant-off coupon potentials unless, "a reference electrode is located very close to the coupon or in a soil-access tube."

A soil-access tube, known variously as a calibration port, monitoring port, reference tube or soil tube, is "a tube that is nonconductive and impermeable to moisture that can be used in conjunction with a coupon and can be filled with electrolyte." It is used to move the measurement reference electrode *electrically* close to a coupon with the intention of minimizing or eliminating voltage gradients in the soil between a reference at grade and the coupon.[2]

Soil-access tubes, along with, "a close-coupled CP coupon and reference electrode [and] a concentric CP coupon and reference electrode" are the recognized methods in Section 4.3 of SP0104 to address cases where, "the magnitude of the IR drop is either not known, considered to be significant, or may change significantly." However, there is an important limitation with using reference electrodes in Section 9.2.4: "The accuracy of any permanently buried stationary reference electrode should be verified periodically." If a soil-access tube is required to measure accurate potentials on a coupon, then there is no reason that a soil-access tube would *not* also be required to measure accurate potentials on a reference electrode. Thus, the use of a stationary (i.e., buried) reference electrode as a replacement for a soil-access tube cannot be considered a good long-term solution, because it is not possible to verify the reference electrode potential without the use of a soil-access tube.

This paper analyzes how measurement errors arise and evaluates the need for soil-access tubes and/or nearby stationary reference electrodes in light of data from a recent pipeline installation in a multi-line corridor.

CONVENTIONAL COUPON DATA INTERPRETATION

Although coupons represent coating defects on pipelines that expose the pipeline steel to the soil electrolyte, the measured potential on a coupon is often different than the measured potential on the pipeline. This difference in potentials will be discussed in the coming sections as background for the requirement for soil-access tubes.

Pipe-to-Soil vs. Coupon Potentials

A 2001 PRCI[(1)] research project compared pipeline instant-off potentials measured with respect to an at-grade reference electrode to coupon potentials measured using soil-access tubes as shown in the unity plot in Figure 1.[3]

[(1)] Pipeline Research Council International (PRCI), 15059 Conference Center Drive, Suite 130, Chantilly, VA USA 20151

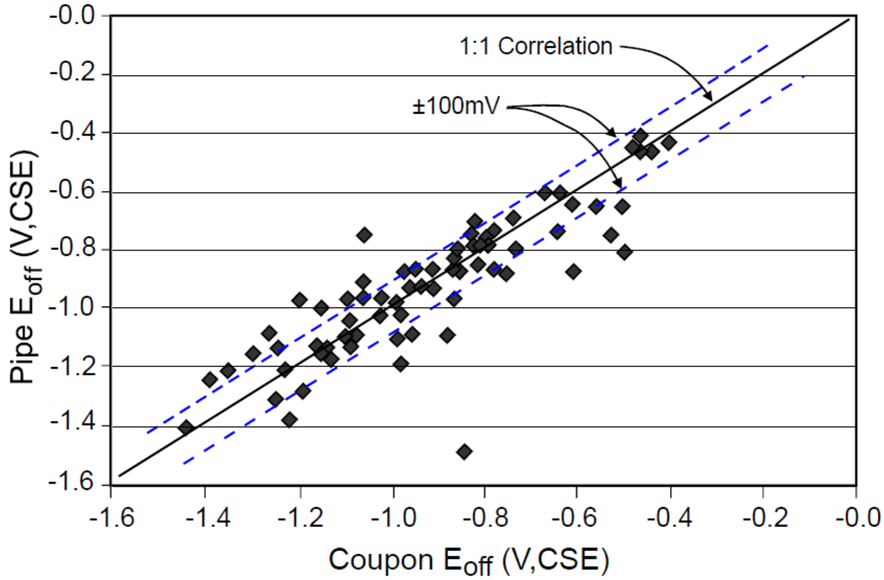

Figure 1: Pipe instant-off vs. disconnected coupon instant-off potentials.[3]

The correlation between the pipe instant-off potential and the disconnected coupon instant-off potential is relatively strong, and most potentials lie within the ±100 mV band. However, there are also a significant number of points where the potential difference lies outside this band, with differences in excess of ±200 mV common. In some cases, the coupons are more electronegative than the pipeline instant-off potentials, while in other cases the coupons are more electropositive than the instant-off potentials.

Thus, coupons are required to accurately determine protection levels, since the instant-off potential could be much more, or much less, electronegative than the true polarized potential. A corollary of this is that a significant difference between the coupon and the pipe instant-off potential measurements does not necessarily mean the coupon measurement is flawed because the pipeline potential is made up of many pipeline coating defects. In theory, the coupon is not intended to represent the instant-off potential or mixed potential of the pipeline, but rather the polarized potential of a singular holiday of a specific dimension at a defined location.

Requirement for Soil-Access Tubes

The same 2001 project considered the requirement for soil-access tubes, as shown in Figure 2, by comparing coupon potentials measured at-grade with and without soil-access tubes.

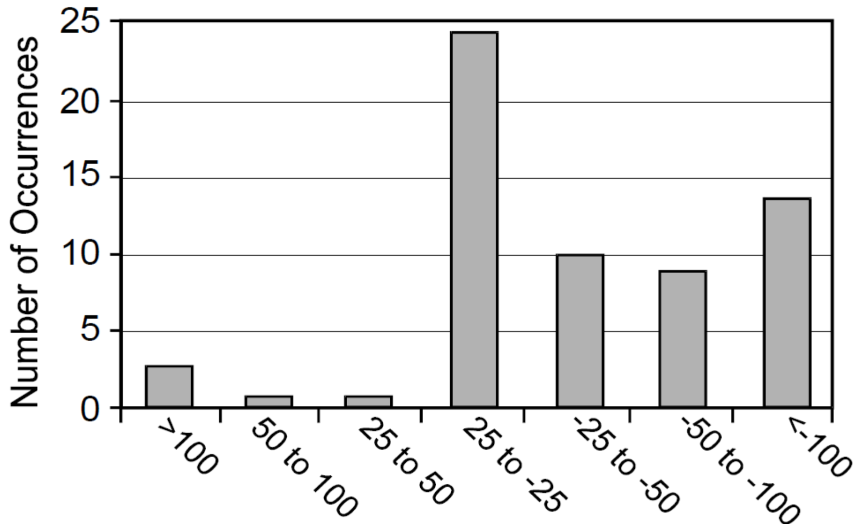

Figure 2: Difference between coupon-to-soil disconnected off-potential measured at grade and through the soil-access tube.[3]

For 38 of the 62 coupons, there was less than 25 mV difference between the measurements with and without soil-access tubes. However, there were some coupons with differences in excess of 100 mV and most of the differences were in the electronegative direction (i.e. the potential without the tube was more electronegative than the potential with the tube), meaning that in many cases measurements recorded without soil-access tubes would overstate the level of polarization. This resulted in a recommendation to include soil-access tubes when coupons are installed.

SP0104, while not mandating the use of soil-access tubes, generally adopts the recommendation of using soil-access tubes.

Proximity and Residual Gradients

Errors due to residual voltage gradients are most commonly associated with CP system operation (including groundbeds, sacrificial anodes and coating defects on cathodically-protected pipelines) plus stray currents. However, with the possible exception of stray currents, these gradients are localized. A rule of thumb for estimating this local distance (i.e. distance to remote earth) is 10-times the structure diameter; that is, for a 1-cm-diameter coating defect, remote earth would be approximately 10 cm away, as illustrated in Figure 1.[4] Similarly, a shallow groundbed with a length of 100 m could be considered remote at approximately 1000 m.

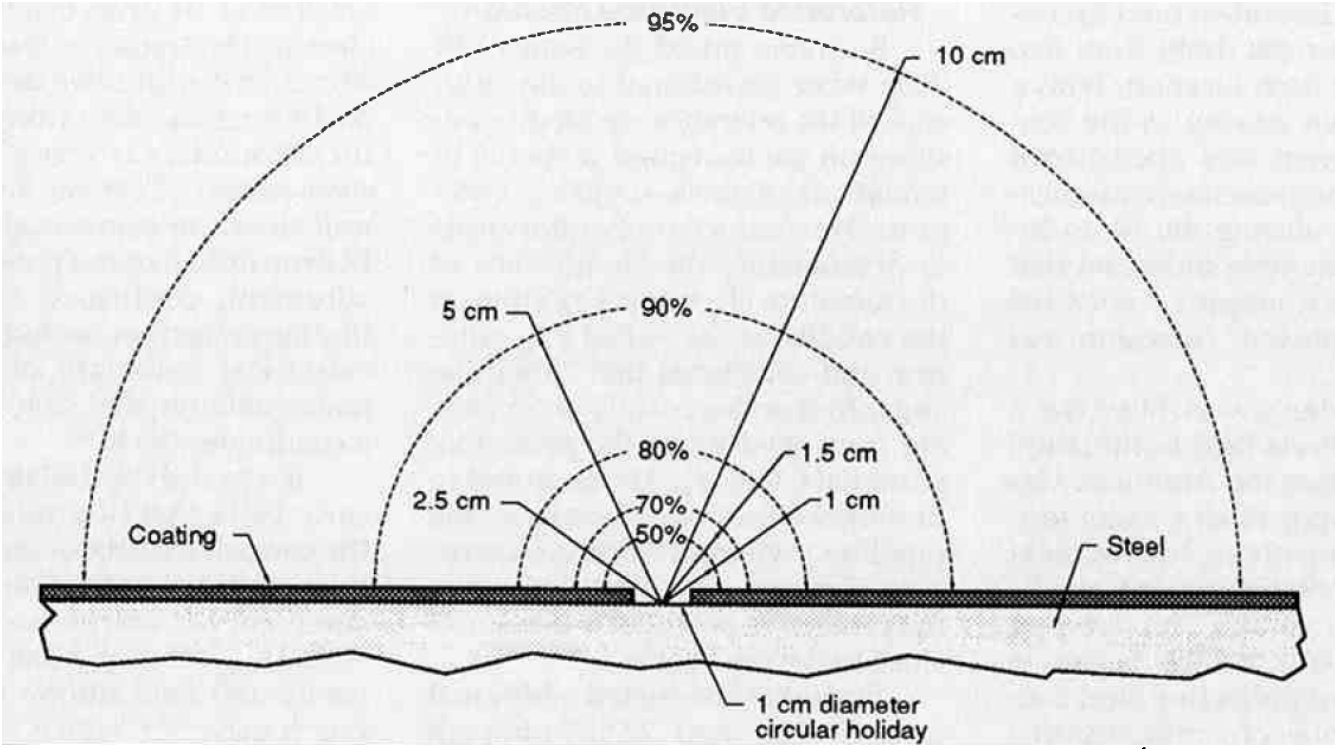

Figure 3: Total voltage drop to remote earth vs. distance from holiday (%).[4]

The voltage gradient is also steeper close to the coating defect, with 50% of the total voltage drop occurring within one diameter of the coating defect. This makes it difficult to eliminate a voltage gradient by placing a reference electrode nearby; furthermore, if a reference is placed close enough to eliminate most of the voltage gradient, it would shield the coupon from CP current. This constraint on placement also applies to soil-access tubes.

The implication of this localized effect on voltage gradients is that soil-access tubes are necessary to eliminate residual gradients if a coupon is close to a coating defect on the pipeline because the coating defect cannot be disconnected.

Long-Line Currents as the Source of Residual Gradients

As was discussed in the previous section, CP system-related gradients only have a localized impact on the measurements. For many pipeline configurations, most of the length of the pipeline will be remote from these CP system-related gradients due to the spacing between rectifiers, physical separation from other pipelines, etc.

The varying protection levels along a pipeline often result in long-line currents[5] and voltage gradients which are proportional to the differences in protection levels along the pipeline. Thus, any given instant-off measurement is likely to include an error term from the coupon itself. These long-line currents impact coupon measurements only when the coupon is part of the CP system, so disconnecting the coupon (and any other local CP system components like magnesium anodes) from the pipeline is critical to eliminating the residual gradients caused by long-line currents. Similarly, coupons and anodes must be disconnected prior to calibrating stationary reference electrodes installed close to coupons.

On new pipelines with excellent coating that are isolated from other pipelines and stations, it might be expected that protection levels would be relatively uniform along the length of the pipeline because the attenuation is very low; while this is true in some cases, coupons are still often specified when the pipeline is not isolated, when decouplers are present, when there is significant local coating damage at a trenchless crossing, or when there is a higher risk of interference from a foreign voltage gradient.

On old pipelines, significant variations in protection levels are expected for several reasons including the distance between a coating defect and the closest rectifiers and the distribution of coating damage along the pipeline. In well-protected areas (e.g. close to a rectifier), this error will typically be in the electropositive direction, meaning that the measured value will be conservative. However, in poorly protected areas, the measured potential will be more electronegative than the true value. This means that an instant-off potential of -850 mV_{CSE} could be measured at a location that has a polarized potential less electronegative than -850 mV_{CSE}.

For old pipelines, coupons are useful to accurately determine protection levels at specific locations of concern, such as locations far from a rectifier with significant coating damage.

In multi-line corridors with bonded pipelines, the combination of new and old pipelines usually results in significant long-line currents between the old and new pipelines. This is another perspective on the concept of coating defects on both the new and old pipelines influencing any given potential measurement. Disconnecting a coupon allows the measurement to be localized to that specific coupon resulting in a measurement that represents a particular pipeline. Therefore, coupons are particularly important on new pipelines in multi-line corridors, because otherwise accurate protection levels on the new pipeline cannot be directly measured.

RE-VISITING COUPON DATA INTERPRETATION

The 2001 PRCI report recommendations regarding soil-access tubes resulted from data collected on specific coupons installed as part of various PRCI projects. Based on the coupon location breakdown in that report, many of the coupons were installed near bare or poorly coated pipelines, and even many of the coupons installed near well-coated pipelines were near existing coating defects. For well-coated pipelines, and especially for new pipelines, coupons will generally not be installed right beside a coating defect because there are very few coating defects on a carefully installed pipeline. Therefore, the soil-access tube recommendation might not be generally applicable. Note that if the pipeline is close to an existing poorly coated pipeline, the likelihood of residual gradients increases.

This section describes techniques to detect residual gradients and considers practical disadvantages with the use of soil-access tubes.

Measurement of Residual Gradients

The purpose of soil-access tubes is the elimination of residual gradients, so if site measurements can be used to demonstrate residual gradients do not exist, the validity of measurements can be established even in the absence of soil-access tubes. For the purposes of this analysis, CP system gradients can be divided into those caused by CP sources, such as impressed current groundbeds or magnesium anodes, and CP sinks, such as coating defects or electrically continuous electrical grounding. CP sources or CP sinks can be further divided into those that are electrically continuous with the pipeline/coupon and those that are electrically discontinuous.

For practical purposes, operators are usually aware of the locations of their own impressed current systems and it is possible to interrupt these sources to eliminate the gradients caused by these sources. Operators might also be aware of the location of galvanic anodes and be able to interrupt (at least for a short time) the anodes if they are connected through a test post; directly connected anodes cannot be interrupted.

The location of foreign CP sources is not generally known, although in some cases the sources might be accessible for interruption.

The location of coating defects on pipelines is usually not definitively known, whether these defects are located on an operator’s own pipelines or on foreign pipelines. Nevertheless, coating defects on an operator’s pipeline can be detected using voltage gradient (VG) techniques such as those described in

NACE TM0109-2009. The same techniques can be modified and applied to coupons to identify the presence residual gradients caused by nearby coating defects.

Coupon to Reference Electrode Voltage Measurement

The VG techniques rely on measuring, at grade, a time-varying VG generated by a time-varying source, either the interruption cycle and CP sources for the DC Voltage Gradient (DCVG) survey or an applied AC voltage for the AC voltage gradient (ACVG) survey. By checking for this time-varying voltage in the measurement between the coupon and a reference electrode at grade, the presence or absence of a nearby coating defect can be determined. This measurement must be done with the coupon disconnected, because otherwise the coupon itself is acting as a coating defect. An example of the data from such a measurement is shown in Figure 4. When the coupon is connected, as shown on the left side of the figure, the ON-OFF interruption cycle is clearly visible. When the coupon is disconnected, the interruption cycle completely disappears from the voltage measurement.

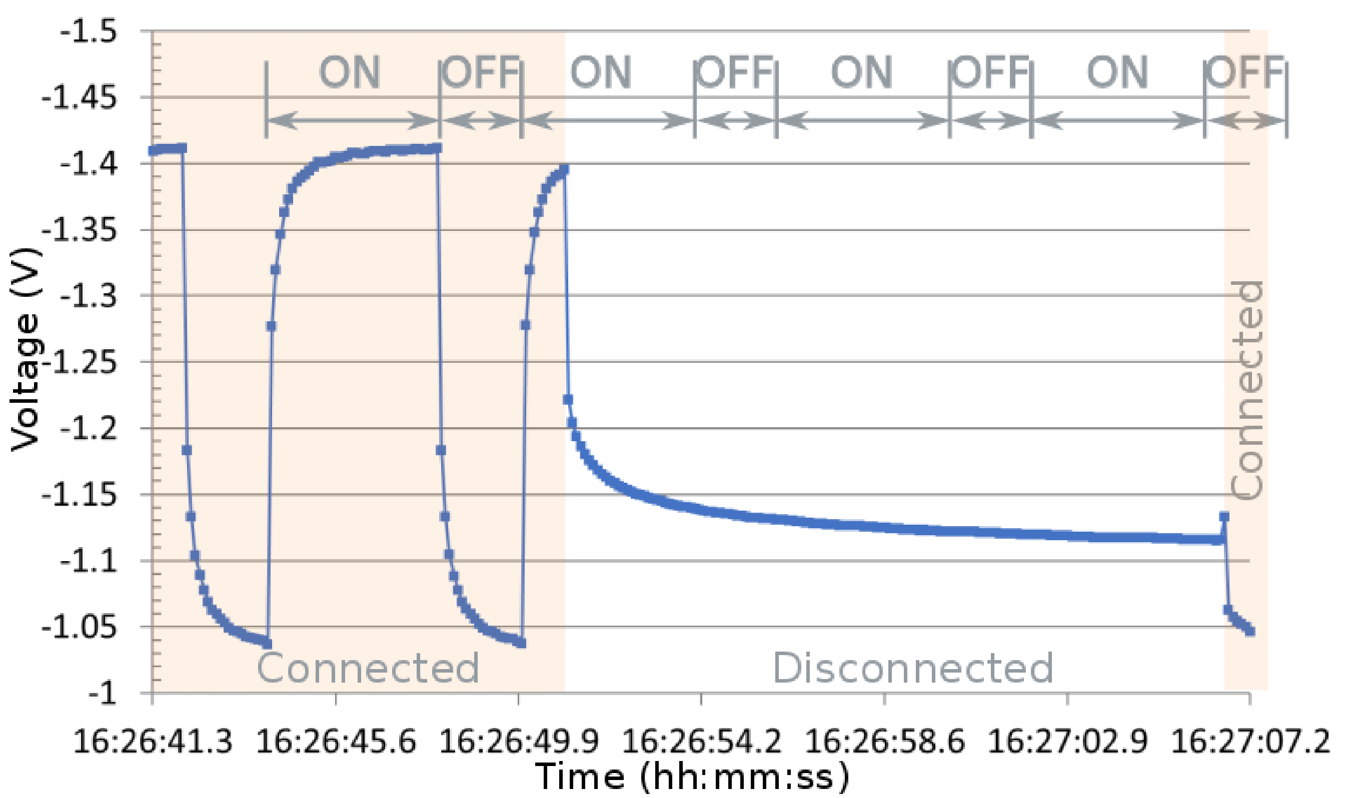

Figure 4: Voltage measurement recorded at 10 Hz between coupon and reference electrode at grade with the coupon connected and disconnected.

If there was a coating defect on the same CP system nearby, the voltage gradient around that coating defect would be time-varying (i.e. due to current pick-up during the ON cycle and either less current pick-up during or current discharge during the OFF cycle). Thus, the absence of an identifiable time-varying component in the disconnected measurement shows that there is no residual gradient from a nearby coating defect.

Nearby galvanic anodes on the same CP system can likewise be identified because they are also subject to time-varying gradients from the time-varying source (e.g. the galvanic anode discharges a small current during the ON cycle and a larger current during the OFF cycle, resulting in a time-varying gradient).

The same technique is applicable to nearby groundbeds which are interrupted. In this case, the measurement between the coupon and reference electrode at grade will vary if there is a nearby CP rectifier cycling that causes a rise in the soil potential during the ON cycle that is eliminated during the OFF cycle.

An example of a voltage measurement at a location with nearby influence is shown in Figure 5. In this example, when the coupon is disconnected the interruption cycle is still clearly visible and there is a substantial residual gradient.

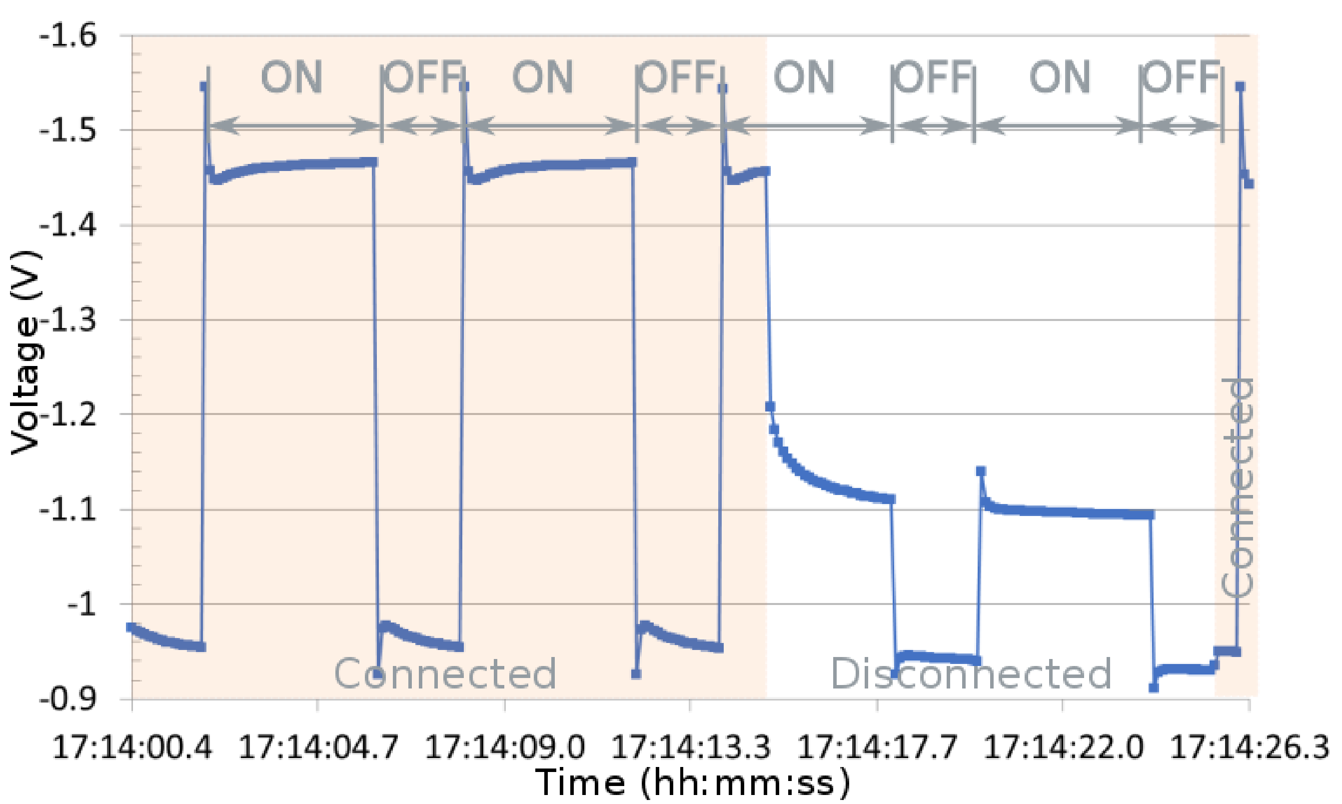

Figure 5: Voltage measurement recorded at 10 Hz between coupon and reference electrode at grade with nearby influence and the coupon connected and disconnected.

Although it may be tempting to assume there is no residual gradient during the disconnected OFF period, it is not demonstrated from this test. Rather, this shows there is a residual gradient during at least part of the disconnected period. The validity of the disconnected OFF data could be tested by temporarily turning off the closest influencing rectifier(s) and checking whether the interruption cycle can be detected; in which case, the disconnected OFF measurement validity could be confirmed.

The coupon to reference electrode voltage measurement is simple and effective at detecting the presence of nearby coating defects and anodes connected to the same CP system as well as interrupted CP sources, whether they are part of the same CP system or not. The technique is also effective at detecting residual gradients from coating defects connected to a different CP system if those coating defects are influenced by an interrupted source. The presence of dynamic stray current can also be detected from this test.

However, this measurement is not effective at identifying residual gradients from coating defects or anodes on a foreign pipeline, nor is it effective at identifying the presence of a nearby uninterrupted groundbed.

<u>Reference Electrode to Reference Electrode Surface Voltage Gradient Measurement</u>

Nearby uninterrupted sources generate a voltage in the soil; the portion of this voltage which exists between the reference electrode and the coupon results in a measurement error. The same sources will generally also create a voltage gradient at grade. This allows the presence of residual voltage gradient to be detected by measuring the surface gradient above the location of the coupon. This method is very similar to the typical DCVG coating evaluation technique but is more limited because there is no interruption associated with the voltage gradient. Note that the coupon must be disconnected before conducting this test.

For a typical DCVG survey, the interruption allows steady-state soil voltage gradients to be differentiated from voltage gradients associated with coating defects on a pipeline. Based on experience from reviewing extensive sets of DCVG data, the magnitude of these steady-state soil voltage gradients not associated with CP systems is usually less than 10 mV and rarely exceeds 20 mV at a spacing of 3 m. The cause of these gradients is not known and further study is recommended to better characterize their impact on the measurement of coupons without soil-access tubes. Nevertheless, the magnitude of these surface gradients is generally relatively low; if the voltage between the reference electrode and the coupon has a similar magnitude, it would rarely be significant in determining whether the CP criterion is satisfied. Further work is also required to determine if there is a reliable relationship between the measured surface gradients resulting from either remote groundbeds or static gradients not associated with CP systems.

One method to test the effectiveness of the surface gradient testing is to attempt the step-wise current reduction technique[6,7] at the coupon, with one surface gradient corresponding to the ON condition and the second surface gradient corresponding to the OFF condition. In the presence of significant surface gradients not associated with the coupon, the regular step-wise current reduction test might not provide self-consistent results.

Since local gradients could exist at either/both the test post location or the coupon location, it might be necessary to measure surface gradients both at the coupon location and at the test post location. Alternatively (and preferably), the surface gradient between the coupon location and the test post can be measured directly.

Summary of Testing

The testing which is relevant to each different CP system component and operator plus the typical relevant proximity are shown in Table 1.

Table 1: Summary of testing for residual gradients from CP systems with the coupon disconnected.

Source of Gradient	Typical Relevant Proximity	If Electrically Continuous	If Electrically Discontinuous (Foreign)
Impressed Current CP Source	100-1000 metres (300-3000 feet)	If source is interrupted, identifiable in the ON-OFF shift (coupon to reference electrode at grade).	If connected source is interrupted, look for ON-OFF shift (coupon to reference electrode at grade). If source is not interrupted, use the surface gradient technique to estimate the influence.
Galvanic CP Source and Decouplers	10-100 metres (30-300 feet)	If any continuous impressed current source is interrupted, identifiable in the ON-OFF shift (coupon to reference electrode at grade).	If *any* connected impressed current source is interrupted, identifiable in the ON-OFF shift (coupon to reference electrode at grade). If connected foreign source is not interrupted, use the surface gradient technique to estimate the influence.
CP Sink	< 10 metres (< 30 feet)	If *any* connected source is interrupted,	If *any* connected source is interrupted, identifiable in the ON-OFF shift (coupon

		identifiable in the ON-OFF shift (coupon to reference electrode at grade).	to reference electrode at grade). If connected foreign source is not interrupted, use the surface gradient technique to estimate the influence.

In the table, decouplers were consolidated with galvanic anodes since they behave as a CP source during an interruption cycle. The AC mitigation wire / decoupled structure acts as the local gradient source (like a groundbed). Depending on the pipeline characteristics, the decoupler could influence a long section of pipeline by acting as a CP source during the OFF portion of the interruption cycle.

Practical Considerations for the Use of Soil-Access Tubes

For some coupons, the coupon is placed immediately adjacent to a test post and soil-access tubes can be conveniently installed. However, at many locations, practical considerations limit the ability to install soil-access tubes, particularly the need to avoid an above-grade appurtenance. For example, coupons installed at foreign crossings or at the entry or exit of a trenchless crossing could create complications for future access and measurements. Even in company-owned facilities, it may not be feasible to install an above-ground appurtenance at the ideal coupon location due to obstacles associated with accessibility. As a result, a requirement for soil-access tubes at all locations would both limit where coupons can be practicably installed and increase the resources needed for execution.

SP0104 also identifies other practical challenges associated with the use of soil-access tubes in sections 6 to 9. These include: the resistance of the column of soil (Section 6.9); chemical leaching from the column of soil (Section 6.9.1); differential aeration (Section 6.9.2); preferential migration of water (Sections 7.1); formation of voids (Section 8.6.2); and soil-access tube caps (Section 9.2.2). Other important issues identified from the authors' experience include proper placement of the soil-access tube with respect to the coupon (i.e. close but not too close) and excessive drying of the soil if a cap is always left in place. In addition, on a recent project which incorporated coupons with internal zinc references, anomalous data was observed at locations with soil-access tubes as opposed to elsewhere. The anomalous data was attributed to the soil-access tubes partially shielding the coupons, resulting in unequal polarization levels on the coupon, thereby causing equalization currents when the coupon was disconnected.

RECOMMENDATIONS FOR THE USE OF SOIL-ACCESS TUBES

Based on the analysis in the previous sections, soil-access tubes are not generally required to eliminate residual voltage gradients due to CP system components. Exceptions to this recommendation remain for limited cases. It was also shown that many residual gradients can be detected after installation to confirm the accuracy of measurements in the absence of soil-access tubes.

Specific cases when a soil-access tube could be required to eliminate residual gradients include installation: very close to coating defects on a pipeline; near a valve or other poorly-coated pipeline component; in close proximity to decoupled or electrically continuous grounding or AC mitigation facilities.

If the coupon is a remedial installation, the voltage gradient can be measured between the actual coupon location (at depth) and grade at the time of installation. This could confirm the presence/absence of a significant gradient to determine if a soil-access tube and/or a stationary reference electrode should be installed prior to backfill to supplement the measurements from grade.

Stray currents are another possible source of residual gradients. In some cases, it is preferable to leave a coupon connected to evaluate the impact of stray current over time. A soil-access tube, if placed properly, would reduce the magnitude of residual gradients. However, to avoid shielding the coupon, the soil-access tube cannot be placed very close to the coupon. Since much of the local voltage gradient occurs very close to the coupon (i.e. within one coupon diameter), most of the local voltage gradient cannot be eliminated using a soil-access tube. Similarly, a stationary reference electrode cannot be placed close enough to the coupon to eliminate the coupon's local voltage gradients.

A more effective way of measuring coupon potential under stray currents is a coupon with an internal reference electrode. This allows accurate measurement of the CP level on the coupon even under the influence of significant stray current, for example for a current requirement test or for transit operation interference testing. The internal reference electrode can be calibrated by disconnecting the coupon and taking a time-averaged or overnight potential measurement.

PRELIMINARY RESULTS ON A PIPELINE IN A MULTI-LINE CORRIDOR

A new pipeline was constructed in a multi-line corridor with several other pipelines. The other pipelines had coating qualities ranging from excellent to very poor, and the new pipeline was typically separated from the other pipelines by at least 10 m.

To validate coupon measurements conducted at grade without soil-access tubes and to determine the significance of residual gradients from the operator's own CP system and pipelines, the coupon to reference electrode voltage data was collected with the coupon disconnected and rectifiers interrupted. The data was checked for ON-OFF shift. A histogram showing the frequency of different ON-OFF shifts for the portion of the line where this testing was performed are shown in Figure 6. Of the 67 coupon locations, 57 locations had no measured shift (i.e. 0 mV) and a total of 61 locations (91%) were within the ±5 mV band usually considered satisfactory for reference electrode accuracy per TM0497-2018 Appendix A. Three locations (4.5%) had more than 10 mV shift, and two of those locations had more than 20 mV shift.

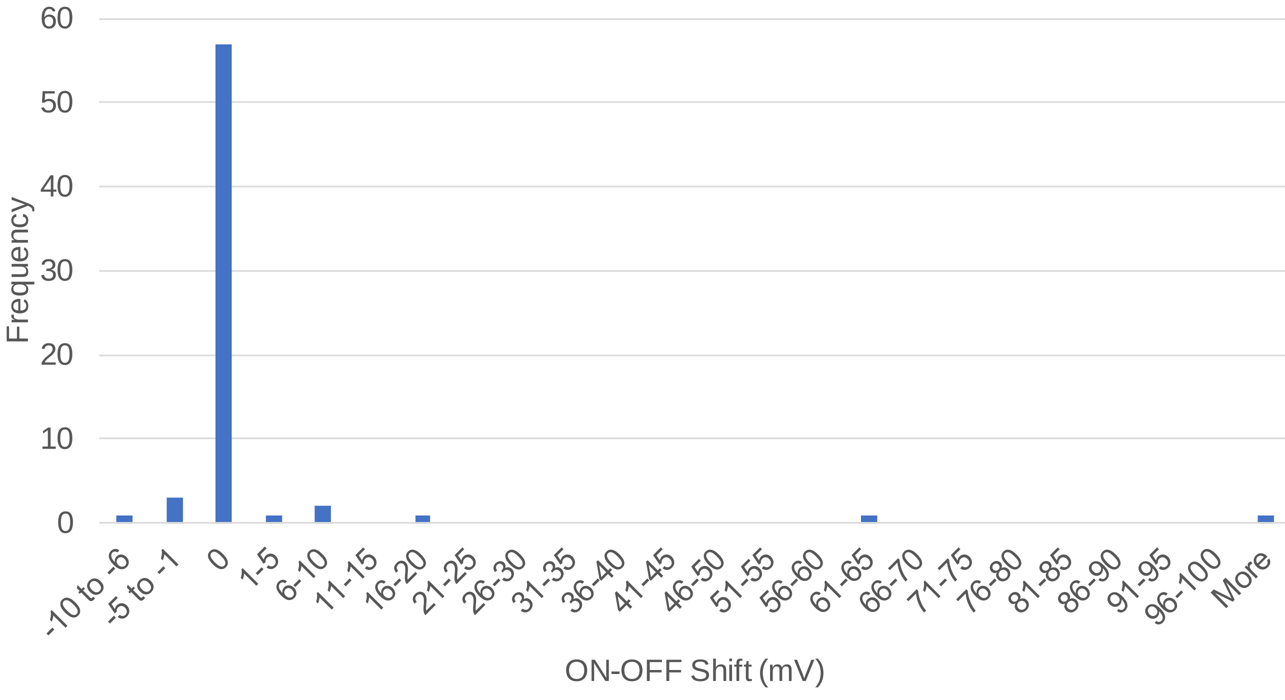

Figure 6: ON-OFF voltage shift recorded with coupon disconnected and pipeline's CP system interrupted.

The locations with more than 10 mV shift were examined to determine if there were any obvious causes for the larger voltage shifts. The location with 166 mV shift, which corresponds to Figure 5, was measured hundreds of meters away from the coupon and had a string of temporary galvanic anodes installed close to the coupon that were mistakenly left connected at the same test post. The two other locations had 20 mV and 66 mV shifts and were in the immediate proximity of company rectifiers. Each of these locations will be retested to determine whether or not the shift is eliminated by disconnecting these suspected sources of influence.

CONCLUSIONS AND FUTURE WORK

The present work re-evaluated the requirement for soil-access tubes to attain accurate coupon measurements. The soil-access tube requirement appears to result from testing on coupons that were installed close to coating defects on pipelines. Common causes of residual gradients were identified, and testing was proposed to determine the presence of residual gradients.

Based on this analysis and the preliminary field testing, soil-access tubes are not generally required to accurately measure disconnected coupon potentials on a pipeline in a multi-line corridor. In addition, the use of soil-access tubes cannot eliminate all residual gradients and can introduce errors.

Further testing is proposed to confirm the parameters under which the surface gradient testing can effectively detect residual gradients from foreign sources and to further validate the frequency at which significant residual gradients are likely to exist on coupons for new pipelines.

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