# COATING QUALITY TESTING OF DIRECTIONALLY DRILLED PIPE SECTIONS

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## ABSTRACT

Methods of determining the coating quality on directionally drilled pipe sections were investigated in a research project sponsored by the Pipeline Research Committee of the American Gas Association. Tests were conducted on FBE coated pipe samples which were buried in three different soil conditions and equipped with steel strip coupons to simulate coating damage. A field test procedure, which can be performed by a CP technician, was developed that estimates coating quality in terms of percentage bare.

Keywords: directionally drilled pipe, coating quality, test method, coating conductance, current requirements

## INTRODUCTION

This paper presents details of a research program, sponsored by PRC International, the pipeline research committee of the American Gas Association, which resulted in the development of a test procedure, that can be conducted by a cathodic protection technician, to estimate the coating quality on directionally drilled pipe sections. This research study assessed the characteristics of coating damage that typically occurs on bored piping, evaluated eight methods of determining the extent of coating damage, chose two methods for field testing on buried pipe samples having known bare areas, and developed a procedure that a corrosion technician can use in the field to estimate the coating quality on a directionally bored pipe section.

## EVALUATION OF COATING TEST METHODS

The following eight test methods, composed of four DC and four AC techniques were evaluated based on a set of weighted criteria:

DC Methods –
  Close Interval Survey, DC Voltage Gradient, Cathodic Protection Current Requirements, Coating Conductance

AC Methods –
  AC Voltage Gradient, Electrochemical Impedance, Waveform Analysis, AC Signal Attenuation

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The evaluation criteria included:

- applicability – the applicability of the method to the situation
- accuracy – the ability of the technique to determine the size and location of the coating damage
- ease of use – ability of field personnel to carry out the testing
- availability of the instrumentation and its cost
- efficiency – the time and labour requirements to conduct the test
- miscellaneous – ability of test to produce other useful corrosion control information

Information on the various methods was obtained from equipment manufacturers literature, from published papers, and from personal experiences. The coating conductance and AC signal attenuation methods received the highest scores in the foregoing evaluation and both these techniques were therefore assessed in the field on buried FBE coated pipe samples where the bareness of the pipe was known and could be varied. The cathodic protection current requirements method was also evaluated in the field, after it was realized that much of the data needed was easily obtainable from the conductance tests.

## FIELD TEST ARRANGEMENT

Strip steel coupons of varying widths were mounted on each of three 11m long, 0.5m diameter, FBE coated, pipe samples. Figure 1 is a section view of the coupon arrangement and Table 1 summarizes the coupon details.
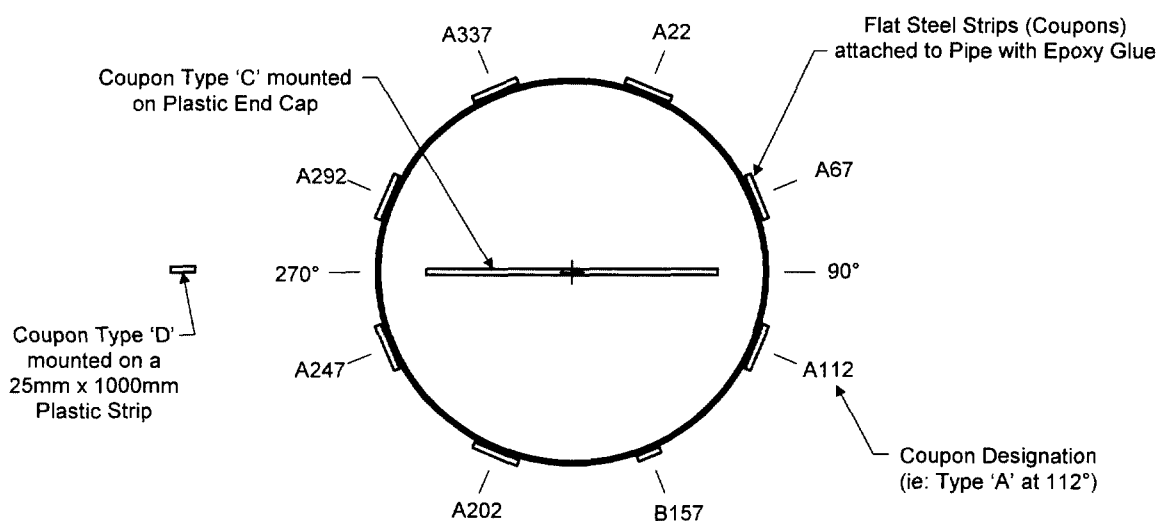


**Figure 1 – Typical Coupon Orientation**

**Table 1 – Coupon Details**

| Type | Dimensions (mm) (W x T x L) | Surface Area m² | % Bare per Coupon | No. per Pipe Sample |
|------|------|------|------|------|
| 'A' | 35 x 0.5 x 3200 | .112 | 0.630 | 21 |
| 'B' | 5 x 0.5 x 3200 | .0160 | 0.09 | 3 |
| 'C' | 2 x 0.5 x 450 | .0009 | 0.005 | 1 |
| 'D' | 2 x 0.5 x 1000 | .002 | 0.01 | 1 |

The percent bare value for each coupon relates to the bare area of the coupon compared to the coated surface area of the pipe sample.

Each coupon was connected to an individual insulated conductor of a multi-conductor cable for each of the three coupon groupings. With this arrangement the bareness of the pipe sample could be simulated from 0.005% to 13% of the coated surface area.
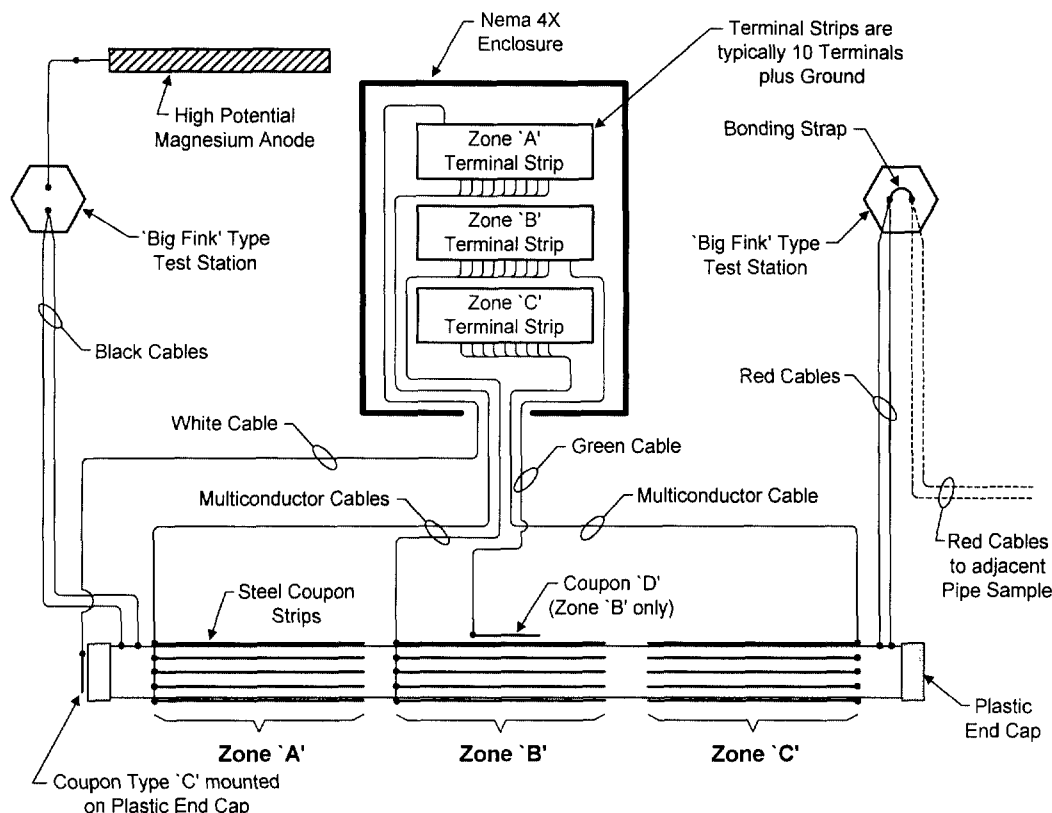


**Figure 2 – Typical Electrical Schematic for Each Pipe Sample**

Each of the pipe samples was buried in soil having a low, moderate, and high resistivity with the intent to have an order of magnitude difference in resistivity between the three soils. The pipe samples were buried in separate excavations as shown in the site plan of Figure 3. Test current was provided by three magnesium anodes, each of which was buried opposite
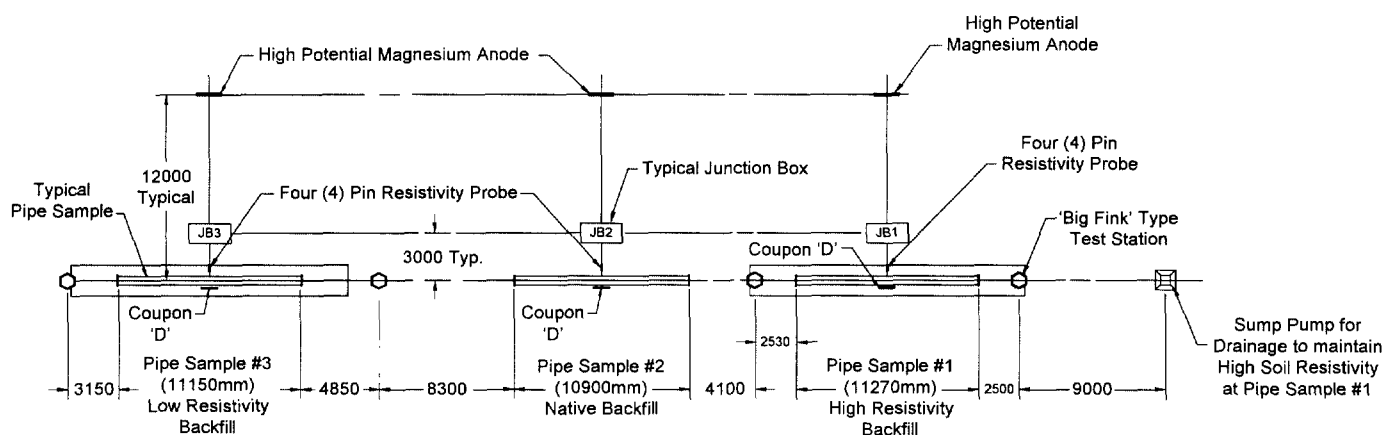


**Figure 3 – Plan View of Pipe Samples**

each pipe sample at a distance of 12 meters. The native soil was clay having a resistivity of about 1800 ohm-cm in which pipe sample 2 was installed. Sample 1 was surrounded with sand, extracted from the Ottawa River, and the excavation contained drainage pipes so that the sand was well drained, therefore producing a relatively high resistivity in the 30,000-

50,000 ohm-cm range. Pipe sample 3 was surrounded by sand that contained sodium chloride in order to produce a soil resistivity of a few hundred ohm-cm. A four pin probe was buried at the mid point and at mid elevation of each pipe sample to facilitate measurement of the soil resistivity periodically during the duration of the field testing. All coupon and pipe conductors were identified, run to a junction box, and connected to individual terminals on a terminal strip. Each terminal strip contained all the coupons and a pipe test lead for one of the coupon groupings. In addition, two test leads were connected to both ends of each pipe sample and run into a separate test station so that the three pipe samples could be bonded together to simulate field conditions in which a drilled pipe section is welded to adjacent piping.

## FIELD TEST PROCEDURE

Coupon potentials and currents were measured and recorded with the reference electrodes located directly above the pipe sample, off-set 3m from the centerline, and 6m remote as per the test circuit schematic illustrated in Figure 4. With this reference electrode positioning and coupon arrangement, the conductance of each pipe sample in each soil condition was calculated and compared over a range of bare areas located randomly on the pipe sample, at the end of the pipe versus the middle, and on the bottom of the pipe versus the top.
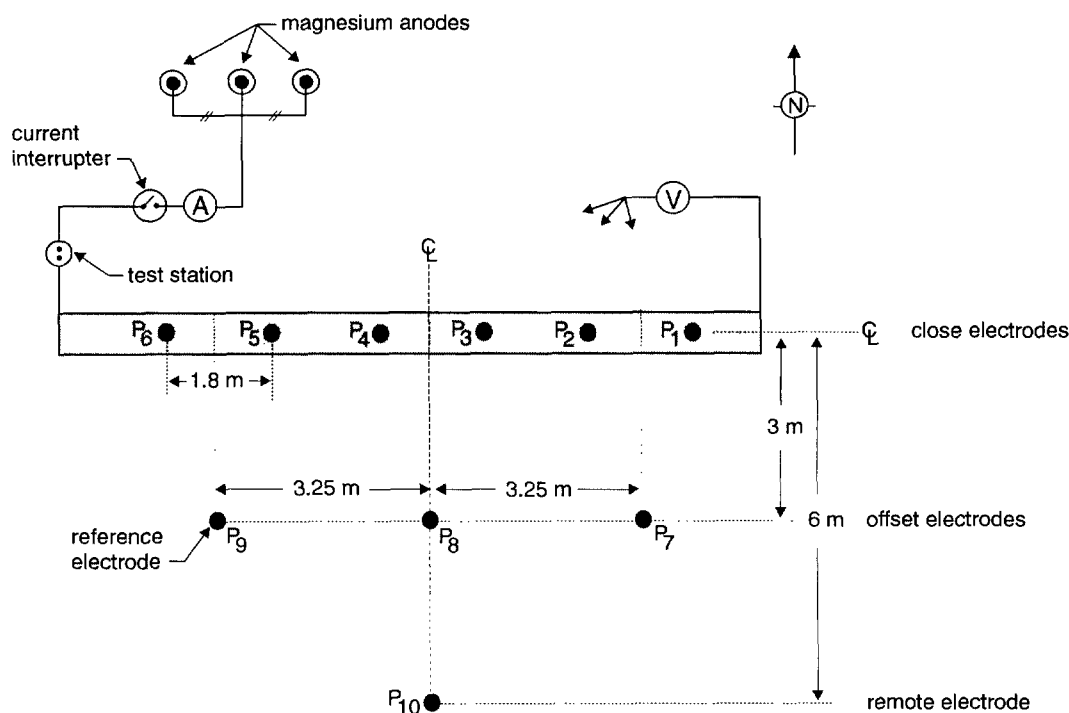


**Figure 4 – Circuit Schematic for Conductance Test on an Isolated Pipe Sample**

After preliminary analysis of the initial data it was decided to add a 'D' coupon having a .002 sq. m surface area in order to provide more data points and therefore greater accuracy for the small percentage bare conditions. In addition, it was realized that if the corrosion potentials of the coupons were recorded and the test current controlled so that hydrogen would not be generated at the steel surfaces, then a current requirements parameter, based on a fixed amount of cathodic polarization, could also be calculated for comparison with the percentage bare. Subsequent testing incorporated these modifications.

Conductance tests were then conducted on each pipe sample with it isolated but with the current controlled to limit the polarized potential to −1050mVcse in order to avoid hydrogen evolution. Each pipe sample was also connected to a remote ground electrode to simulate connection of a directionally bored pipe section to adjacent piping and conductance tests were repeated. The test circuit used for the foregoing tests is shown in Figure 5.
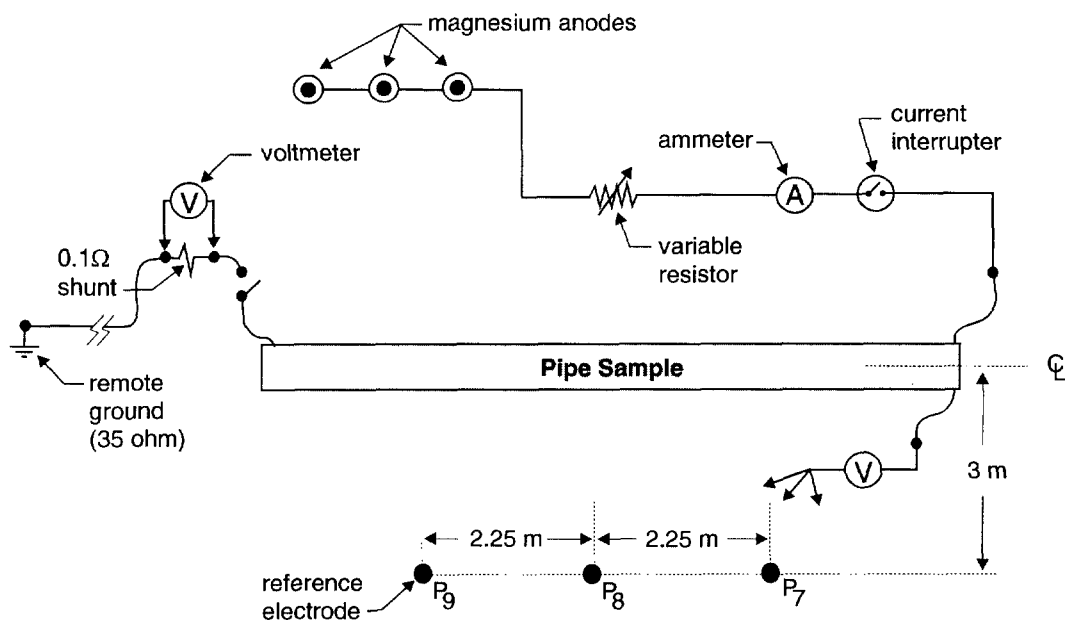
**Figure 5 – Test Schematic for Measurement of Conductance with the Pipe Sample Grounded or Isolated and With or Without Current Control**

To evaluate the attenuation method of calculating pipe conductance, the pipe samples were interconnected through 0.1 ohm shunts and to a remote ground electrode. This arrangement, as illustrated in Figure 6, was also utilized to assess the Radiodetection PCM instrument for measuring current attenuation along the pipe sample network. The transmitter of this instrument produces a 4Hz AC current that, because of its low frequency, has conduction characteristics similar to DC current.

Proton based magnetometers were also employed in an attempt to measure DC current along the same piping arrangement as illustrated in Figure 6.
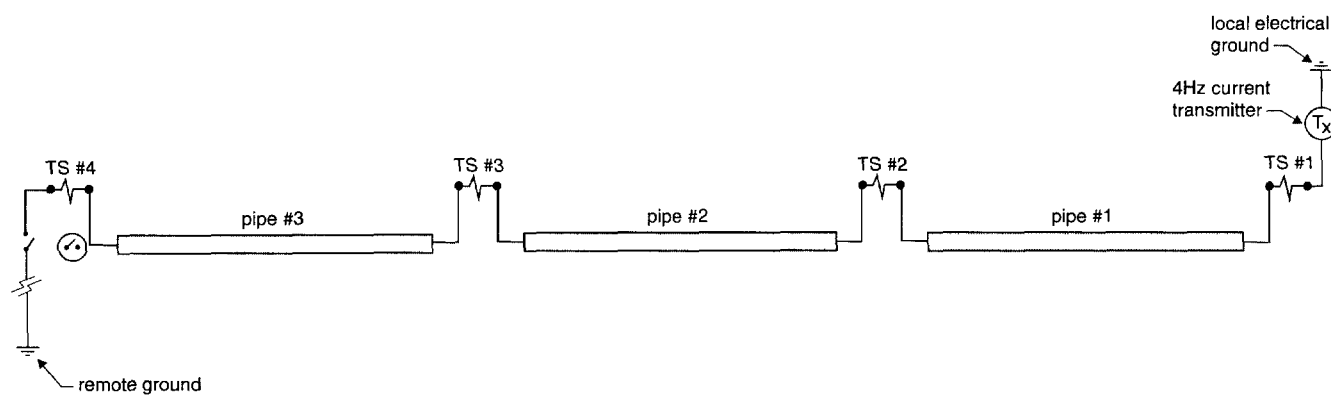


**Figure 6 – Schematic for Current Measurement with Pipe Samples Interconnected and Grounded**

## General

Conductances, as calculated by the general method, expressed in $\mu S/m^2$ (micro-siemens per sq. m), when plotted on a log-log graph versus pipe percentage bare generally produced straight line correspondence with a high degree of correlation [i.e. $R^2$ values of 0.9 or greater]. The general method calculates the conductance (g) of the pipe by dividing the test current $(\Delta I_t)$ by the average change in potential $(\Delta V_{ave})$ and the surface area $(A_s)$ of the pipe sample as per the following equation:

$$g = \frac{\Delta I_t}{\Delta V_{ave} x A_s} \left( \mu S / m^2 \right)$$ 

[1]

Hence, for comparison of the results for the different variables, because the data extended over several orders of magnitude, the log of the conductance expressed in micro-siemens per sq. m was plotted against the log of percentage bare.

## Conductance Versus Soil Resistivity

As illustrated in Figure 7, the highest conductance was in the low resistivity soil and the lowest conductance was in the high resistivity soil. In general the ratio of the calculated conductance for any two soil resistivities at any percentage bare were the same or similar to the ratio of the soil resistivities. This means that to use conductance effectively as an indication of coating quality, the conductance values must be normalized to a singular resistivity, such as 1000 ohm-cm. Measurement of soil resistivity at pipe depth in the field is therefore required to determine the average soil resistivity.
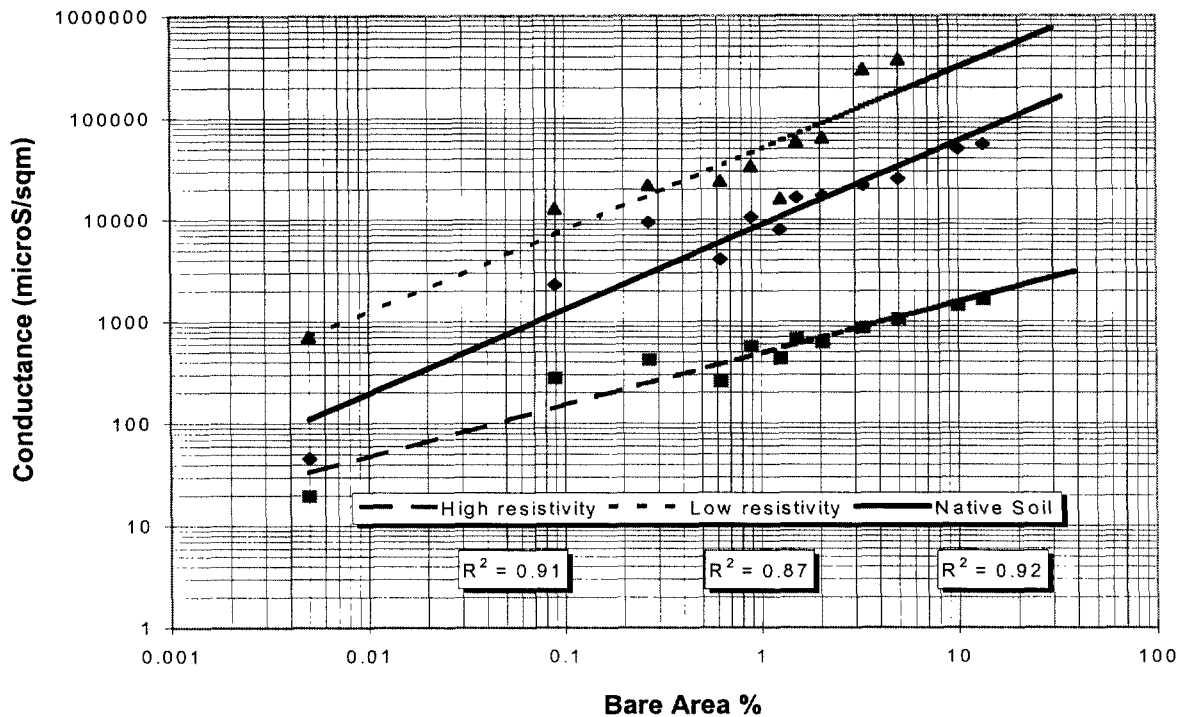


**Figure 7 – Comparison of Conductance versus Bare Area for an Isolated Pipe Sample in Three Different Soil Resistivities**

Conductance Versus Coupon Location

Conductance was found to vary with coupon location between top and bottom compared to randomly located bare areas in all three soil resistivities, although the effect was most pronounced for the high resistivity soil surrounding sample 1, as shown in Figure 8. Bare areas located on the bottom quadrant of the pipe exhibited a higher conductance than either those randomly located or those on the top quadrant. This was attributed to the fewer current paths available to the top quadrant bare areas, because the pipe was buried about 1 meter below grade, as well as to a soil moisture gradient from top to bottom in the sand backfill with the highest moisture and hence highest conductance being at the bottom quadrant. Bottom coupons also exhibited the highest conductance on pipe sample 2 compared to the top and to randomly located coupons. In this case the entire difference was attributed to the reduced current paths for the top quadrant as there was no significant moisture gradient in the native clay soil. Regardless, these differences were not considered a serious restriction on the use of the conductance technique in the field since the bored pipe is normally at considerable depth where the geometry of the current paths for top or bottom coating damage would be virtually identical and where the soil moisture would likely be relatively uniform.
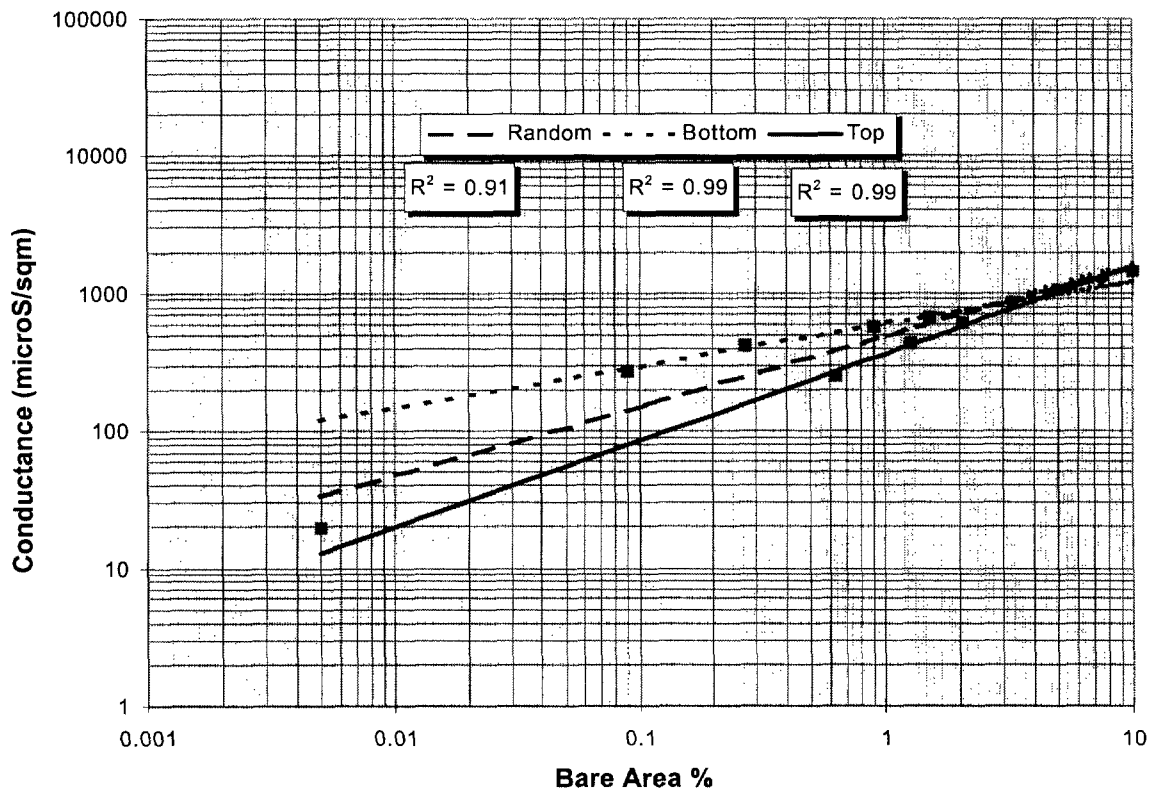


Figure 8 – Conductance versus Bare Area – Comparison Between Top and Bottom Coupons on Isolated Pipe Sample #1 in High Resistivity Soil

There was no significant difference in calculated conductance between equal sized bare areas located in the middle of the pipe compared to the end for pipe sample 2 located in the native clay soil. For both the high and low resistivity environments however, the bare areas located at the end of the pipe sample had a higher conductance than the middle. The difference was attributed to resistivity variations within the sand backfill in each of these excavations. The conductance differences for end versus middle bare areas should be negligible because the symmetrical positioning of the reference electrodes should result in the same average change in potential regardless of bare area location as long as the bare areas are of equal size. Nevertheless, when applying this technique to long sections of pipe, where the reference electrodes are placed only at the two ends, there could be a significant difference in the calculated conductance due to the location and size of the bare area. A comparison of the average potential change at each end of the pipe must be made before proceeding with the conductance calculations to insure that an error is not introduced.

Conductance Versus Reference Electrode Position

There was a high degree of correlation between the conductances calculated using potentials recorded by the offset references and the remote reference, as illustrated in Figure 9 for pipe sample 2 in the native soil conditions. This observation was also true for the other two soil conditions. Conductances calculated from potentials recorded by the close electrodes did show some minor variations with both the offset and remote references. It is apparent that, if a closely placed reference electrode is located opposite a localized bare area, then an error will be introduced compared to a more remote reference.
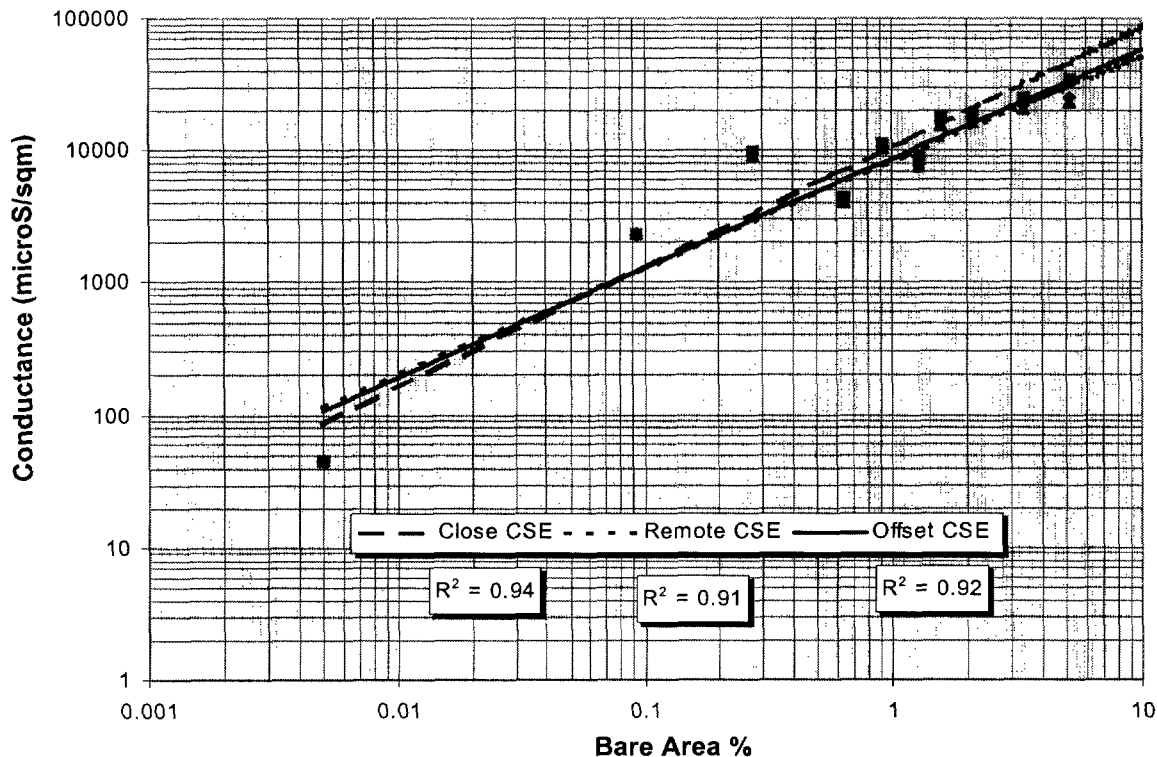


**Figure 9 – Conductance versus Bare Area with respect to Close, Offset and Remote Reference Electrodes for Pipe Sample #2 in Native Soil Conditions**

Conductance Variation with Grounding of Pipe Samples

Each pipe sample was tested to determine the effect on the measured conductance with the pipe sample connected to a 35-ohm ground and compared with the results when the pipe section was isolated. The circuit schematic for this series of tests is illustrated in Figure 5 and illustrates that the potential measurements were made only with respect to three offset references.

Figure 10, which shows the results of these tests, indicates that the conductance versus bare area curve is virtually identical for the grounded and current controlled-isolated case on pipe sample 2 in the native soil conditions. In the high resistivity soil however, the calculated conductance was greater for the grounded condition than the current controlled case, ostensibly because the ground electrode was in low resistivity soil. It appears that where the ground electrode is located in a markedly different soil resistivity (1500 ohm-cm versus 31,000 ohm-cm) an error is introduced which makes the pipe section appear to have a higher conductance.
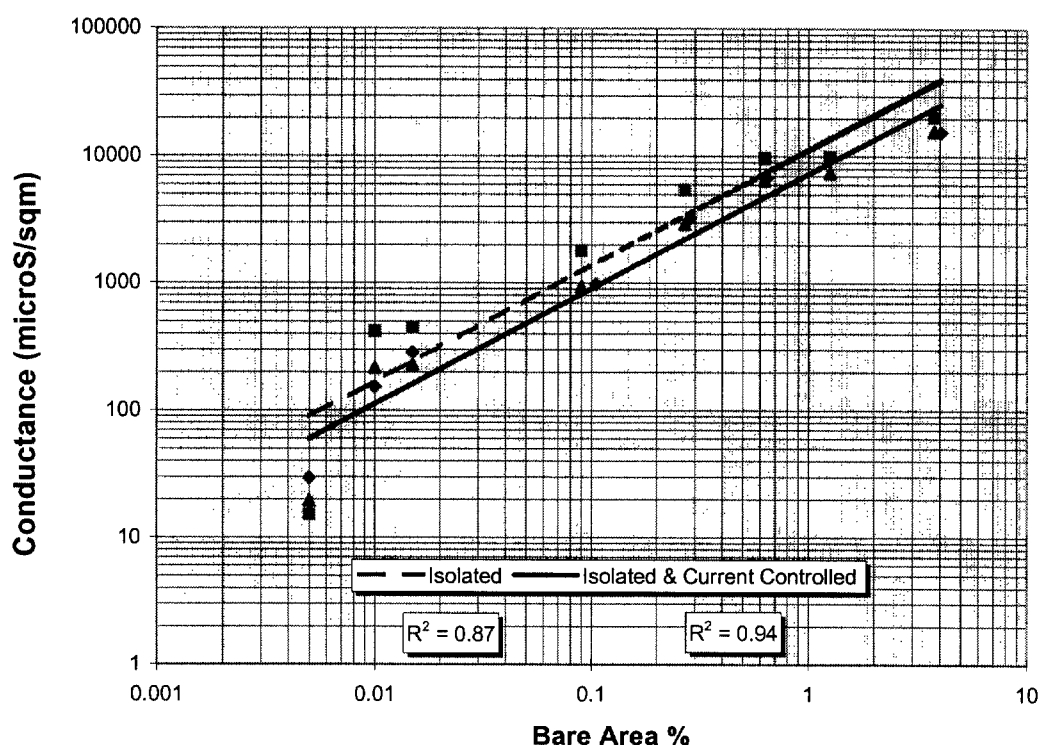
**Figure 10 – Conductance versus Bare Area – Comparison Between Isolated and Isolated with Current Control for Pipe Sample #2 (Native Soil)**

Conductance Versus Polarized Potential

The test circuit of Figure 5 was also used to determine the effect on conductance while controlling the magnitude of the test current to maintain polarized potentials less negative than −1050mVcse. This current control test was applied to pipe sample 2 in the native clay conditions since, during the isolated test, polarized potentials routinely became more negative than −1100mVcse, where hydrogen would likely be produced at the bare surfaces of the coupons. When the current was controlled to limit the polarized potentials, the calculated conductances were significantly lower for equivalent bare areas as shown in Figure 10.

Current Requirements Versus Bare Area for Different Soil Resistivities

Polarized potentials and currents recorded during the conductance tests on the isolated samples were used to calculate a current requirement factor based on the current density needed to produce 100mV of cathodic polarization. To determine the amount of polarization shift, the coupons were disconnected for a four-week period after which their corrosion potentials were measured and the difference between the polarized potential and the corrosion potential was calculated.

As indicated on Figure 11, the current requirements factor of $\mu A/m^2$ (micro-amperes per sq. m) demonstrated a linear relationship versus the percent bare on a log-log graph with a reasonably high degree of correlation, similar to that obtained with conductance testing. Unlike the conductance parameter however, the current requirements were not dependent on the soil resistivity, although there was some variation in the current requirements between large areas and small bare areas for the three resistivity conditions. This difference was attributed primarily to the fact that corrosion potentials were measured for groups of coupons rather than for each individual coupon on every pipe sample. Otherwise, it was expected that pipe sample 1 buried in the high resistivity sand would exhibit generally higher current requirements, because of the higher oxygen availability at the bare surfaces, compared to pipe sample 2 in the native clay soil and pipe sample 3 located in a high water table. This appeared true only for the larger bare areas possibly because of oxygen concentration polarization at the small surface area coupons.
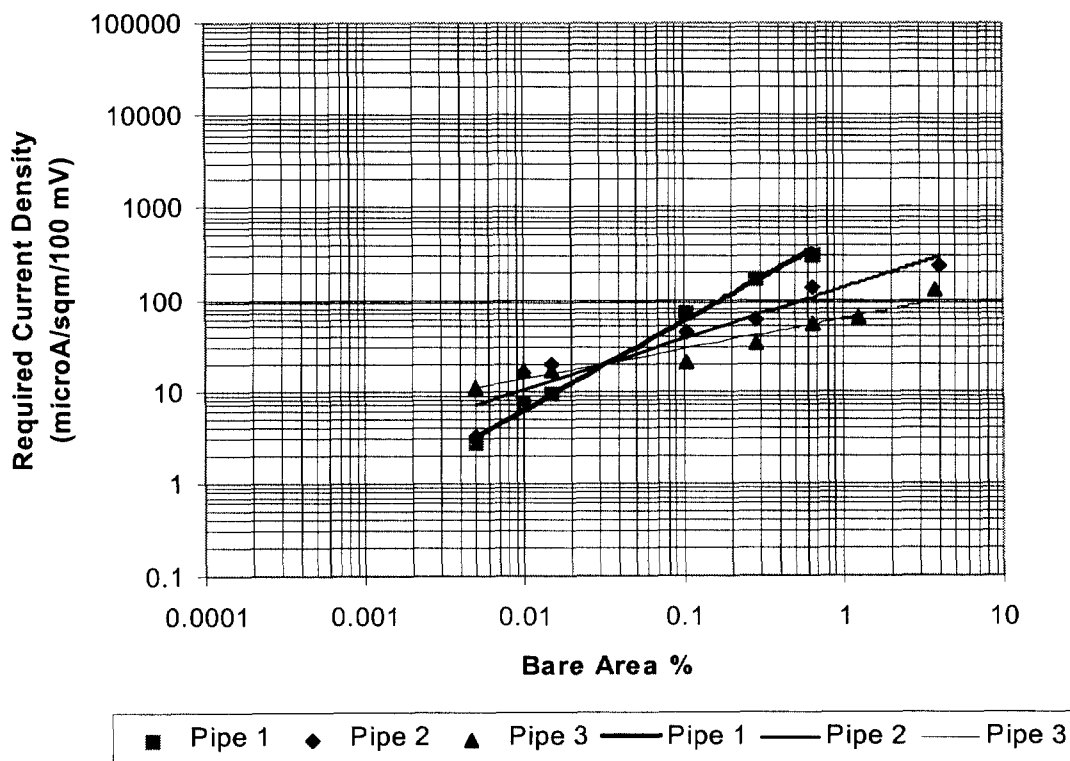
**Figure 11 – Current Density Factor vs. Bare Area
– Comparison of Pipe Samples #1, #2 and #3**

Pipe Current Measurements

Pipe sections were interconnected through adjacent test stations and 0.1 ohm shunts with one end grounded, as depicted in the circuit schematic of Figure 6, to test the feasibility of using the attenuation method for determining pipe conductance and to test the accuracy of measuring pipe currents with magnetometer based instrumentation.

For small bare areas on each of the pipe samples the change in current pick-up was too small for the attenuation method to be accurate. Moreover when the classical attenuation equations are applied to lengths of piping for which there is small current attenuation then the equations simplify to the 'general method' that was used to calculate the conductance in the first instance.

When using the Radiotection Pipeline Current Mapper [PCM] some measurement inaccuracies were discovered that were thought to be caused by sudden changes in elevation of the bonding cables connecting the pipe sections together. This was particularly noticeable near the test station and at the edge of the excavation for pipe samples 2 & 3. The PCM was operated at current outputs of 100mA and 2Amps and the PCM current readings between pipe samples were compared to DC current measurements using the shunts. As shown in Figure 12, the percentage of the total signal current recorded by the PCM along the piping run was similar to the DC but the PCM current accuracy of ±5mA was unacceptable for accurate calculation of the conductance. Similar attempts, using a Scintrex ENVI proton magnetometer to measure the DC current, also produced highly inaccurate results.
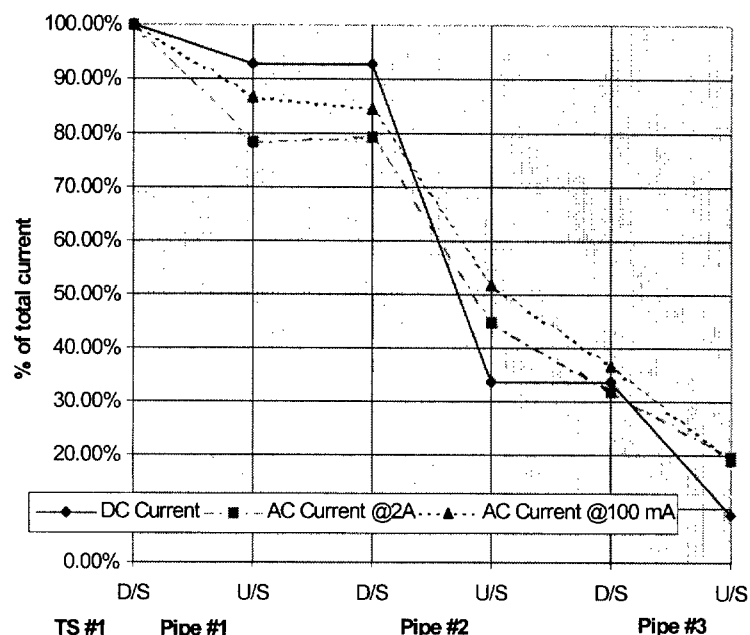
**Figure 12 – Comparison of PCM and DC Current as a Percentage of Total Current Measured Along the Piping Run**

Summary of Results

Because both the conductance and current requirement parameters exhibited a high degree of correlation and a linear relationship with the percentage bare of the pipe samples, when plotted on a log-log scale, it was decided to incorporate both techniques into a field test procedure. In both cases calibration curves needed to be produced for which data from pipe sample 2, buried in the native clay soil, was utilized. For the conductance curve the data was selected from tests in which the pipe sample was isolated and the current controlled to limit the amount of hydrogen evolution on the bare surfaces. The data was then normalized for a soil resistivity of 1000 ohm-cm by multiplying the conductance values by the ratio of the two resistivities (1500/1000). The resulting plot, shown in Figure 13, gave values of conductance that compared favorably to those cited in the literature[1,2,3] pertaining to estimated coating quality as summarized in Table 2.
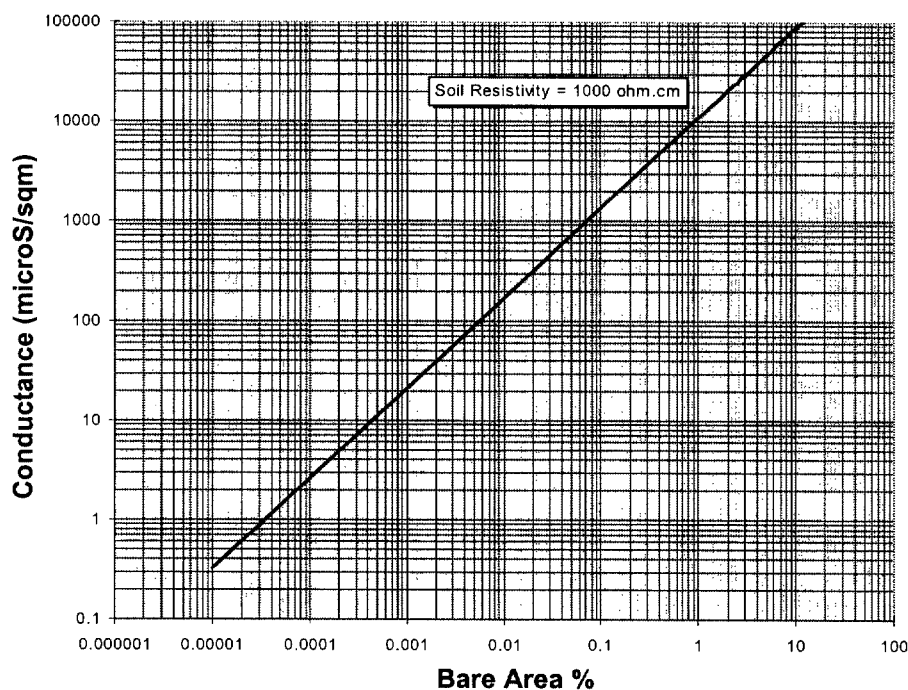


**Figure 13 - Conductance versus Bare Area Normalized for a Soil Resistivity of 1000 ohm-cm – Calibration Curve**

**Table 2 – Table of Specific Coating Conductance vs. Coating Quality**

| Coating Quality | Specific Conductance Range ($\mu S/m^2$) |
|---|---|
| Excellent | < 100 |
| Good | 100 - 500 |
| Fair | 500 - 2000 |
| Poor | > 2000 |

The plot of the current requirement factor of $\mu A/m^2$ (micro-amps per sq. m) versus percentage bare as shown in Figure 14 also produces values that are consistent with the literature[4,5,6] with regard to estimating coating quality. The concern that the data from the pipe sample in the clay environment (deaerated) might not be applicable to actual field conditions was discounted, since pipe bored at considerable depth and surrounded by drilling mud should be exposed to the same degree of aeration as pipe sample 2.
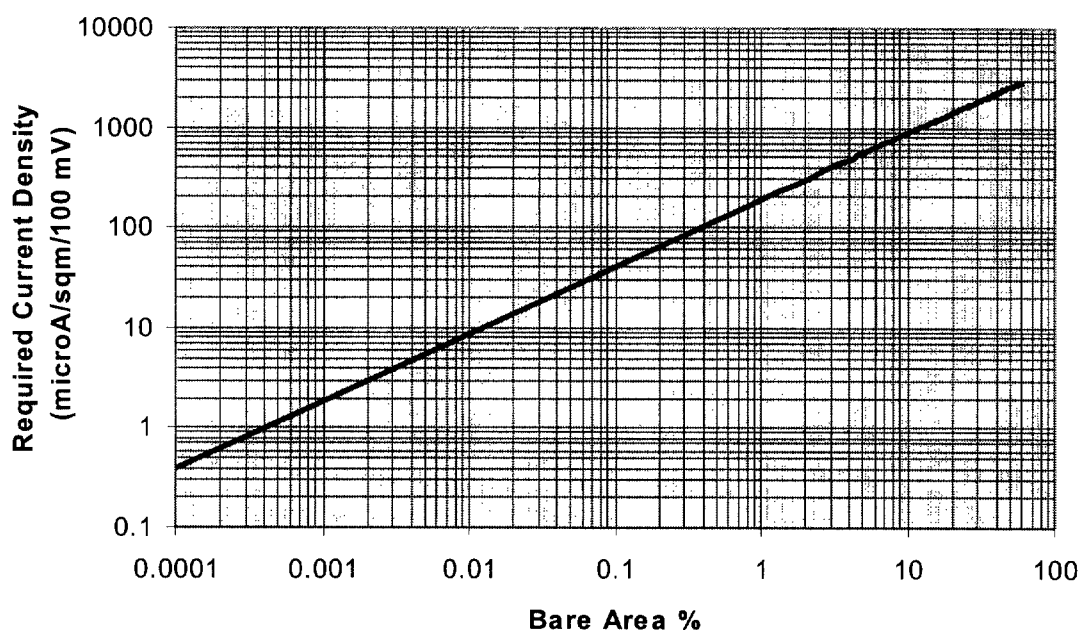


**Figure 14 – Current Density Factor versus Bare Area – Calibration Curve**

Table 3 equates coating quality estimations from the literature for different values of current density.

**Table 3 – Approximate Current Requirements for Cathodic Protection of Steel**

| Environment & Coating Quality | icp ($\mu A/m^2$) |
|---|---|
| Soil – bare | 10,000 - 30,000 |
| Poorly coated in soil or water | 1,000 |
| Well coated in soil or water | 30 |
| Very well coated in soil or water | $\leq 3$ |

Field Trial of Test Procedure and Results

The test procedure developed from this research program was used in the field on three different directionally drilled pipe crossings using the test circuit schematic illustrated in Figure 15. Each of the three field tests were conducted by a different corrosion technician. Details of the test results are tabulated in Table 4 which illustrates the excellent agreement between the conductance and current requirement parameters in estimating the percent bare.
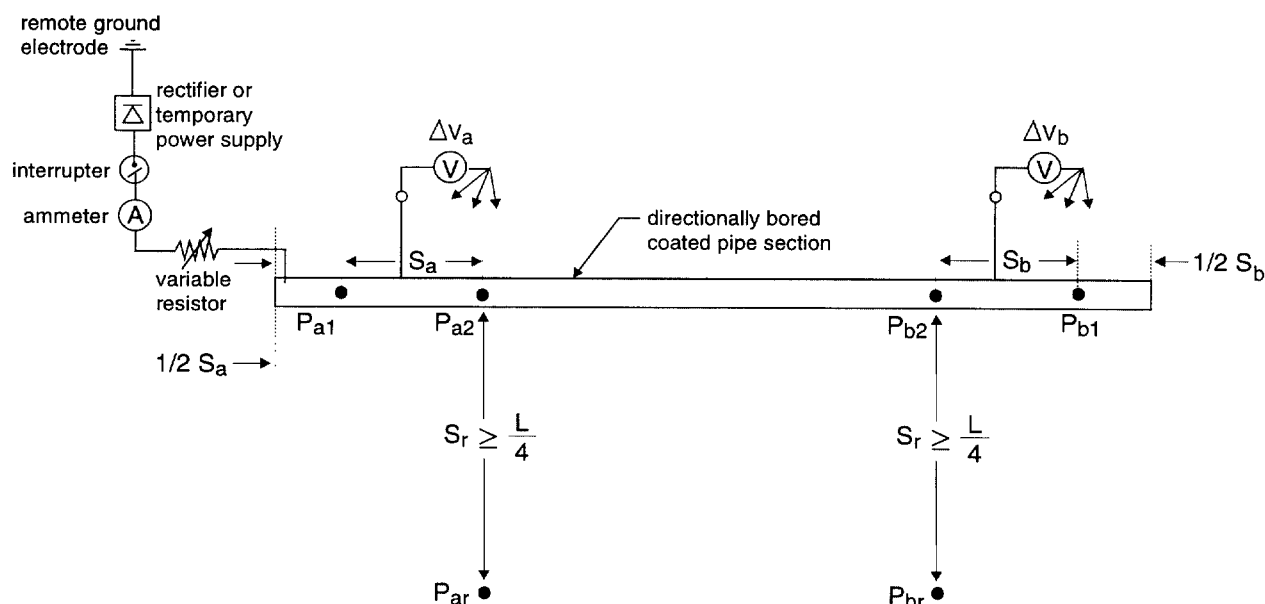


**Figure 15 – Test Schematic for Field Trials on Directionally Drilled Pipe Sections**

**Table 4 — Summary of Results from Three Field Tests**

| Test Nº | Pipe Dimensions | | Coating Type | Average Soil Resistivity ohm-cm | Calculated % Bare | |
|---|---|---|---|---|---|---|
| | Ø (m) | Lgth (m) | | | Conductance Method | Current Requirements Method |
| 1 | 0.31 | 37 | Double Extruded Yellow Jacket | 104,550 | 2.42 | 2.48 |
| 2 | 0.508 | 400 | Polyurethane over FBE | 2,010 | 0.55 | 0.56 |
| 3 | 0.76 | 41 | FBE | 2,920 | 0.003 | 0.002 |

Additional field testing on directionally bored piping in very rocky soils did not show the same agreement between the conductance and current requirement parameters. It appears that when the current requirements are small, which indicates a well coated pipe, the resistivity of the drill mud and ground water should be used in the conductance calculations rather than the resistivity of the rock. In high resistivity rocky soils therefore, more weight should be placed on the current requirements parameter than the calculated conductance in assessing the percent of the pipe surface that is bare.

# CONCLUSION

The final objective of the research program, which was to develop a field test that could be conducted by a corrosion technician to indicate, with reasonable accuracy, the extent of coating damage on a bored pipe, was achieved. The resulting test procedure can be conducted with a minimum of training using equipment to which a corrosion technician would normally have access. This test procedure can estimate the percentage bare of a coated directionally drilled pipe as long as the pipe is not connected to adjacent piping. The test method uses two parameters, coating conductance and cathodic protection current requirement, to arrive at separate but comparable estimates of the bare area on the test section. The final report on this research contract (PR-262-9738), including software and a copy of the test procedure, is available from the American Gas Association, 400 North Capitol Street, N.W., Washington, DC, 20001.

# ACKNOWLEDGEMENT

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