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Coating Conductance Characterization Using Trenchless Crossing Data

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ABSTRACT

Coating resistance or conductance values are critical input parameters for the accurate modelling and design of AC mitigation and cathodic protection (CP) systems for pipelines. However, there are relatively few sources for real-world coating resistance values in the literature. To attempt to fill this gap, data from coating quality tests performed on thousands of trenchless pipeline installations was used to characterize the coating resistance of new, primarily fusion bonded epoxy (FBE)-coated pipelines. The tests assess damage incurred as part of the trenchless installations and cover the full range from pristine coating to significant scratches with bare metal. This allows the dataset to provide insight into both a baseline for open-trench coating quality and a range of practical coating qualities for trenchless installations.

It was found that specific coating resistance values varied from less than 100 $\Omega\cdot m^2$ to >1 $M\Omega\cdot m^2$ but that there was no specific threshold that could be associated with pristine FBE coating. However, the data clearly validated the '300 mV shift' design guideline for CP systems, which also demonstrates the link between CP current requirement and coating quality. Considering this, the implication of requiring a certain current density irrespective of coating quality is illustrated.

Key words: Coatings, Corrosion control, Cathodic protection, Simulation and modeling, Coatings performance

INTRODUCTION

Coating conductance tests for pipeline trenchless crossings provide information about coating damage sustained during installation. The test essentially measures the pipeline resistance[a] to the earth and a relationship between the coating conductance and the percentage of bare pipeline was developed.[1] The test methodology was later improved with the addition of a visual assessment and a current requirement test.[2] The applicability of the methodology to deep HDDs was also confirmed experimentally[3,4]. While the primary purpose of these coating conductance tests, which have now been conducted on thousands of trenchless installations varying from track bores to kilometre-long HDDs, is to assess and mitigate for *in situ* coating quality when traditional coating inspections are impossible, the data is also applicable to

[a] Coating resistance and coating conductance are inverses of each other.

more general design practices. Although trenchless installations are expected to sustain more damage than traditional open trench installations, this paper explores the possibility of establishing a practical target for specific coating resistance based on the aggregate coating quality data, with the best trenchless installations representing the excellent coating quality representative of open trench installations.

The design parameter that captures coating quality for cathodic protection and AC mitigation design is the specific coating resistance. This factor is influenced by the volumetric resistivity of the factory- and field-applied coatings, coating thickness and coating damage sustained during installation. For modern coatings with minimal damage, soil resistivity plays a negligible role in the overall pipe resistance.

The volumetric resistivity of the factory-applied coating is generally a known material property but the specific coating resistance calculated from this resistivity is out of the range typically considered realistic for pipeline coatings. For example, the specific coating resistance for one brand of 0.36 mm thick (14 mil) single-layer FBE with a volumetric resistivity[5] of 1.2×10^{13} Ω·m would be 4.3×10^{9} Ω·m² since:

$$r = \rho \times t$$

where:

r = specific coating resistance (Ω·m²)
ρ = resistivity of coating (Ω·m)
t = coating thickness (m)

Under longer exposure at ambient temperature, a stable value of $\sim1\times10^{7}$ Ω·m² was reported on a single-layer FBE.[6] However, there is relatively little data in the industry for specific coating resistances on as-installed pipelines. These lab values far exceed the "Excellent" value for transmission pipelines of "$>10^{4}$ Ω·m²" provided by the NACE CP3 course manual.[7] Practical design values based on experience for FBE are in the range of $8\text{-}10\times10^{4}$ Ω·m².

The most likely source for the large difference between lab and design data is coating damage sustained during installation. A rough approximation can be made of the impact of coating damage: by calculating the resistance R of a single 1 cm² coating defect (diameter d = 0.0113 m) in ρ_{soil} = 10 Ω·m soil ($R = \rho_{soil}/(2d)$) on a 1 km-long section of NPS12 (0.324 m diameter) pipeline, the equivalent specific coating resistance can be shown to drop from the values identified above to 4.3×10^{5} Ω·m². Under these circumstances, the volumetric coating resistivity of the factory-applied coating is almost completely dominated by the single coating defect (note: a coating with infinite resistivity paired with a 1 cm² defect would have an equivalent specific coating resistance of 4.5×10^{5} Ω·m²).

Whether design calculations are performed manually or the CP and AC systems are modelled using specialized software, establishing a realistic value for the specific coating resistance would allow the industry to design more accurate, efficient and cost-effective CP and AC installations.

COATING CONDUCTANCE DATA

More than 3800 coating conductance tests were analyzed to characterize *in situ* coating resistances. In most cases, the coating was a two-layer fusion bond epoxy (FBE) system, identified variously in the field as dual-FBE, dual powder system, abrasion resistant, double FBE or FBE with an abrasion resistant overcoat. Coating thicknesses reported from the field varied from 12-137 mils and crossing lengths ranged from 10 m to 3.5 km with the distribution shown in Figure 1. Nearly half of the tests were conducted on bores less than 50 m in length.

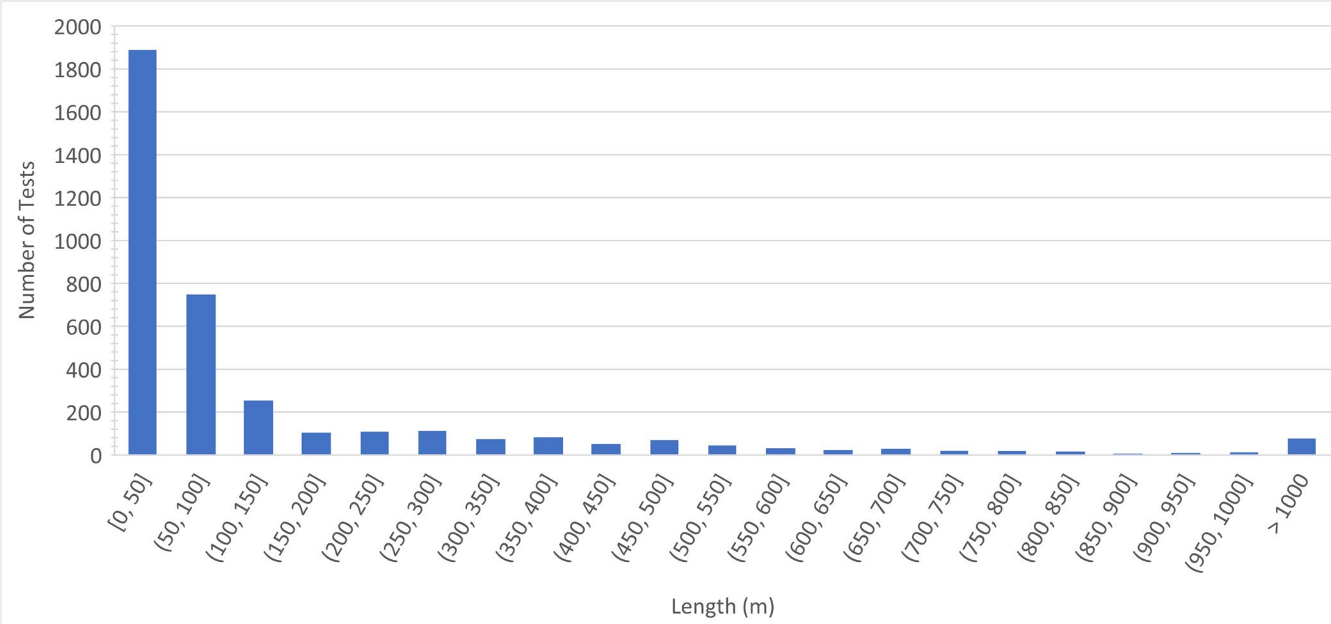

Figure 1: Number of Tests per Crossing Length Range

For 44% of the tests, the specific coating resistance was not determined because the pipe had insufficient contact with the soil to measure a stable potential. In some cases, it is possible that shorter crossings, especially for oversized bores, may have had voids and/or minimal contact between the pipe and soil. These tests, which had an average length of 47 m versus 148 m for the entire dataset, were excluded from the subsequent analysis, leaving a pool of 2131 test results with an average length of 227 m.

A histogram of the specific coating conductance for the 2131 tests is shown in Figure 2. 24% of the tests sustained enough coating damage that the specific coating resistance was below 1×10^4 $\Omega\cdot m^2$ whereas 28% of the tests had a specific coating resistance in excess of 2×10^5 $\Omega\cdot m^2$.

A second histogram for the same data is shown in Figure 3 to provide more granularity for the higher coating resistance range. Although 54% of the tests had specific coating resistances less than 1×10^5 $\Omega\cdot m^2$, a significant percentage (7.3%) exhibited specific coating resistances in excess of 3×10^6 $\Omega\cdot m^2$. The maximum measured specific coating resistance was 2.2×10^8 $\Omega\cdot m^2$. By comparison, based on the reported coating thickness of 40 mils, the theoretical specific coating resistance using the volumetric resistivity indicated above would be 1.2×10^{10} $\Omega\cdot m^2$ (assuming the girth welds were also factory-coated).

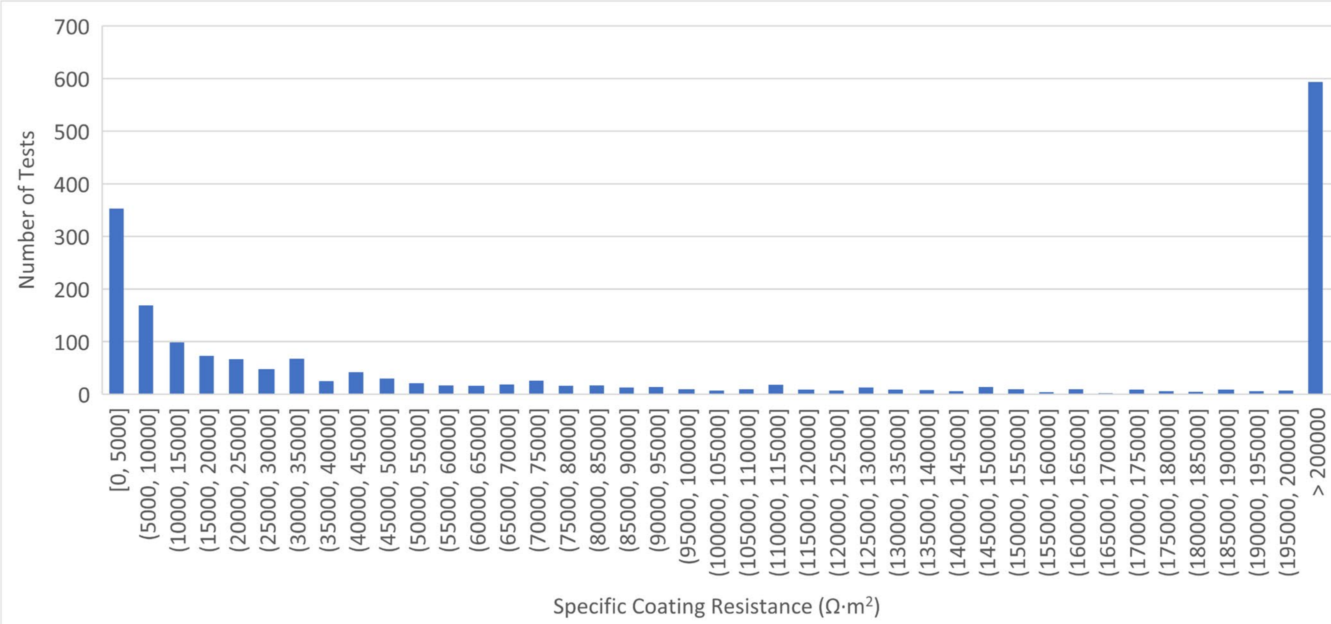

Figure 2: Number of Evaluations per Specific Coating Resistance Range (Moderate Ranges)

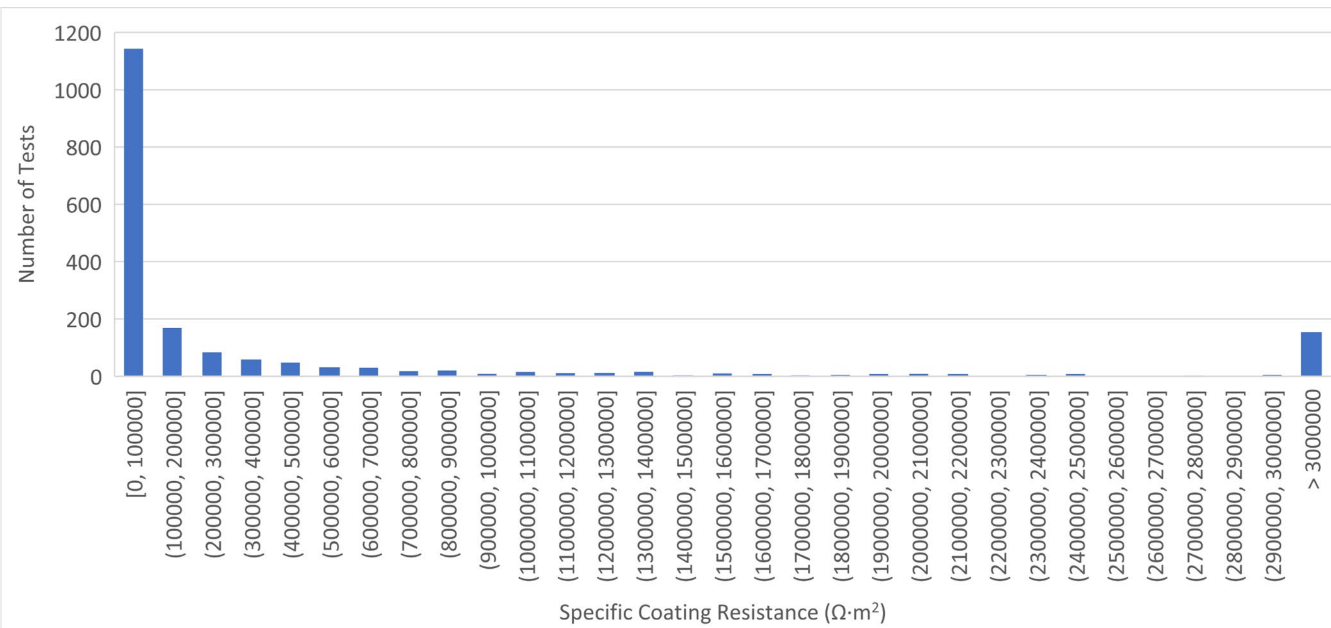

Figure 3: Number of Evaluations per Specific Coating Resistance Range (High Ranges)

The specific coating resistance versus crossing length is shown in Figure 4. Although there is a trend of decreasing coating quality as crossing length increases, the scatter at even short crossings is large. Note that unstable potentials (i.e., the tests without calculated coating conductance) were reported at more of the shorter crossings, so the distribution shown is not entirely representative. Nevertheless, a short crossing is no guarantee of excellent coating quality, as shown by the wide range of specific coating resistances for shorter crossings, with the most extreme case a 15 m crossing with a 245 $\Omega \cdot m^2$ coating.

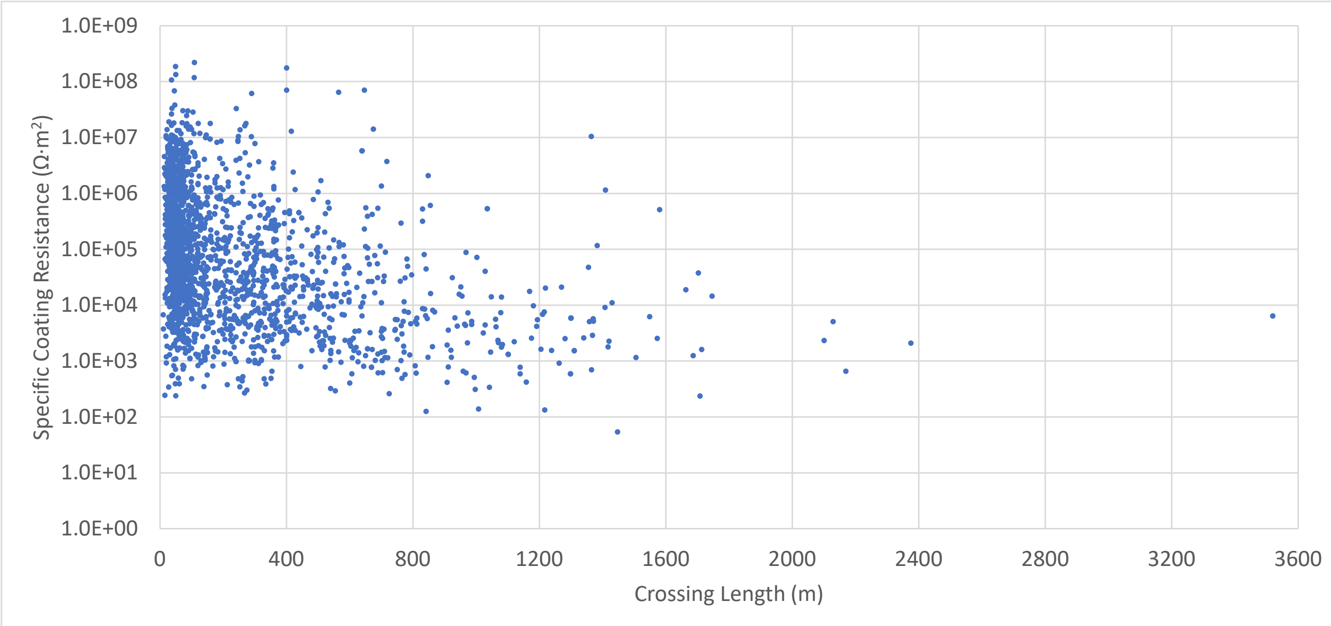

Figure 4: Specific Coating Resistance vs. Crossing Length

There are few hard guidelines which can be pulled from this dataset, which indicates the importance of the coating quality tests, although generally coating resistance decreased as the crossing length increased. However, even for short crossings the resistance varies by 6 orders of magnitude, and still by 5 orders of magnitude for crossings longer than 700 m. For longer crossings, which would have proportionally larger impact on the CP system operation, the resistances were generally lower, with most tests (84%) indicating a resistance less than 20 kΩ·m^2 for pipes longer than 1 km. As a result, it would be prudent to incorporate a lower resistance for crossings into the CP design process. The values shown in Table 1 could be considered for design guidance.

Table 1: Specific Coating Resistance Thresholds vs. Length

Length	Specific Coating Resistance which 90% Exceeded (Ω·m^2)	Median Specific Coating Resistance (Ω·m^2)
Less than 100 m	35,000	140,000
100 m to 1000 m	1900	26,000
More than 1000 m	590	4100
All tests	*2200*	*46,000*

This is a summary, but at one extreme, a value only two orders of magnitude lower than the material's volumetric resistivity was measured, whereas many other locations, even for short crossings, had specific coating resistivities five or six orders of magnitude lower than this. This variability is attributed to the quality of the installation, which is likely a function of the soil/access conditions (e.g. rock vs. soil), quality control procedures, coating type(s), company standards and installation contractor experience. With the high variability in the data, no threshold could be identified that would correspond to excellent open trench installations.

One limitation for these test results is illustrated by data from Singh and Cox, as shown in Figure 5.[6] For approximately 5 days after installation, FBE absorbs moisture. Therefore, if the conductance test is performed before a steady-state is attained, the resistance could be expected to drop. Nevertheless, the moisture absorption might have minimal impact on tests with resistances much lower than ~1×10^7 Ω·m^2 since these lower resistances are expected to be dominated by the coating damage.

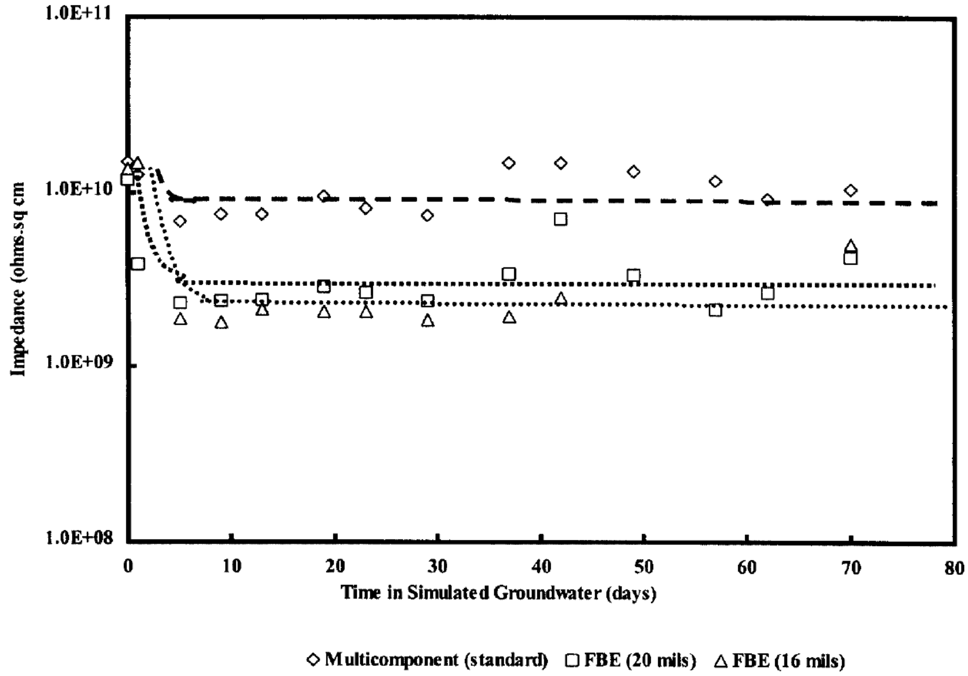

Figure 5: Impedance of Powder Coated Multi-Component Coating and FBE from EIS Measurements (from Singh and Cox)

CURRENT REQUIREMENT DATA

In addition to collecting coating resistances, current requirement testing to achieve 100 mV polarization was performed as part of the tests. For most tests, this data was collected twice: first, in a way that was incidental to the main conductance test; and second, as a one- or two-hour remedial CP assessment. The duration of the first test data could vary significantly based on actual test conditions (number of technicians performing the test, site access, etc.). However, as the incidental current requirement test data is more complete, these values are plotted with respect to the specific coating resistance in Figure 6.

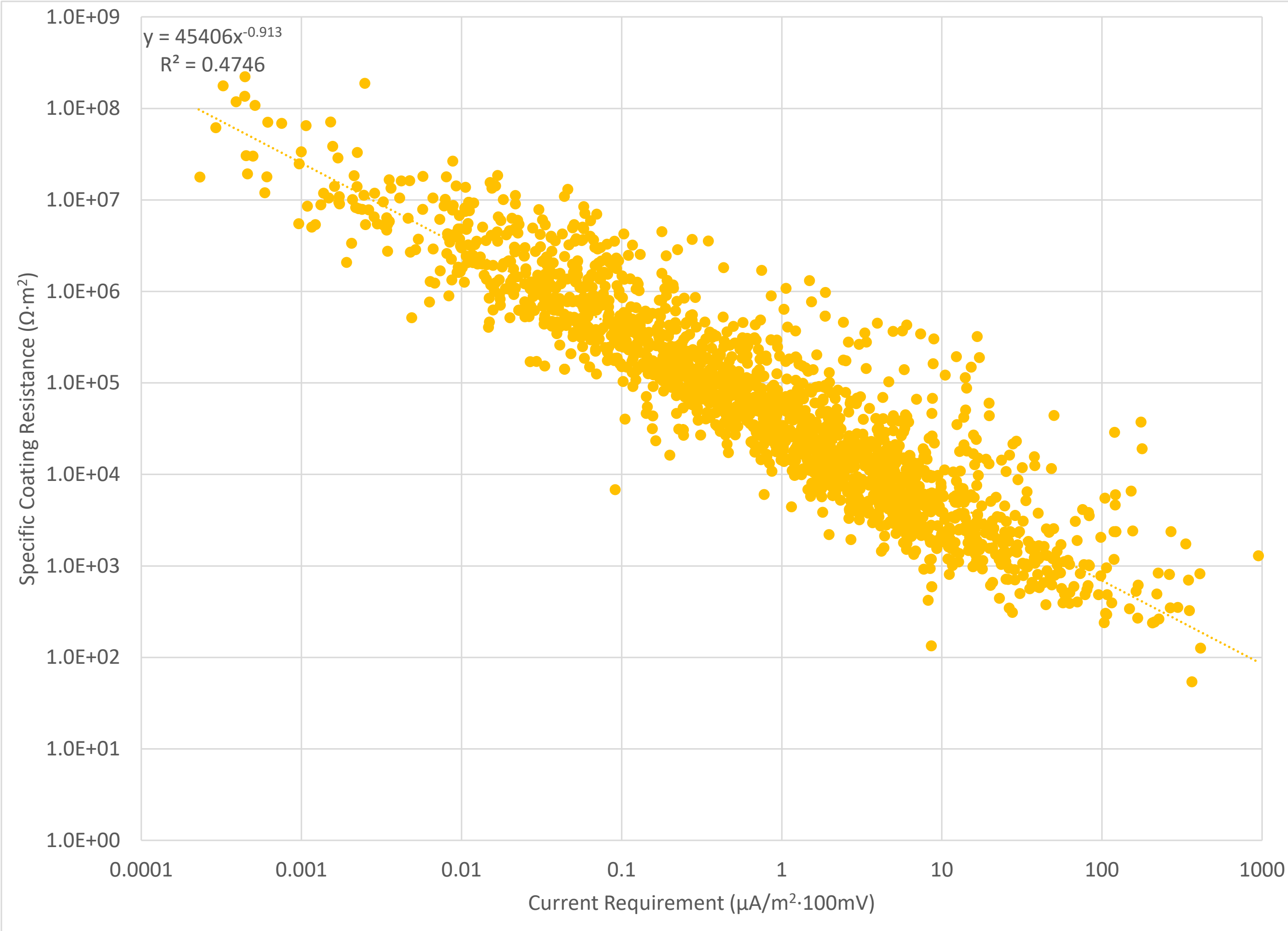

Figure 6: Specific Coating Resistance vs. Current Requirement from Incidental Test

Fitting the data with a power function gives a relationship of:

$$r = 45406i^{-0.913}$$

where:

r = specific coating resistance ($\Omega\cdot m^2$)

i = current requirement ($\mu A/m^2$)

The author is not aware of another experimental dataset providing this type of relationship between specific coating resistance and current requirement, although it is important to note that this is short-term (and hence conservative) current requirement data. This data indicates that for a given coating resistance, the practical current requirement at a specific coating resistance varies by about two orders of magnitude, e.g. at 1×10^5 $\Omega\cdot m^2$, the current requirement varied from 0.1 $\mu A/m^2$ per 100 mV up to 14 $\mu A/m^2$ per 100 mV.

This current requirement relationship is compared in Figure 7 with the traditional '300 mV shift' design guideline[b] (equivalent to $r = 300000i^{-1}$), a design approach under which at least 300 mV is applied across the coating. The data from the 1-2 hour current requirement data were also plotted and show that on average the remedial current requirement tests required 71% of the current indicated by the (typically shorter) incidental tests.

[b] The 300 mV guideline used to appear as a protection criterion in RP0169, the predecessor to SP0169 "Control of External Corrosion on Underground or Submerged Metallic Piping Systems". It appeared in the 1983 version but was removed during the 1992 revision.

95% of the incidental current requirement data and 98% of the 1-2 hour current requirement data would be satisfied using the 300 mV shift guideline. This indicates that the 300 mV would be a suitable CP design approach for most isolated cross-country pipelines.

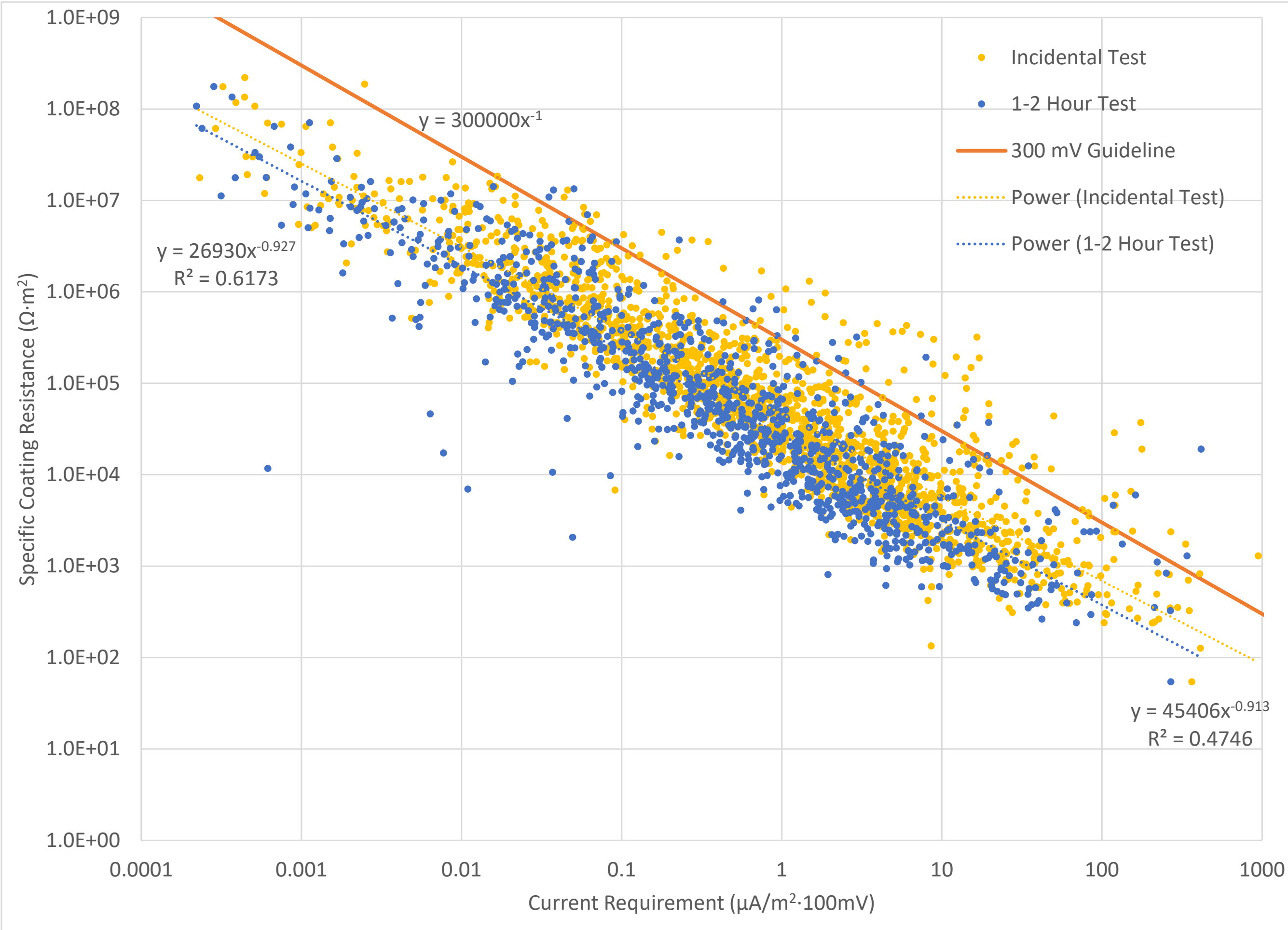

Figure 7: Current Requirement Data and 300 mV Shift Guideline

This finding also highlights the interplay between current requirement and coating resistance, with better quality coatings generally requiring a lower current density. This impacts CP design in the sense that specifying a current requirement, e.g. 10 μA/m², irrespective of coating type and quality may result in unrealistic restrictions. For the specific case of zinc sacrificial anodes, which at the -850 mV_{CSE} protection criterion nominally have a 250 mV driving voltage, the maximum coating quality that could be protected if 10 μA/m² is specified would be 25 kΩ·m². In other words, for better quality coatings, this calculation approach would indicate zinc cannot provide adequate protection. This is generally not realistic, as shown in Figure 8 where zinc could be used to protect 94% of the tested pipes based on the incidental data or 97% of the pipes based on the 1-2 hour current requirement data and the 100 mV polarization criterion.

The requirement for both coating quality and current requirements is the result of different environmental conditions having different polarization characteristics.

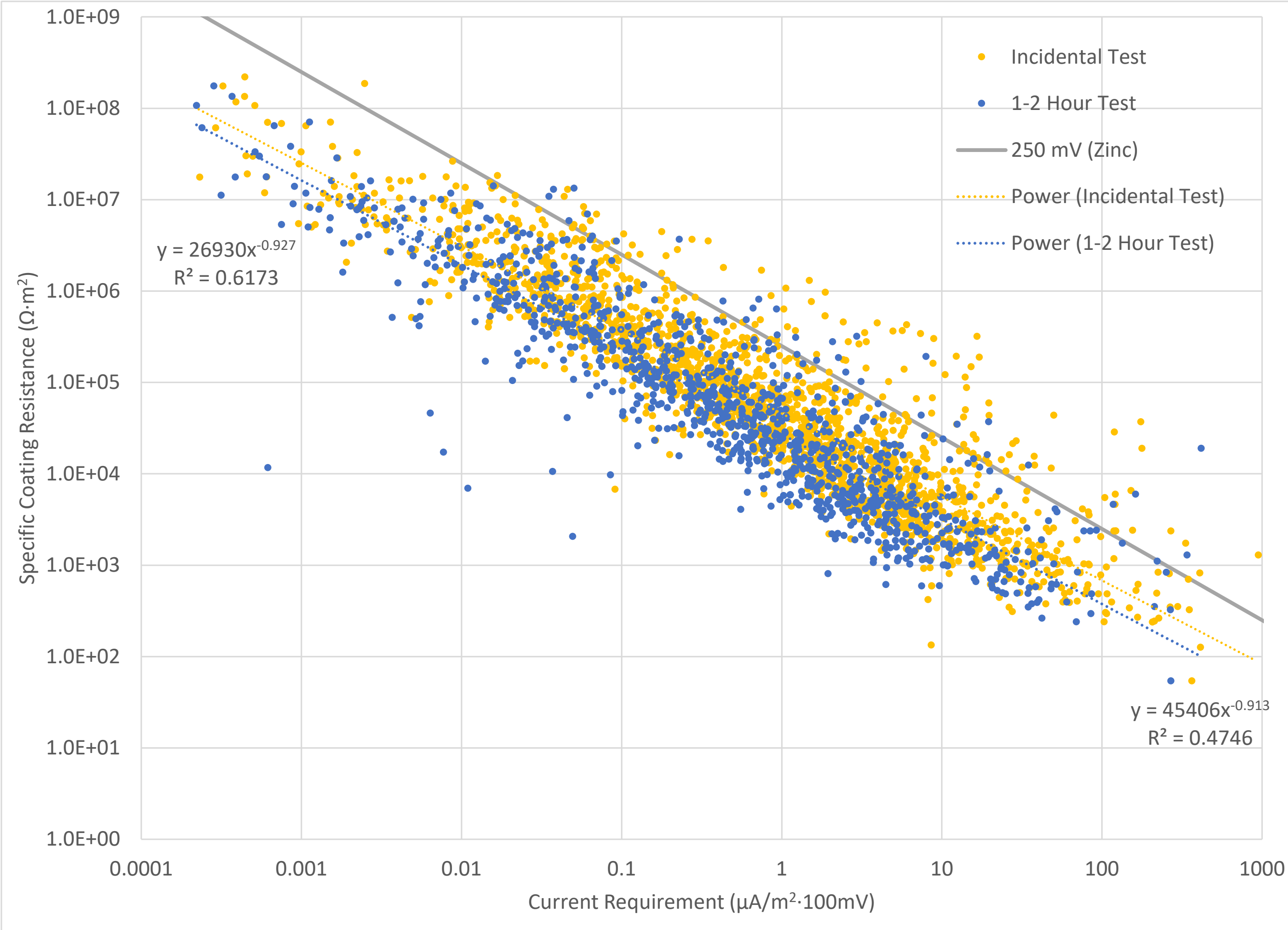

Figure 8: Current Requirement Data and 250 mV Zinc Driving Voltage

CONCLUSIONS AND RECOMMENDATIONS

Although the stated objective was to identify a practical specific coating resistance value for design purposes, this was not possible based on the available data. Instead, the coating resistance was found to be highly variable and is likely heavily dependent on the quality of the installation, which in turn is impacted by the soil/access conditions, bore length, quality control procedures, coating type(s), company standards, installation contractor experience, etc.

A statistical dataset on coating conductance obtained from 2131 coating quality tests of trenchless crossing pipelines was provided. A guideline for CP design for trenchless crossing pipelines was also analyzed. The dataset was used to confirm that the 300 mV guideline is usually appropriate for design to achieve 100 mV polarization. It is probable that longer-term current requirement data would indicate that the 300 mV guideline would also be appropriate for satisfying the -850 mV copper-copper sulphate polarized potential criterion in most cases. To confirm these findings, repeated coating conductance tests should be performed over the first 5-10 days after installation to assess the impact of moisture absorption on specific coating resistance. It would also be beneficial to characterize current requirements versus application time to determine how well shorter polarization periods correlate with longer term current requirements.

The confirmation of the 300 mV guideline provides added benefit that Operators may be able to include in their standard practices. By including it in their Operating or Design standards the operator would have the confidence to know that their pipeline will achieve 100 mV of polarization. This could possibly allow for more standardization and consistencies for the Operator.

Furthermore, future testing to determine the effects on various field weld coatings and non FBE coatings would be beneficial to determine if the data trends noted above remain true. It would also be beneficial to conduct coating conductance tests on stretches of isolated cross-country pipelines to establish current requirements and coating resistances under the open trench scenario.

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