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Equalization Currents and Metallic IR Drop: Impediments to True Potential Measurements

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ABSTRACT

Recent close-interval potential surveys have raised concerns about the accuracy of potential measurements on some older, poorly-coated pipelines. Two significant sources of error were identified: metallic IR-drops and equalization currents. These resulted in measured on and off potentials which differed by hundreds of millivolts from the true potentials, even though the measurements were conducted in accordance with industry best practice.

Examples of these phenomena will be discussed and the electrical theory will be explained. Both interrupted test post surveys and close-interval potential surveys are susceptible and these errors can be difficult to detect. This can have a significant impact on interpretation of survey data, External Corrosion Direct Assessments, and remedial program decisions.

Guidance for identifying when these issues may be relevant and methods for detecting and compensating for these issues will be provided.

Key words: close-interval potential survey, CIPS, CIS, ECDA, equalization current, IR free, measurement error, metallic IR drop.

INTRODUCTION

Close-interval potential surveys (CIPS) are used extensively in the cathodic protection industry to provide a more comprehensive view of the cathodic protection levels along a pipeline. These surveys may be used independently to guide remedial programs or may be leveraged as part of External Corrosion Direct Assessment (ECDA) or other assessment techniques. If the potential measurements are found to be inaccurate, this can distort the conclusions of these efforts, leading to lower confidence in a company's programs, sub-optimal use of resources, and ultimately to increased risk profiles.

During several recent CIPS on older, poorly-coated pipelines in western Canada, anomalous potential measurements were observed despite the surveys being conducted using industry best practice. The cause of these problems was investigated, and two inter-related phenomena were identified: metallic IR-drop and equalization currents. All close-interval surveys and interrupted test post surveys are susceptible to these effects, with the degree of impact ranging from negligible to very significant.

MOTIVATION

Figure 1 shows an example of a dataset collected on a 15-km section of a pipeline where these effects were found to be significant. Along most of this section, this 1950's era NPS 12 pipeline runs alone in the right-of-way and all influencing rectifiers that could be identified were interrupted. Rectifiers and test posts are shown for reference.

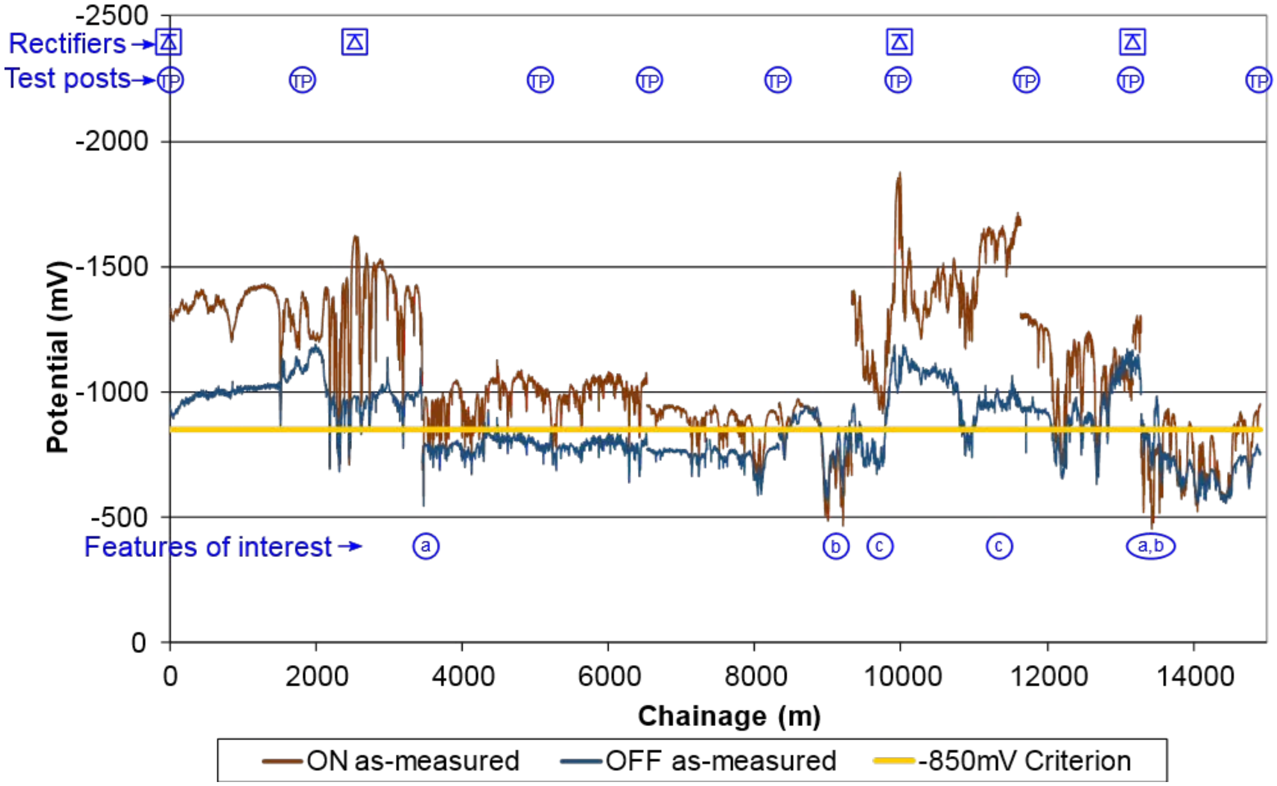

Figure 1: As-measured close-interval potentials on an NPS 12 pipeline.

There are several features which initially motivated a more in-depth study, including:

- Discontinuities (i.e. sudden changes) in both on-potentials and off-potentials at changes in connection points (generally tests posts), such as chainage 3.5 km and chainage 13 km: ⓐ
- Off-potentials more electronegative than on-potentials near chainage 9 km and chainage 13 km, which is typically indicative of DC interference: ⓑ
- Without changing connection point, on-potentials initially decreased then showed a noticeable increase again as the surveyors moved away from rectifiers, such as moving upstream and downstream from the rectifier at chainage 10 km: ⓒ

A close-interval survey on an NPS 4 pipeline of similar vintage showed some of the same features, but in a less exaggerated way, as shown in Figure 2. In this case, the surveyor started surveying in the downstream direction and arrived at a test post at chainage 7.1 km. Upon measuring near-ground and far-ground potentials at the test post, the potential shift was observed to be very different (64 mV instead of 1000 mV) and both the on- and off-potentials differed by more than 200 mV, although the alignment sheets indicated there was a test post located there. The surveyor made a field judgement that the test post was broken and went to the next downstream test post and surveyed back to this location, with the results shown on the same figure. In this case, the difference in the off-potentials was relatively small, and the difference in the on-potentials appeared much more reasonable, as shown.

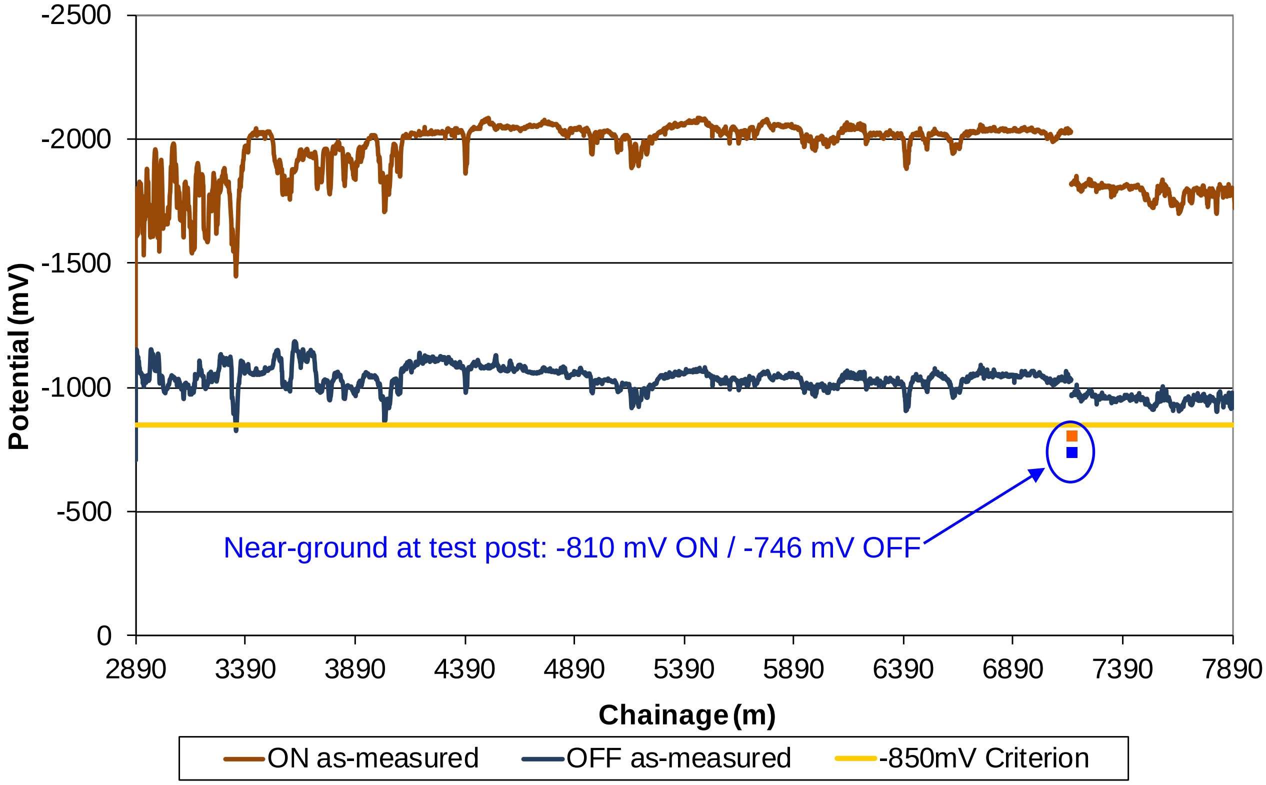

Figure 2: As-measured close-interval potentials on an NPS 4 pipeline.

However, when the data was reviewed in the office, the potentials on the test post could not be explained as there was no foreign crossing reported at this location. The pipeline owner mobilized quickly to correct the deficiency of only a single lead at this location, and it was found that the initial short lead reading was indeed the correct potential measurement at this location.

The issues identified in these datasets were attributed to a combination of metallic IR-drop and equalization currents. The following sections describe these phenomena, suggest approaches for overcoming their impacts, and outline the situations under which these phenomena may be expected to occur.

METALLIC IR-DROP

Overview

Metallic IR-drop results from current in the pipeline during the measurement. The NACE CP3 course expresses this error as $I_{pipe} \cdot R_{pipe}$[1], but this assumes constant pipeline current and lineal resistance. This relationship was expressed more generally by the author to account for these variations: formally, the metallic IR-drop $V_{metallic\text{-}IR}$ is the integral of the pipeline current $i_{pipe}(x)$ multiplied by the lineal resistance of the pipeline $r(x)$, evaluated from the survey connection point S (i.e. the test post) to the measurement point x:

$$V_{\text{metallic-IR}} = \int_S^x i_{\text{pipe}}(x) r(x) dx$$

This is illustrated in Figure 3 with the electrical measurement circuit shown in Figure 4.

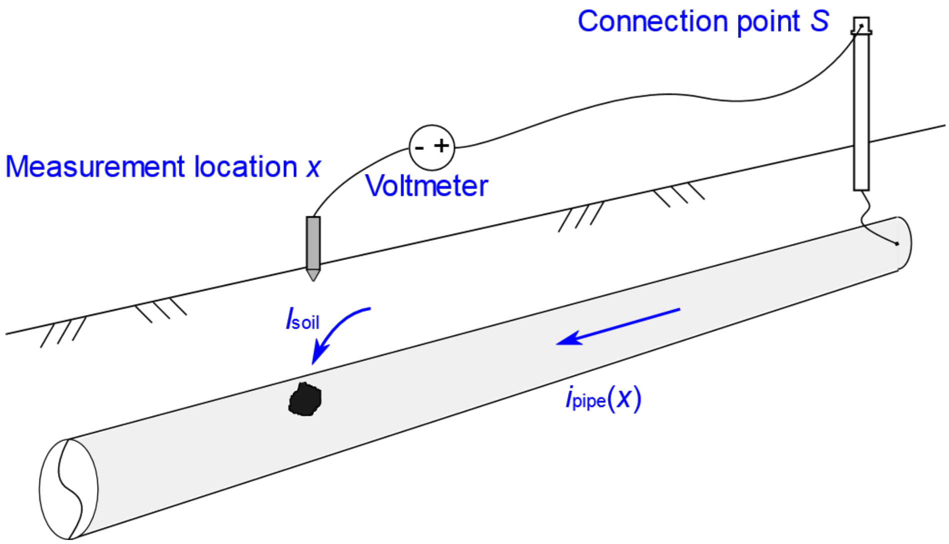

Figure 3: Illustration of the metallic IR-drop phenomenon.

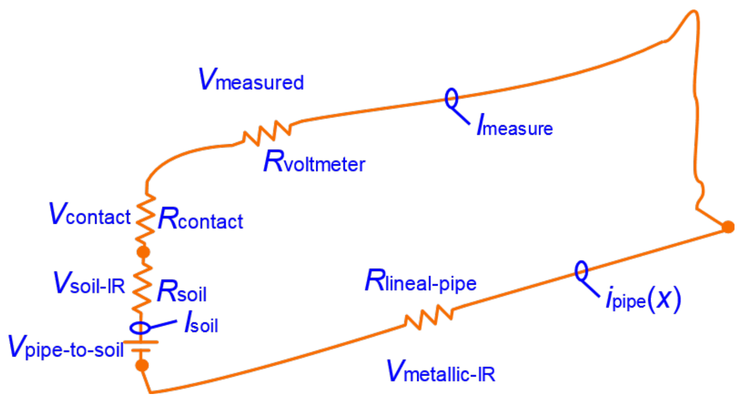

Figure 4: Simplified electrical measurement circuit illustrating metallic IR-drop.

Circuit branches are delineated by dots and only the most significant current in each of the branches of the circuit is shown. The complete circuit for the pipe current i_{pipe} and soil current I_{soil} are not shown, only their interactions with the measurement circuit. The pipe lineal and soil resistances are lumped into single values for simplicity of illustration. $V_{pipe\text{-}to\text{-}soil}$ is the true potential which should be compared with NACE SP0169's structure-to-electrolyte potential criteria.

Metallic IR-drop differs from the more well-known soil IR-drop, which is normally accounted for by conducting an interrupted survey as described in NACE SP0207-2007 section 5[2], in that it is a result of residual current in the pipeline as opposed to residual current in the soil. In most cases, it is observed primarily during the on-cycle when the rectifiers are energized and providing normal cathodic protection current to the pipeline network. As the on-potentials contain significant soil IR-drops, the off-potentials are usually relied upon to judge cathodic protection levels and an error in the on-potential may not have significant implications for the conclusions of the survey.

At least two NACE standards reference this phenomenon. SP0207-2007, in section 7.5.2, briefly describes the problem and suggests a very pragmatic but limited approach to gaining more information about the true protection levels, namely surveying in the opposite direction to accumulate the opposite error term. Although only on-potential errors are mentioned, the same theory applies to off-potentials.

The description in TM0497-2012 section 7.1.2[3] is more complete and provides two figures to describe the error term. However, guidance is not provided for how to properly account for this term.

Characteristics
Based on the formula for $V_{metallic\text{-}IR}$ given at the start of this section, the following observations about the metallic IR-drop term can be made:

- Test post measurements are not impacted; only measurements conducted away from the connection point can be impacted, which are most typically CIPS measurements
- The magnitude generally increases as the distance from the connection point increases
- Higher metallic IR-drops will result in areas with higher pipeline currents, typically close to rectifier drain connections
- The error can be either polarity, meaning the measurements could show better or worse protection levels, depending on the direction of survey with respect to the direction of the pipeline current
- The error is generally much larger for on-potential measurements because the pipeline current is higher. However, due to un-interrupted rectifiers or high equalization currents (which are described later), it is also possible that significant metallic IR-drops will be observed during the off-potential measurements

It is a partial misconception that metallic IR-drop will be more significant for small diameter pipelines with higher lineal resistances; for the same pipeline current, it is true that smaller diameter pipelines are more susceptible. However, the pipe surface area is proportional to the pipeline diameter and the pipeline lineal resistance is inversely proportional to the pipeline diameter. This means that a large diameter pipeline, particularly if it has a lot of coating damage, can be susceptible to significant metallic IR-drop because even though the lineal resistance is low, the current required to protect the pipeline is high.

Detection and Compensation
Metallic IR-drop is usually detected by conducting both far-ground and near-ground measurements at every connection point.[2,4] For both measurements, the position of the reference electrode must remain the same to avoid errors due to local gradients. The metallic IR-drop can also be measured directly by measuring the voltage between the trailing wire and the new connection point. Note that this measurement may be subject to telluric variations because the pipeline current can be influenced by telluric currents.

Depending on how the pipeline current varies, it may be possible to estimate the effect on the collected measurements without directly calculating the pipeline current by assuming the error varies linearly with the distance from the connection point.[4] This assumption matches the case of a pipeline with uniform current and wall thickness, meaning a pipeline with perfect coating acting as a conduit between a CP rectifier and another structure. However, it also matches the real case of a well-coated pipeline connecting a rectifier to a station or older mainline. For other cases, the integral should be solved using a reasonable assumption for the current distribution.

Figure 5 shows the compensated data for the case introduced in Figure 2. The measured parameters are tabulated in Table 1 assuming a steel resistivity of 18 µΩ·cm. As the pipe had widespread coating degradation, an exponential current attenuation was used to calculate the IR-drop rather than a constant/average current, but this average pipeline current was calculated and included in the table as a reference point.

Table 1: Example of metallic IR-drop data for NPS 4 pipe.

Pipe diameter [mm]	Wall thickness [mm]	Cross-sectional area [mm^2]	Lineal resistance [µΩ/m]	Distance between test posts	Measured metallic IR-drop [mV]	Calculated average pipe current [A]

				[m]	ON	OFF	ON	OFF
114.3	4.8	1651	109	4269	-1232	-290	2.65	0.62

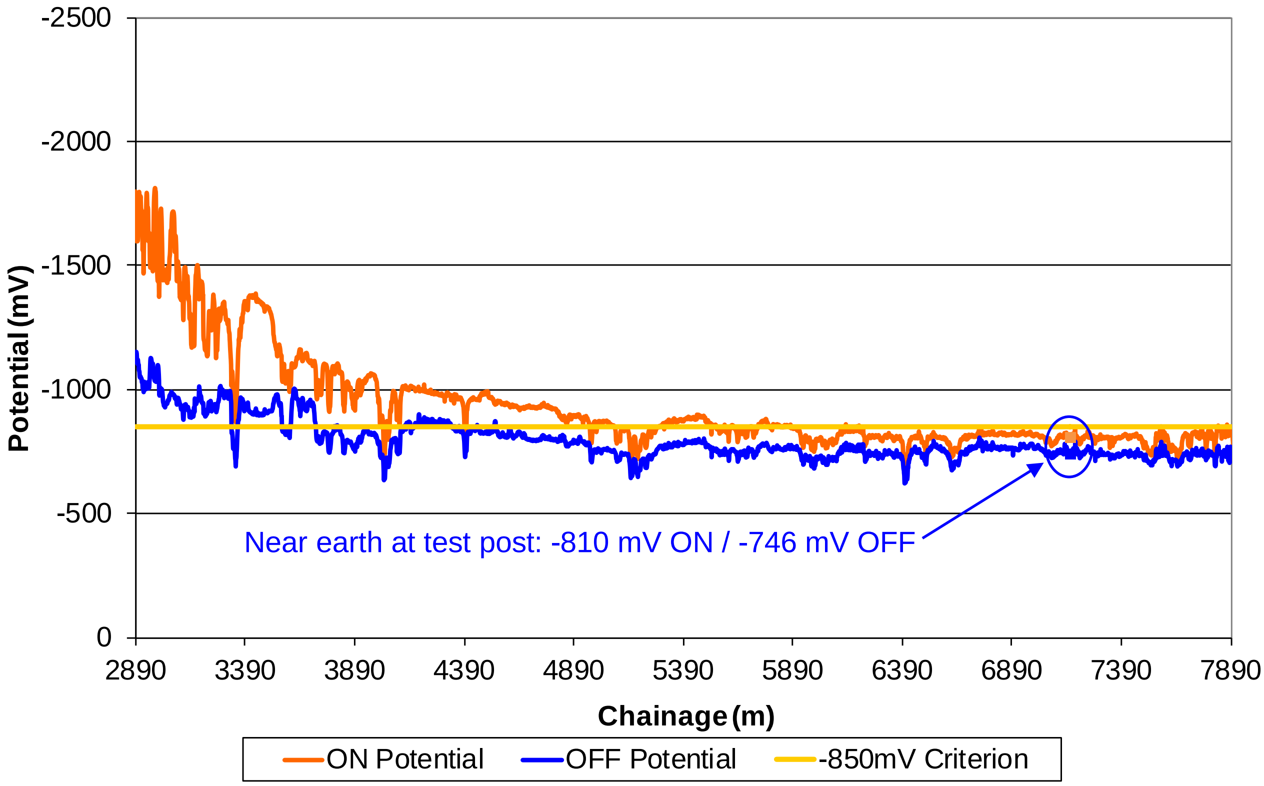

Figure 5: Close-interval potentials from Figure 2 compensated for metallic IR-drop.

Two notes of caution: first, because the compensation forces the potentials to match the values recorded at test posts, it is important not to automatically assume that matching potentials on the graph are equivalent to correct compensation; second, the linear approximation must not be applied when there is a rectifier connection but no accessible test lead between two test posts where a metallic IR-drop measurement is recorded.

EQUALIZATION CURRENTS

Overview

Equalization currents, also known as equalizing or long-line currents, result from varying potentials along a structure. For a cathodically protected pipeline, the potential variations primarily result from differing polarization levels. A bare or poorly coated pipeline, for example, would have a much higher degree of polarization near the rectifier connection. The differences in polarization are due to proximity effects to the groundbed and metallic IR drops along the pipeline, which consume the driving voltage. If the rectifier is subsequently interrupted, then during the off portion of the cycle the well-protected sections will tend to discharge a current to the poorly-protection sections, essentially acting as direct-connected galvanic anodes. This current results in residual soil IR-drop error plus metallic IR-drop along the pipeline. In poorly-protected areas, the measured off potentials will be more electronegative than the true off potentials, and in well-protected areas, the measured off potentials will be more electropositive than the true off potentials.

The equalization current phenomenon as it could occur during the off-cycle (i.e. zero rectifier current) is illustrated in Figure 6. In this case, the smaller coating holiday on the left is more polarized than the larger coating holiday on the right. Due to this voltage difference, the smaller coating holiday discharges current to the larger coating holiday, thereby acting as a CP source and resulting in soil IR-drop. The current returns via the pipeline, resulting in metallic IR-drop.

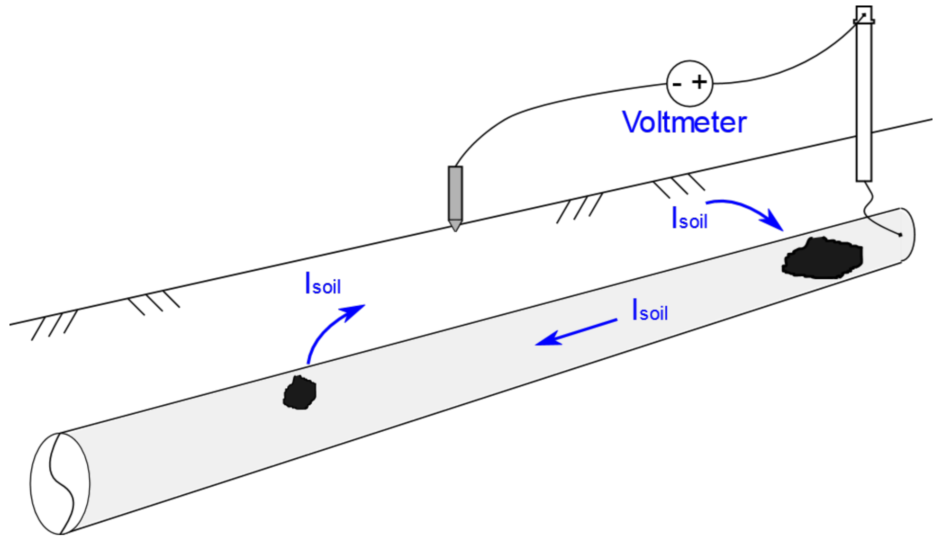

Figure 6: Illustration of very simple equalization currents during the OFF-cycle.

This simplified case does not reflect exactly what occurs on a real pipeline because each coating holiday will interact with more than one other coating holiday, the position of the rectifiers has a significant influence on the levels of polarization that develop at each coating holiday, etc. Nevertheless, the two main effects are illustrated: the generation of a soil IR-drop during the OFF-cycle due to non-zero I_{soil} at the coating holidays and the generation of an associated metallic IR-drop.

Although NACE SP0169-2013[5] does not directly address equalization currents, in Appendix B it cites the German and ISO standards; DIN 50 918 is quoted as stating, "equalizing currents that flow between different parts of the surface that have different polarities after the current has been switched off". ISO 15589-1[6] states that the 100 mV polarization criterion, "shall be avoided … when … equalizing currents … might be present". NACE TM0497-2012 sections 9.2.4 and 10.2 refer to long-line currents as a source of error which can impact instant-off potentials used for both the -850 mV_{CSE} and 100 mV criteria.

Characteristics

Compensation for equalization currents is more difficult than for metallic IR-drop because there is no direct measurement for the error. The error due to equalization currents is akin to soil IR-drop error, which is typically addressed using rectifier interruption and/or coupons rather than calculation. However, it is not possible to interrupt the sources of the equalization currents because they are part of the pipeline itself.

Potential measurements conducted during the steady-state condition (i.e. on-potential measurements) cannot be subject to equalization currents. This is because the differences in polarization are sustained by the operation of the CP system, and it is precisely the temporary absence of the CP system which results in these currents. Therefore, only off-potential measurements are subject to this error. Unlike pure metallic IR-drop errors, however, both close-interval and test post off-potential measurements are subject to this error.

Figure 7 shows a close-up of the CIPS data collected on the NPS 12 impacted by equalization currents.

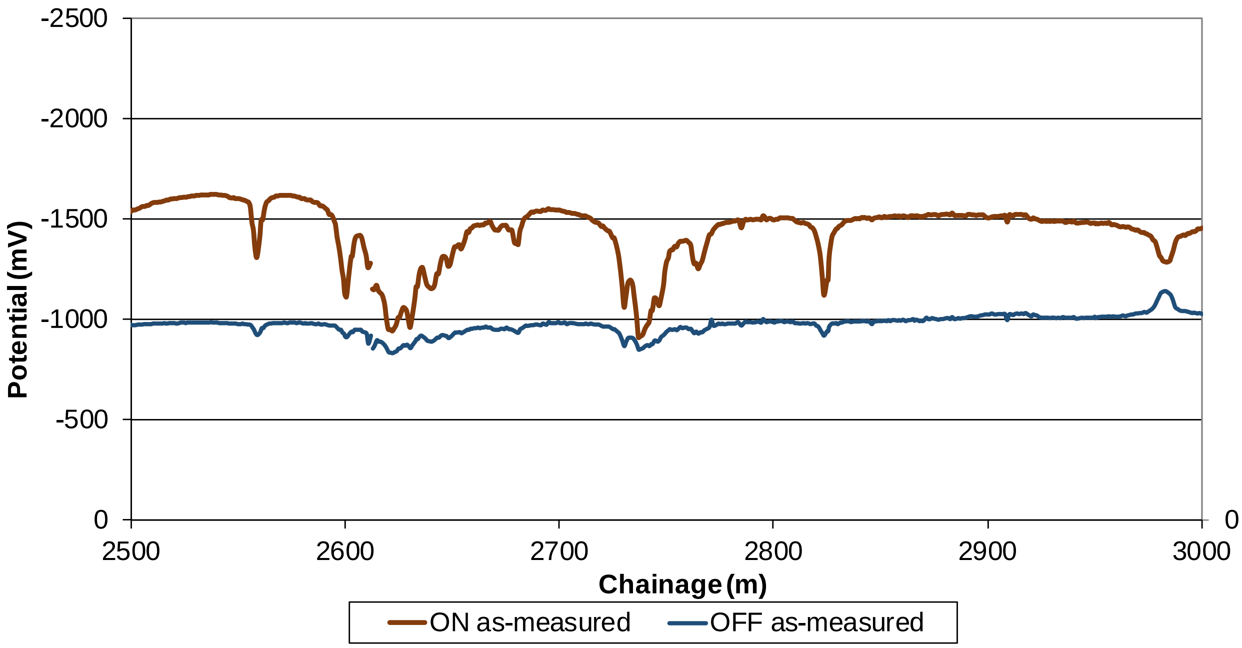

Figure 7: CIPS data from NPS 12 pipeline on section impacted by equalization currents.

The dips in on-potentials are typical for locations with coating defects. The characteristic dip shape results from the soil IR-drop being reduced as the surveyor approaches a coating defect, then being increased as the surveyor moves further from the coating defect. This type of IR-drop effect results from a coating defect picking up CP current.

The presence of a residual current during the off-potential measurements is confirmed for the coating defects between chainage 2550 and chainage 2850 by the presence of similar, but smaller, dips. In other words, during the off-potential measurements these coating defects continue to receive CP current and the true protection levels are more electropositive than the off-potential measurements.

At the indication near chainage 2980, however, the on-potential dips in the normal way, but the off-potential actually peaks at the indication. This electronegative peak shape is typical of magnesium anodes and results from current discharge.[7] The true protection level is between the off-potential measurement and the on-potential measurement. Note that although this isolated case could be attributed to a partially consumed magnesium anode, other locations with this characteristic have been excavated and confirmed to be coating defects.

Equalization currents are generally significant on bare/poorly-coated pipelines, but are present to some degree on all pipelines because in practice differing degrees of polarization always exist. The simplest approach to dealing with equalization currents on a pipeline is to elevate the protection criterion above the -850 mV_{CSE} because the measured polarized potentials are more electronegative than the true polarized potentials at locations with the lowest protection levels.

Alternatively, the use of IR-free coupons to estimate the magnitude of the soil IR-drop is a better approach, and the European CP community has reported success with inferring the IR drops based on the measured gradients, the so-called intensive or lateral gradient technique, which accounts for this residual current.[8,9]

Precise modelling of these effects requires a detailed understanding of the actual conditions on a given pipeline, including the location and extent of coating damage. In these specific cases, more extensive coating damage was observed near rectifiers and short sections with much higher or lower protection levels were found, despite similar proximity to rectifiers. Current attenuation rates may also vary due to different soil types (e.g. resulting from calcareous deposits). It was also observed that even though all the influencing rectifiers were interrupted, there were more locations picking up current during the off-cycle than there were locations discharging current during the off-cycle.

In addition to producing soil IR-drops, equalization currents also result in metallic IR-drops along the pipeline. The magnitude of this term would generally be low for well-coated pipelines. If this term is determined to be significant, in general it cannot be compensated using the same current approximation methods as the on-potentials since the equalization currents will have significant variation along the length of a pipeline and will in some cases reverse direction. Having test posts spaced more closely together would help to limit the impact of these metallic IR-drops on the measurements, especially near rectifiers where the affect is accentuated.

GUIDELINES FOR CONCERN AND CONCLUSIONS

This paper has described the impact of metallic IR-drops and equalization currents on potential measurements. These effects are most pronounced on bare or poorly-coated pipelines, which for the subject pipelines were 1950's era asphalt or coal-tar coatings. Two examples of the as-found coating quality are shown in Figure 8 and Figure 9. It is apparent that although some of the coating fell away during the excavation, the coating quality was very poor. It is under these conditions that the problems with metallic IR-drop and equalization currents will be most significant.

Figure 8: Extremely poor coating and calcareous deposits were observed on the NPS 12 pipeline.


Figure 9: Initial exposure of NPS 4 pipeline, prior to coating collapse.

The CP rectifiers were operating at very high currents in order to provide sufficient CP based on on-potential measurements at test posts and the coating deterioration was more pronounced near the rectifiers. The high currents also resulted in calcareous deposits at many locations, and at some of these locations calcareous deposits had developed on the outside of the coating. A section of pipeline with well-developed calcareous deposits is shown in Figure 10. To complicate the protection level assessments further, the operator has also observed significant seasonal variation in potentials on these pipelines, so the very low potentials measured in the summer are not necessarily representative of average protection levels on these pipelines.


Figure 10: Calcareous deposits on NPS 12 pipeline.

Although equalization currents are often considered in the context of multi-pipeline corridors, single pipelines are also susceptible. In addition, although a pipeline may look at first glance to be well-protected, it is important to carefully examine the available data and reconcile any deficiencies, especially in areas of the field reports where large disparities in data exist or non-expected results are found by the field survey crews. In addition, it should be noted that if coating and/or environmental conditions change, that these effects may become important on lines that were not previously susceptible to these significant measurement errors.

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