CATHODIC PROTECTION PROCEDURE NO. 4

Diagnostic Testing (Current Requirement)

4

1.0 INTRODUCTION

The purpose of diagnostic testing (DT) is to outline a process to test for deficiencies in a cathodic protection (CP) system, to identify the cause(s) of such deficiencies, and to determine the requirements to enhance the level of CP to the structure.

In an existing CP system, the DT is to first determine if the cause of low CP levels can be eliminated and, if not, what additional current is required, in addition to how and where it can be applied.

The CP Technician must have a good understanding of the criteria as well as the special conditions and precautionary notes that apply to these criteria.(1)

2.0 TOOLS AND EQUIPMENT

The following equipment will vary, depending on the test selected:

- Multimeter capable of measuring 1 mV_{DC} to 40 V_{DC}, complete with leads with insulated probes
- Copper-copper sulfate reference electrode
- Isolation checker
- Soil resistivity meter, complete with wires and four pins

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[1] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement.

- Multimeter, including alternating current (AC)/direct current (DC) volts and an ohmmeter
- Current interrupter
- DC ammeter sized for test current
- Battery and control resistor or portable controlled DC power supply
- Pipe locator transmitter and receiver
- Test wires as necessary for the applicable test
- Small hand tools

3.0 SAFETY EQUIPMENT

- Standard safety equipment and clothing, as required by the company's safety manual and regulations
- Electrically insulated clips and probe handles for meter leads
- Only personnel who have received training and are qualified in accordance with local codes and regulations are to work on DC power sources or their supply

4.0 PRECAUTIONS

The following precautions are in addition to those that must also be followed when working on a particular facility.

4.1 Measure the voltage between the rectifier case and ground before touching the case.

4.2 Open the case expecting to find biting insects, rodents, or snakes inside and take the appropriate precautions.

4.3 Inspect the rectifier for abnormal sounds, temperature, or odors and, if noted, turn it off.

4.4 Switch off the AC voltage supply before installing a current interrupter or each time the taps are adjusted.

4.5 Secure any exposed electrical terminals in a locked container when the rectifier is not attended.

4.6 Measure a structure AC voltage to ground on the structure before taking CP measurements. If the AC voltage to ground is equal to or exceeds 15 V_{AC}, safety measures detailed in NACE SP-0177[7.1] must be followed, and other personnel working on the structure of the hazard must be advised of such.

4.7 When working near high-voltage AC (HVAC) power lines, take AC structure-to-ground voltage readings at frequent intervals as these voltages can change with the power line load and geometry.

4.8 Do not work on the structure when lightning is in the area.

4.9 When working near a fence, confirm that it is not an electric fence for livestock (look for insulators) and that an AC voltage is not being induced on it by a parallel HVAC power line.

5.0 PROCEDURE

5.1 Information Required Prior to Diagnostic Testing

5.1.1 Previous annual survey data
5.1.2 Rectifier routine monitoring and annual data
5.1.3 Drawings
  5.1.3.1 Structure details
  5.1.3.2 CP installation details and location
  5.1.3.3 Test station types and locations
  5.1.3.4 Bond details and locations
5.1.4 Hazardous AC voltage tests (if applicable)
5.1.5 DC interference test results and mitigation effectiveness (if applicable)
5.1.6 Critical bond monitoring data
5.1.7 Isolation information
5.1.8 Road and railroad casing data (if applicable)
5.1.9 Close interval potential survey data (if applicable)
5.1.10 Pipeline coating information
5.1.11 In-line inspection or other inspection results (if applicable)
5.1.12 DT testing results

5.2 Investigate the Cause of Poor Cathodic Protection

5.2.1 Inspect the DC power sources and compare with the target DC volts and DC amperes. If the target outputs are significantly different from the target, complete the following inspections:

5.2.1.1 If there is 0 to ~2 V_{DC}(2) and 0 A_{DC} output, look for trouble in the rectifier or the AC supply to the rectifier. Confirm that the ~2 V_{DC} reading is from the DC power source by turning it off and disconnecting one DC cable. If the reading stays at ~2 V_{DC}, then it is from the DC power source. If it drops to 0 V, then it is the galvanic difference between the structure material and the anode or the carbon in the coke breeze.

5.2.1.2 If there is a normal voltage output but 0 A_{DC} output, look for the trouble in the cables, anodes, structure, or connections external to the rectifier.

5.2.1.3 If there is approximately one-half normal voltage and approximately one-half normal current, then investigate the possibility of a failed diode, causing the rectifier to half-wave.

5.2.1.4 If a problem exists in the rectifier or the external DC circuit,(3) complete repairs before proceeding with DT.

5.2.2 Inspect the DC bonds and repair any broken bonds found.

5.2.3 Test all isolating features.(4)

5.2.4 Test all road or railroad casings, if applicable, to confirm that they are isolated.(5)

5.2.5 If the problems causing the loss of CP, when corrected, restore protection, then the DT is completed.

5.2.6 When the preceding faults are corrected but a CP criterion has still not been met, proceed with the DT.

5.3 Structure-to-Electrolyte Potentials

5.3.1 Use structure-to-electrolyte potentials(6) to determine if the criterion for CP is being met.[7.2,7.3]

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[2] Approximately 2 V_{DC} may be the galvanic difference between the steel in the structure and the carbon in the coke breeze, indicating that the DC power source is off.

[3] *See* Cathodic Protection Procedure No. 1: Rectifier Adjustment, Inspection, and Basic Troubleshooting.

[4] *See* Cathodic Protection Procedure No. 9: Electrical Isolation.

[5] *See* Cathodic Protection Procedure No. 10: Road and Railroad Cased Crossings (Basic).

[6] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement.

5.3.2 Take structure-to-electrolyte potentials with a high-input impedance voltmeter (10 MΩ minimum) in conjunction with a copper-copper sulfate ($Cu/CuSO_4$) reference electrode (CSE).

5.3.3 Calibrate the field CSE by measuring a potential to a new, clean standard CSE that was recently charged with distilled water and copper sulfate crystals.(7) To calibrate the CSE, place the field CSE and the standard CSE reference electrodes in a nonmetallic container of clean water (alternately, hold the two porous plugs together) and measure the DC potential difference between them, using a good-quality voltmeter set on the low voltage scale. Service the field reference electrode, or replace it if the potential difference is greater than 5 mV.

5.3.4 Connecting the voltmeter positive to the structure and the negative to the reference electrode is now the preferred method. When connected in this manner, structure-to-electrolyte potential readings should then be negative and recorded as such. Connecting the voltmeter with the voltmeter negative to the structure is still permissible; however, the tester must realize that when a positive structure-to-electrolyte potential value is obtained, the reading is negative and must be recorded as such.

5.3.5 In rocky, sandy, very dry soils, or frozen ground, add water to the ground surface or a damp sponge attached to the reference electrode. In extreme conditions, a multiple-input impedance interface or multi-input impedance meter may be used. The potential measurements at a minimum of two input impedances must be the same; otherwise, the reference cell circuit resistance must be further reduced.

5.3.6 Document all techniques and raw data used to improve the quality of the data.

5.3.7 Take instant OFF structure-to-electrolyte potentials, with all influencing DC power sources interrupted, wherever practical.

5.3.8 Record the instant OFF potential reading between 0.6 and 1.0 s after interruption. If using a digital voltmeter, record the second

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[7] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement, Appendix A.

reading displayed after interruption as the first display may be an average of the dropping values from the ON potential.

5.3.9 Except for close interval potentials, the spacing of the test station structure-to-electrolyte (pipe-to-soil) potential measurements should be from 2 to 3 km.

5.4 Dynamic Stray Current

5.4.1 Confirm that the structure under testing is not affected by a dynamic DC stray current.(8)

5.4.2 Retest adjacent potential readings that change in excess of 20% immediately to confirm proper reference electrode contact with the ground by the addition of water or by exposing moist soil.

5.4.3 Telluric or other dynamic stray current activity that requires calibration can be defined as an OFF potential fluctuation exceeding 20 mV peak to peak over the duration of the testing.

5.4.4 If a telluric or another dynamic stray current is detected, install data loggers at each end of the section to be tested to record structure-to-electrolyte (pipe-to-soil) potentials versus time and leave them recording for a period of approximately 22–24 hours, where practical.

5.4.5 Alternately, measure structure-to-electrolyte potentials manually and record the values and the time of each reading. Plot the results to see any trends.

5.4.6 If the test section is less than 1.6 km (1.0 mi), a single data logger may be installed at the test site.

5.4.7 Record each test station structure-to-electrolyte potential with another data logger for a period of 5 minutes (min). Take CIS potentials as normal, except the readings are to be time stamped.

5.4.8 Figure 5.1 illustrates that the wave prints of portable and stationary data loggers 10.5 km (6.5 mi) apart can be very similar. Although there was a small amount of telluric current in this time period, it is also demonstrated that a current interrupter failed in

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[8] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement, Sections 5.7 and Section 6.2; and *see* Cathodic Protection Procedure No. 8: Direct Current Stray Current Interference.

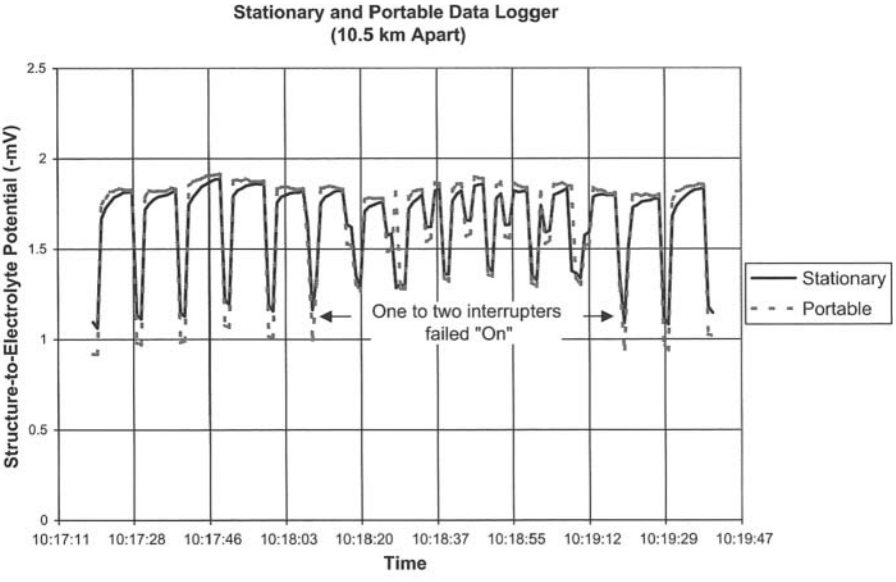


Figure 5.1 Comparison of wave prints of two data loggers 10.5 km (6.5 mi) apart, indicating current interrupter failure in addition to some telluric activity, is shown.

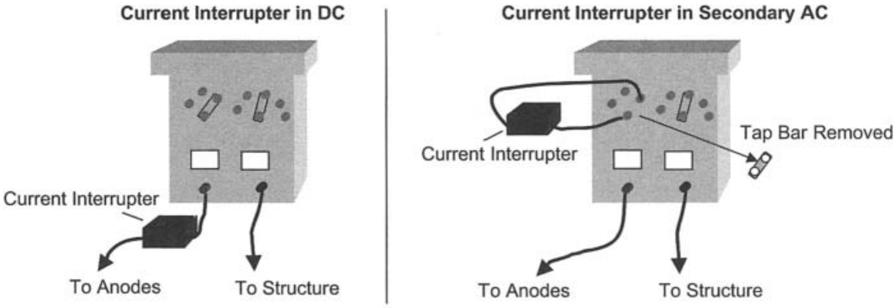
the ON position, typical of some Global Positioning System (GPS) interrupters, and another went out of synchronization; therefore, an incorrect reading may have been taken manually in this time frame without this knowledge.

5.5 Direct Current Power Source and Interrupter Installation

5.5.1 Record the nameplate data, tap setting, voltage, and current output of existing impressed current DC power sources and circuits in both the as-found and test conditions.

5.5.2 For sacrificial anode systems, record the size of the shunt, the millivolt reading measurement across it, and the current output.

5.5.3 Turn the DC power supply off and install a current interrupter in either the AC supply, the AC secondary taps, or the DC output of all influencing rectifiers, as shown in Figure 5.2, or in the DC output of other DC power sources. Install an interrupter in series with the sacrificial anodes and any bonds.



Note: Only qualified personnel to install current interrupters

Figure 5.2 Typical current interrupter installations are shown.

5.5.4 For more than one current source, use synchronized interrupters, preferably GPS time-synchronized interrupters.

5.5.5 Select a long ON and a short OFF cycle to minimize the loss of polarization during the period of interruption, and record the timing of the cycles.

5.5.6 Adjust the rectifier, as necessary.(9)

5.5.7 If the feature exists, program the interrupters to turn off after the survey day ends and start again just before it begins to further maintain polarization.

5.6 Close Interval Structure-to-Electrolyte Potential

5.6.1 A detail procedure is given in "Cathodic Protection Procedure No. 7: Close Interval Potential Survey."

5.6.2 Connect the structure to the wire reel and move the reel with the voltmeter and reference electrode, as shown in Figure 5.3. In this way, a small break in the wire will still be part of the protected structure. A break in the insulation to the reference electrode will introduce an error in the reading when it comes in contact with the electrolyte.

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[9] *See* Cathodic Protection Procedure No. 1: Rectifier Adjustment, Inspection, and Basic Troubleshooting.

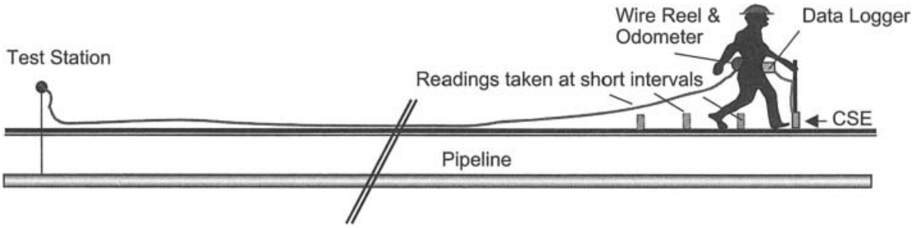

Figure 5.3 Close interval structure-to-electrolyte potential survey with trailing wire connected to structure, as recommended, is shown.

5.6.3 Take a structure-to-electrolyte potential directly to the structure and compare it to one taken to the wire in the reel, also connected to the structure. A difference in the reading will indicate a poor connection.

5.6.4 Keep the spacing of the reference cell 10 m (30 ft) or less in remote areas and no greater than 3 m (10 ft) in urban areas.

5.6.5 The direction of each survey segment should be recorded in the data.

5.6.6 The trailing wire is to be reconnected to the next test station or pipeline appurtenance, but prior to abandoning the previous pipe connection, a pipe-to-electrolyte potential measurement is to be taken to both the trailing wire and the next test station, with the reference cell in the same position. Both measurements are to be recorded. A small difference in these readings is to be expected due to the *IR* drop in the pipeline to the prior test station. If the new pipe connection is determined to be faulty, then the close interval survey may be continued using the previous pipe connection and noting this fact in the data. The voltmeter connection must not be made to a current carrying wire.

5.7 Baseline Survey

5.7.1 Obtain a complete set of baseline data, which may include but is not limited to the following:

5.7.1.1 AC structure-to-ground voltages measured prior to the DC structure-to-electrolyte potentials

5.7.1.2 ON/OFF structure-to-electrolyte potential tests, with all influencing current sources being interrupted to relate to the polarized potential criterion. All current sources include DC power sources (rectifiers; thermoelectric generators; and solar, wind, and engine generators), sacrificial anodes, and bonds. A close interval structure-to-electrolyte potential survey (CIS)(10) is advisable to confirm that all low-potential areas are addressed.

5.7.1.3 ON structure-to-electrolyte potential tests where current sources cannot be interrupted. In this case, additional testing must be completed to predict the *IR* drop error.(11) A CIS survey is advisable.

5.7.1.4 Depolarization potential tests (preferably a CIS), in which the current is left off after an ON/OFF potential test, are advisable.

5.7.1.5 DC current source outputs and bond current data

5.7.1.6 In addition to the CIS on the structure, measurement of structure-to-electrolyte potentials on each side of isolating features, on foreign structures, and on road or railroad casings

5.7.1.7 Comparison of the baseline survey data to the latest survey results to confirm that the location being tested is the intended area and that the operation of the CP system is similar

5.7.2 ON/OFF Structure-to-Electrolyte Potential Test

5.7.2.1 Determine the time cycle of the ON and OFF structure-to-electrolyte potential measurements.

5.7.2.2 Interrupt all influencing DC current sources on a recorded, timed ON and OFF cycle, preferably a long ON cycle to minimize the loss of polarization.

5.7.2.3 Install a stationary data logger to witness the interruption cycles and to confirm that all interrupters continue to operate and remain in synchronization. The stationary recorder will also serve to verify synchronized

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[10] *See* Cathodic Protection Procedure No. 7: Close Interval Potential Survey.

[11] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement.

interruption and if depolarization occurred during the survey interruption period.

5.7.2.4 Measure ON/OFF structure-to-electrolyte potentials and identify each location with a stake or paint so that the reference electrode can be placed in the exact position for subsequent tests.

5.7.3 ON Structure-to-Electrolyte Potentials

5.7.3.1 Determine the frequency of structure-to-electrolyte potential measurements.

5.7.3.2 Measure ON structure-to-electrolyte potentials and identify each location with a stake or paint so that the reference electrode can be placed in the exact position for subsequent tests.

5.7.3.3 Determine the *IR* drop component that is included in each ON structure-to-electrolyte potential.(12)

5.7.3.4 Calculate the true polarized potential by removing the *IR* drop error from the ON potential that was measured.

5.7.4 Depolarization Potentials

5.7.4.1 Determine the frequency of structure-to-electrolyte potential measurements.

5.7.4.2 Interrupt all influencing DC current sources on a long ON and OFF cycle and record the time for each cycle.

5.7.4.3 Measure ON/OFF structure-to-electrolyte potentials and identify each location with a stake or paint so that the reference electrode can be placed in the exact position for subsequent tests.

5.7.4.4 Turn off all current sources and record spot structure-to-electrolyte potentials over time, until the potentials have become relatively stable. In some cases, this may take up to several days. A stationary data logger will facilitate this test.

5.7.4.5 When the potentials have stabilized or reached the desired values, measure the depolarized potential with the reference electrode placed in the same exact locations as

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[12] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement.

during the ON/OFF structure-to-electrolyte potential survey.

5.7.4.6 Calculate the depolarization at each measurement location using Equation (5.1):

$$\Delta E_{dp1} = E_{\mathrm{off}\,1} - E_{\mathrm{depol}}, \tag{5.1}$$

where

ΔE_{dp1}	depolarization (millivolts)
$E_{\mathrm{off}\,1}$	instant OFF structure-to-electrolyte potential (millivolts)
E_{depol}	depolarized structure-to-electrolyte potential (millivolts)

5.7.5 During baseline and current drain tests, measure foreign structure-to-electrolyte potentials where they may be affected by the proposed new CP installations. Where foreign facilities are affected, make a sketch of the configuration of the foreign facilities relative to the protected structure.

5.7.6 With the foreign owner's permission, test other locations to note the effect of the proposed CP system. Make sketches of the foreign structure and reading locations.

5.7.7 Existence of bonds with foreign structures should be recorded, including current and its direction.

5.8 Auxiliary Current Drain Tests

5.8.1 Install a temporary anode bed, such as ground rods, at the location that is anticipated for a new current drain point.

5.8.2 Install an ammeter, a control resistor, a DC power source, and a current interrupter in series between the structure and a temporary anode bed (ground rods), with the positive terminal connected to the temporary anode bed, as shown in Figure 5.4. If an adjustable DC current source is used, then the control resistor is not required. The wires and connections are to be sized for the expected current.

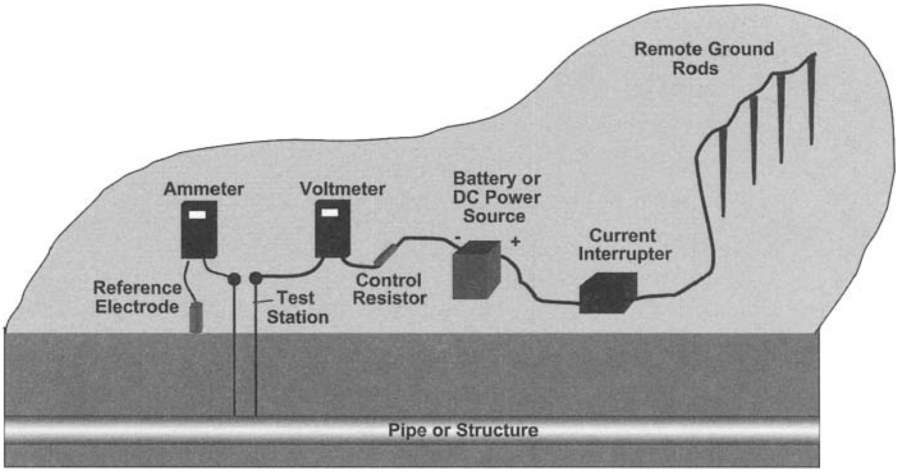

Figure 5.4 Typical temporary current drain test setup is shown.

5.8.3 Adjust the current to give a significant shift in the structure-to-electrolyte potential and confirm that the potentials are going more negative when the current comes on.

5.8.4 Take spot structure-to-electrolyte potentials at low CP points found in the baseline test to confirm that there is a response in the potentials from the temporary current being applied.

5.8.5 If the amount of polarization noted during this test does not exceed approximately 50 mV, then increase the current at the current drain test point and repeat the spot structure-to-electrolyte potentials. The amount of polarization will be the difference from the instant OFF potential less the baseline potential measured in the baseline survey (Equation [5.2]):

$$\Delta E_{p1} = E_{\text{off }1} - E_{\text{base}}, \tag{5.2}$$

where

ΔE_{p1}	polarization from DT temporary current
$E_{\text{off }1}$	instant OFF potential from DT temporary current
E_{base}	potential measured during baseline test

5.8.6 Measure ON/OFF structure-to-electrolyte potentials at each baseline reference electrode position, including isolating features, road casings, and foreign structures.

5.8.7 If a suitable response in structure-to-electrolyte potentials is not seen at all locations, either increase the current further or move the temporary current drain point to another location and repeat the preceding tests.

5.8.8 Calculate the true OFF structure-to-electrolyte potential by adding the amount of polarization in this test to the baseline polarized (instant OFF) structure-to-electrolyte potential.

5.9 Pipeline Current Measurements

5.9.1 Measure the current in a pipeline at intervals, if possible, to determine the distribution of current with the test current both ON and OFF.(13)

5.9.2 Pipeline Current Span

5.9.2.1 Calibrate the resistance or calibration factor of a four-wire pipeline current span, as described in "Cathodic Protection Procedure No. 3: Direct Current Measurements." Measure the millivolt drop across the two inside wires and calculate the current (Figure 5.5).

5.9.2.2 With a two-wire test station, determine the distance between the wires, the diameter, the wall thickness, and the material of the pipeline at that location to determine the resistance of the pipeline current span by resistance tables or by the material resistivity.

5.9.3 Clamp-On Ammeter

5.9.3.1 If the clamp-on ammeter is an AC/DC type, ensure that the setting is on DC.

5.9.3.2 Center the coil on the pipeline and record the ON/OFF current, the polarity of each, and, thus, the direction of the current (Figure 5.5).

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[13] *See* Cathodic Protection Procedure No. 3: Direct Current Measurements, Section 5.4.

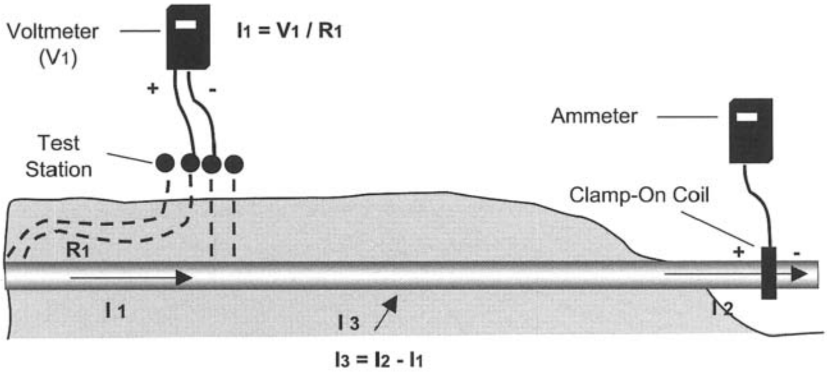

Figure 5.5 Two methods of measuring pipeline current are shown.

5.9.3.3 Record the current and the positive polarity as being upstream or downstream.

5.9.3.4 Reverse the coil and repeat the measurement to ensure that both readings are close and, therefore, representative.

5.9.3.5 Average the current readings for the final value, but record all data.

5.10 Coating Conductance[7.3]

5.10.1 Select a section where the current can be measured at each end, either by a current span or by a clamp-on ammeter.

5.10.2 Install a current interrupter in a nearby CP current source or install a temporary current drain, as shown in Figure 5.4.

5.10.3 An example of the tests to be completed is illustrated in Figure 5.6. Pipeline current can also be measured by a clamp-on ammeter, as shown in Figure 5.5.

5.10.4 Measure the ON/OFF current in the pipeline at one end (location 1 in Figure 5.6). If using a pipeline current span, measure the millivolt drop between the two inside wires of the span and calculate the current from Equation (5.3):

$$I = \frac{\text{mV}}{1{,}000R} \tag{5.3}$$

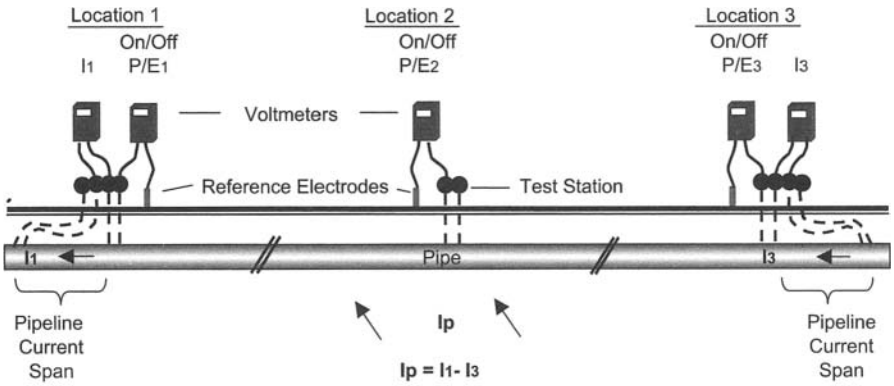

Figure 5.6 Coating conductance tests are shown.

where

I	current in a pipeline current span (amperes)
mV	voltage across pipeline current span
R	resistance of pipeline current span (ohms)
1,000	converts millivolts to volts

5.10.5 If using a clamp-on ammeter, take current readings in both directions to confirm that they are approximately the same and then calculate the average.

5.10.6 Measure the ON/OFF current in the pipeline at the other end (location 3 in Figure 5.6).

5.10.7 Note that there will likely be residual current in the pipe with the DC current source OFF. The current (I) of interest is the difference between the pipeline current with the test current ON (I_{on}) and with it interrupted (I_{off}) in each case (Equation [5.4]):

$$I = I_{\mathrm{on}} - I_{\mathrm{off}}. \tag{5.4}$$

5.10.8 Measure the ON/OFF structure-to-electrolyte potentials at each end and at accessible locations in between (locations 1, 2, and 3 in Figure 5.6).

5.10.9 If the current cannot be measured, or if the difference between the ON and OFF potentials is less than 50 mV, then apply more current and repeat the preceding tests.

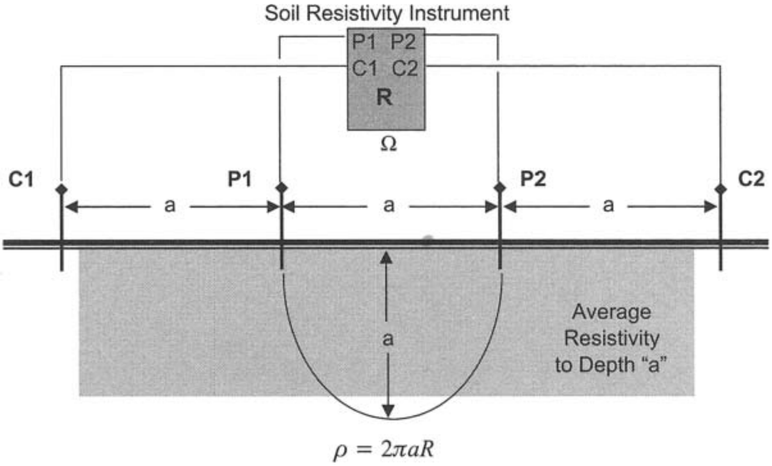

Figure 5.7 Soil resistivity using the four-pin method is shown.

5.11 Soil Resistivity

5.11.1 Take soil resistivity measurements$^{(14)}$ using the four-pin method, as shown in Figures 5.7 and 5.8, at each possible CP anode bed site. Make certain that the pins are connected exactly as shown.

5.11.2 If a remote anode bed is planned, obtain soil resistivity measurements in a 30-m (100-ft) grid pattern throughout the proposed anode site at each soil depth to a depth greater than the anticipated anode depth, and another to a depth between that and the surface. Extend the grid until the lowest uniform soil resistivity has been determined to encompass the area of the proposed anode bed (Figure 5.8).

5.11.3 If the proposed corrosion remedial design is a deep anode system, then take resistivity tests to different depths, with the deepest depth exceeding the anticipated total anode bed depth (e.g., 25 m, 50 m, 75 m, 100 m [82 ft, 164 ft, 246 ft, 328 ft]). Note that three times this distance on the surface is needed for the three equal spacings between the pins. The soil resistivity instrument may not be sensitive enough for deeper

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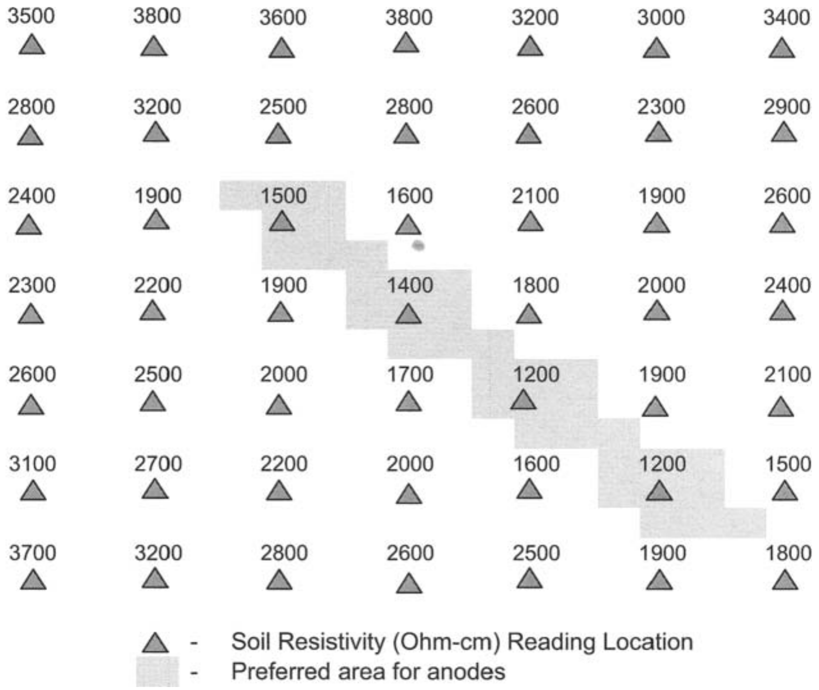
[14] *See* Cathodic Protection Procedure No. 12: Soil Resistivity Measurement.



3500	3800	3600	3800	3200	3000	3400
2800	3200	2500	2800	2600	2300	2900
2400	1900	1500	1600	2100	1900	2600
2300	2200	1900	1400	1800	2000	2400
2600	2500	2000	1700	1200	1900	2100
3100	2700	2200	2000	1600	1200	1500
3700	3200	2800	2600	2500	1900	1800

Figure 5.8 Soil resistivity grid pattern for anode location is shown.

measurements, in which case, refer to "Cathodic Protection Procedure No. 12, Soil Resistivity Measurement."

5.11.4 If a distributed anode system is planned, soil resistivity measurements are to be taken every 30 m (100 ft), and if there is a 2:1 or 1:2 change in resistivity between consecutive readings, reduce the spacing by half in those areas.

5.11.5 Soil resistivity pin alignment is to be perpendicular to a metallic structure when it is nearby.

5.12 Additional Cathodic Protection Design Information

5.12.1 Obtain the following information in addition to the preceding test data:

5.12.1.1 Drawing of the temporary current drain, showing location of temporary anode bed(s)

5.12.1.2 Drawing with dimensions of the proposed anode bed locations, with dimensions to structure, power lines, topographical features, foreign structures, roads, and landowner divisions
5.12.1.3 All underground or aboveground power lines and AC voltage (single phase or three phase) related to the structure
5.12.1.4 Structure or pipeline drawings showing the location of the possible anode beds, test stations, foreign structures (pipelines), power line locations, and access
5.12.1.5 Bodies of water (sloughs, creeks, rivers, lakes, swamps), especially at possible anode bed locations
5.12.1.6 Details of foreign structures and foreign CP systems
5.12.1.7 Description of soil and significant soil features (e.g., granite, muskeg)
5.12.1.8 Topography (hills, low areas)
5.12.1.9 The location and size of existing rectifiers and ground beds
5.12.1.10 Possible sources of AC or DC stray current
5.12.1.11 Photographs of the anode bed area and unusual features of the structure or area

6.0 ANALYSIS

6.1 Criteria to Be Met

6.1.1 CP criteria are detailed in Section 6 of NACE SP0169.[7.3] (15)

6.1.2 There are currently three structure-to-electrolyte potential criteria for submerged or buried steel structures in the absence of specific data that demonstrate that adequate CP has been applied, including the following:

6.1.2.1 A negative (cathodic) potential of at least 850 mV (with respect to a CSE contacting the electrolyte) with the cathodic protection applied but with voltage drops other than across the structure-to-electrolyte interface (*IR* drop)

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[15] Use most recent version of criteria.

removed. IR drops between the reference electrode and the structure-to-electrolyte boundary are an error in this reading and must be removed from the ON potential before applying this criterion, as illustrated by Equation (6.1). NACE SP0169[7.3] discusses methods to evaluate the IR drop, which is essentially the difference between the ON potential and the instant OFF potential:

$$E_c = (E_{\text{on}} - IR), \tag{6.1}$$

where

E_c	potential for criterion (millivolts; -850 mV_{CSE} or more negative)
E_{on}	potential with current applied (millivolts)
IR	voltage drop between the reference electrode and the structure-to-electrolyte boundary (millivolts)

6.1.2.2 A polarized potential equal to or more negative than 850 mV relative to a saturated copper-copper sulfate reference electrode contacting the electrolyte. This is obtained when all current sources influencing the structure have been temporarily interrupted and an instant OFF potential (E_{off}) is read.

6.1.2.3 A minimum of 100 mV of cathodic polarization between the structure surface and a stable reference electrode contacting the electrolyte. Polarization is the change in potential from the native or free corroding potential and the instant OFF potential, as illustrated by Equation (6.2). It can be measured during formation or decay after all influencing power sources have been turned off:

$$E_p = (E_{\text{off}} - E_{\text{native}}), \tag{6.2}$$

where

E_p	polarization for criterion (100 mV or greater)
E_{off}	potential with all current momentarily interrupted

E_{native} native potential before CP current is applied if in formation or depolarized potential after current is interrupted for a period of time if in decay.

6.1.3 Only one of these criteria needs to be met. For example, if a polarized potential is more electropositive than −850 mV_{CSE}, a depolarization survey may prove that the 100-mV criterion is being achieved. See NACE SP0169[7.3] for special conditions.

6.2 Cause of Subcriterion Potentials

6.2.1 Some common causes of a system's inability to meet criteria, tests, and cures are listed in Table 6.1. Exceptions can always be encountered.

6.3 Structure-to-Electrolyte Potentials

6.3.1 Compare the structure-to-electrolyte potentials with the historical data.

6.3.2 Readings that are more electronegative than before and at the same current output may suggest that the structure has been reduced in size, possibly by a faulty bond, thus, isolating part of the structure, or that a CP system associated with another structure at a more electronegative potential is now shorted. The potential of the remaining structure will become more electropositive.

6.3.3 Readings that are more electronegative than before at the same current output may also suggest anodic interference; that is, a DC ground or anode bed of a foreign DC power source is in close proximity to the structure.

6.3.4 Readings that are less electronegative than before may indicate one or more of the following problems:

6.3.4.1 Low DC output from the DC power source due to the following:

6.3.4.1.1 Failing anodes

6.3.4.1.2 No AC power or energy source to the DC power supply

Table 6.1 Summary of Identification of Cathodic Protection Trouble, Tests, and Causes

System Component	DC Power Source		Secondary AC Voltage	Structure-to-Electrolyte Potentials	Trouble Suspected	Tests	Remedy
	Volts	Amperes					
Sacrificial Anode							
		A−		P−	May not be trouble. Anode current will decrease when potential becomes more negative.	No action	
		A+		P+	Opposite to above	Test for shorts or faults in the structure system.	Repair as required.
		A−		P+	Anodes failing	Measure anode-to-electrolyte potential. Perform anode voltage gradient test.	Replace anodes as necessary.
DC Power Source							
	0 to ~2*	0	0	P+	No AC power or failed DC power components. Trouble is before or in DC power source.	Confirm AC supply, check circuit breaker, test fuses, poor connections, or broken wires in DC power source. Check for signs of heat. If a battery supplemented source, test batteries for charge.	Confirm cause and correct before re-energizing.
						If circuit breaker trips, look for short.	If no short, reduce DC output voltage.

	0 to ~ 2*	0	0	P+	No secondary AC voltage at taps	Test AC supply and circuit breaker.	If AC supply and circuit breaker are OK, then test transformer.
	0 to ~ 2*	0	V	P+	Fuse(s) in DC power source, failed rectifying element, poor connections or faulty wire	Test fuse(s), rectifying element, connections, and wires.	If fuse, test for short. If none found, lower voltage and re-energize. Otherwise, replace or repair as required.
	~1/2 V	~1/2 A	V	P+	One-half wave DC output. One part of rectifier bridge circuit is open.	Turn off, remove rectifying element connections, and test each diode or element.	Replace rectifying element(s).
	?V	?A	V	P	Faulty meters	Calibrate meters.	Replace as necessary.
DC Cables/Anode Bed							
	V	0	V	P+	Faulty cable, connections, or anodes	Trace cable to structure and anodes. Perform anode voltage gradient test.	Repair or replace as required.
	V	Dropping over time	V	P+	Failing or dry anodes	Potential profile over anodes to confirm status. Turn off to note recovery.	Temporary cure may be to water anodes. Replace anodes as required.

(*continued*)

Table 6.1 *(continued)*

System Component	DC Power Source		Secondary AC Voltage	Structure-to-Electrolyte Potentials	Trouble Suspected	Tests	Remedy
	Volts	Amperes					
Structure							
	V	A	V	P+	Shorted isolation, accidental contact to foreign structure, faulty bonds, deteriorating coating	Test isolation and bonds. Trace for contacts. Coating conductance test. Complete DT.	Repair isolation or bonds. Separate any contacts to foreign structures. Add CP capacity for poor coating or recoat.

Legend:

V	Normal voltage
A	Normal current
P	Normal structure-to-electrolyte potential
V+	Greater than normal voltage
V−	Lower than normal voltage
A+	Greater than normal current
A−	Lower than normal current
?V, ?A	Abnormal readings or varying
P+	Structure-to-electrolyte potential more electropositive
P−	Structure-to-electrolyte potential more electronegative
*	~2 V may be due to galvanic difference between steel and anode or carbon in the coke breeze and not an indication of power

        - 6.3.4.1.3 Faulty components in the DC power source
        - 6.3.4.1.4 Faulty cables or connections in the external DC circuit
        - 6.3.4.1.5 A short in the AC or DC circuitry
    - 6.3.4.2 Shorted isolation, adding a foreign structure to the CP system and increasing the current requirements if the foreign system is at more electropositive potentials
    - 6.3.4.3 Shorted casings, adding more bare metal to the structure and, therefore, increasing the current required for protection
    - 6.3.4.4 A contact to a foreign structure, thereby increasing the current required as the structure-to-electrolyte potential on both structures has to be brought more negative simultaneously
    - 6.3.4.5 Deteriorating coating, resulting in an increase in the current necessary to achieve criteria
    - 6.3.4.6 A faulty interference bond or new interference from a foreign DC power source

6.4 Dynamic Stray Current

- 6.4.1 Telluric or other dynamic stray current activity requiring calibration is defined as an OFF potential fluctuation exceeding 20 mV peak to peak over the duration of the testing.(16)
- 6.4.2 Where data loggers have been installed, process the structure-to-electrolyte potential data collected and prepare a corrected profile. Note any repeating waveforms in the original profile suggesting a man-made source.
- 6.4.3 Match the portable data log potential profile to the stationary data log profile at the same precise time.
- 6.4.4 Determine the true potential at the stationary data loggers first, either by finding a quiet period in the data or, under moderate conditions, by taking an average over the test period. For each potential measurement along the line, calculate the difference in

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[16] *See* Cathodic Protection Procedure No. 8: Direct Current Stray Current Interference.

potential between that and the stationary data logger at the same moment in time. This difference added to the difference to the true potential at the stationary data logger is the correction factor for the portable data logger reading. Equations are presented for the following situations:

- If two stationary data loggers are used, the method shown in Equations (6.3) and (6.4) can be used:

$$\acute{\varepsilon}_b = [\acute{\varepsilon}_a(c - b)/c] + [\acute{\varepsilon}_c(b - a)/c], \tag{6.3}$$

where

a	first stationary potential location
b	portable potential location
c	second stationary potential location
$\acute{\varepsilon}_a$	error in potential at a at time x
$\acute{\varepsilon}_b$	error in potential at b at time x
$\acute{\varepsilon}_c$	error in potential at c at time x

and

$$E_p = E_{p\ \text{measured}} - \acute{\varepsilon}_b, \tag{6.4}$$

where

E_p	true potential at the portable data logger location
$E_{p\ \text{measured}}$	potential at the portable data logger location

- If only one stationary data logger was used, then Equation (6.5) applies:

$$E_p = E_s - (E_{sa} - E_{pa}), \tag{6.5}$$

where

E_p	true potential at the portable data logger location
E_s	true potential at the stationary location
E_{sa}	stationary potential at time a during the data logging
E_{pa}	portable potential at time a during the data logging

6.4.5 Other methods can also be used to correct for dynamic stray currents.

6.4.6 The stationary recorder will also serve to verify synchronized interruption and if depolarization occurred during the survey interruption period.

6.5 Close Interval Potential Survey

6.5.1 Review the structure-to-electrolyte potentials(17) to determine if they meet one of the criteria(18) for CP throughout.$^{7.1}$

6.5.2 In the event that the −850 mV_{CSE} is not met, review the depolarized potentials to determine if the 100-mV criterion is achieved. If a depolarized test was not conducted, determine the practicality of conducting this test.

6.5.3 The structure-to-electrolyte potentials will attenuate gradually away from the current drain point where the coating is uniform.

In Figure 6.1, more rapid attenuation is seen where there is a large amount of bare metal exposed to the soil electrolyte, either in the form of large coating holidays or another structure in contact. A recovery of the potentials will normally be seen when the better coating is reached. This voltage gradient is a reflection of the higher current density at the bare metal.

6.6 Direct Current Power Source Interruption

6.6.1 Review stationary data log profiles to confirm that the interrupters at all influencing rectifiers continued to function during the test (see Figure 5.1).

6.6.2 Identify any structure-to-electrolyte potential readings that may have been affected by an interrupter malfunction.

6.6.3 Note the amount of depolarization that took place during the interruption period.

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[17] *See* Cathodic Protection Procedure No. 2: Structure-to-Electrolyte Potential Measurement.

[18] *See* Section 6.1.

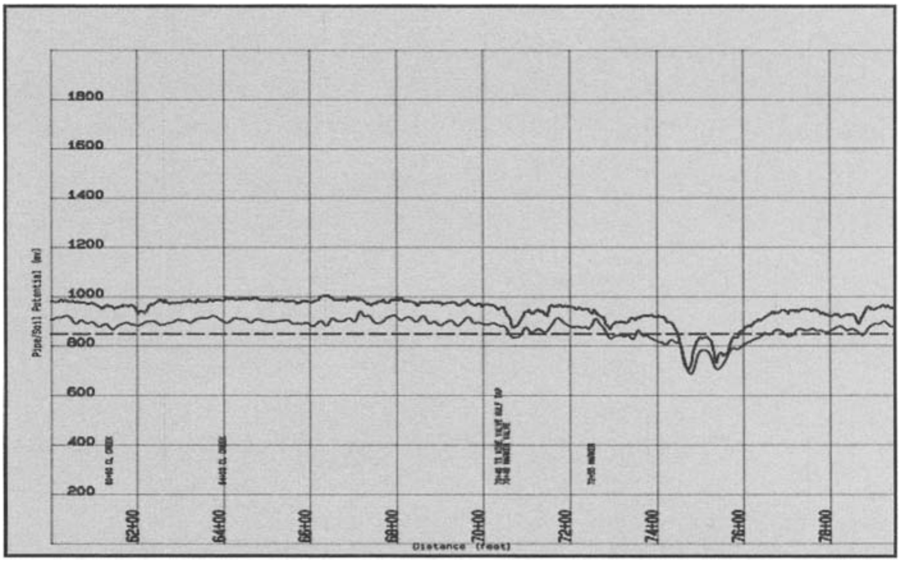

Figure 6.1 Typical close interval structure-to-electrolyte potential profile is shown. (*Source:* NACE CP Technician Course.)

6.7 Baseline Tests

6.7.1 Compare the results of the other DT tests with the initial baseline tests to note the effect of the repair work or the additional testing.

6.7.2 This baseline only applies to this DT survey, as the intent is to make improvements either by making repairs to the system or by adding to the capacity of the CP system.

6.7.3 A new baseline will be established after the DT recommendations have been implemented. Providing that the structure system is not modified, the current requirements have not increased, and the ON structure-to-electrolyte potential has not changed, the new baseline can be used for the following year or so.

6.8 Auxiliary Current Drain Tests

6.8.1 Where the temporary current drain test did not achieve the CP criteria but is relatively close, Equation (6.6) can approximate the current necessary to meet the -850-mV$_{CSE}$ criterion:

$$I_{\text{reqd}} = \frac{(-850\,\text{mV} - E_{\text{native}})}{(E_{\text{off}} - E_{\text{native}})} \times I_{\text{test}}, \tag{6.6}$$

where

I_{reqd}	current required to achieve –850-mV$_{CSE}$ criterion (amperes)
E_{native}	native structure-to-electrolyte potential (millivolts)
E_{off}	instant OFF (polarized) structure-to-electrolyte potential (millivolts)
I_{test}	test current applied for E_{off}(amperes)

Note: Include polarity of potential readings.

6.8.2 Equation (6.7) can approximate the current necessary to meet the 100-mV criterion from the temporary test current:

$$I_{\text{reqd}} = \frac{(-100\,\text{mV})}{(E_{\text{off}} - E_{\text{native}})} \times I_{\text{test}}, \tag{6.7}$$

where

I_{reqd}	current required to achieve the 100-mV criterion (amperes)
E_{off}	instant OFF (polarized) structure-to-electrolyte potential (millivolts)
E_{native}	native structure-to-electrolyte potential (millivolts)
I_{test}	test current applied for E_{off} (amperes)

Note: Include polarity of potential readings.

6.9 Pipeline Current Measurement

6.9.1 Current Span Method (see also Cathodic Protection Procedure No. 3 Direct Current Measurements, Section 6.4).

6.9.1.1 To facilitate this type of test, special current span test leads must exist. A current span must be located at each end of the pipe section being tested.

6.9.1.2 A four-wire current span is to be calibrated first by measuring the resistance of the span in ohms or

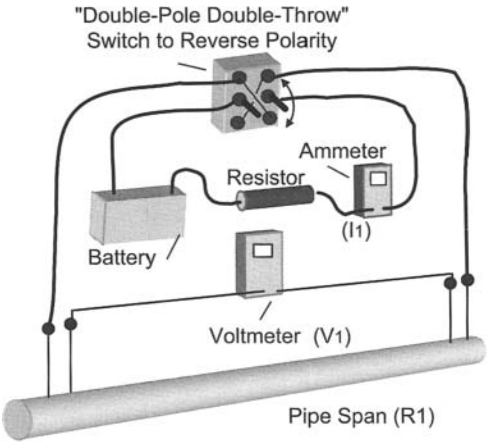

Figure 6.2 Pipe current span is shown.

calculating a calibration factor for the span in amperes per millivolt.

6.9.1.3 Calculate the resistance of the pipe span (Figure 6.2) by Ohm's law from Equation (6.8):

$$R_1 = \frac{\Delta V_1}{\Delta I_1}, \tag{6.8}$$

where

R_1 resistance of the pipe span (ohms)

ΔV_1 net test voltage across the pipe span ($V_{\text{on}} - V_{\text{off}}$; volts)

ΔI_1 net test current through the span ($I_{\text{on}} - I_{\text{off}}$; amperes)

6.9.1.4 Alternately, calculate the calibration factor from Equation (6.9):

$$\text{CF}_1 = \frac{\Delta I_1}{\Delta \text{mV}_1}, \tag{6.9}$$

where

CF_1 calibration factor of span 1 (amperes per millivolt)

ΔI_1 net current through the span (amperes)

$\Delta \text{m}V_1$ net voltage across the pipe span (millivolts)

6.9.1.5 Where two-wire spans exist, calculate the resistance from the pipe dimensions and the resistivity of steel ($\sim 18 \times 10^{-6}$ Ωcm), as shown in Equations (6.10), (6.11), and (6.12). These equations are shown in metric units; however, imperial units can be used, provided they are all consistent in type of unit:

$$R_{\text{span}} = \rho \frac{L_{\text{span}}}{A}, \tag{6.10}$$

$$A = \pi \frac{(\text{OD}^2 - \text{ID}^2)}{4}, \tag{6.11}$$

$$\text{ID}_{\text{pipe}} = \text{OD}_{\text{pipe}} - 2wt, \tag{6.12}$$

where

R_{span}	steel pipe resistance (ohms)
ρ	resistivity of steel (ohm-centimeters)
A	cross-sectional area of pipe (centimeters squared)
wt	wall thickness (centimeters)
OD_{pipe}	pipe outside diameter (centimeters)
ID_{pipe}	pipe inside diameter (centimeters)
L_{span}	length of span (centimeters)
π	constant 3.1416

Note: 1 in = 2.54 cm = 25.4 mm; 1 ft = 30.48 cm = 0.3048 m; 1 m = 100 cm = 39.37 in = 3.27 ft.

6.9.1.6 Alternately, calculate a calibration factor *CF* in amperes per millivolt, as shown by Equation (6.13):

$$F_1 = \frac{\Delta I_1}{\Delta \text{mV}_1}, \tag{6.13}$$

where

F_1	calibration factor of the pipe span (amperes per millivolt)
ΔI_1	net current through the span (amperes)
ΔmV_1	net voltage across the pipe span (millivolts)

6.9.1.7 Current is calculated for a pipeline current span either from Equation (6.14), if resistance is known, or from Equation (6.15), if the calibration factor is known. Note the units in each case.

- Using resistance,

$$I_1 = \frac{V_1}{R_1}, \tag{6.14}$$

where

I_1	current through the span (amperes)
V_1	voltage across the pipe span (volts)
R_1	resistance of the pipe span (ohms)

- Using the calibration factor,

$$I_1 = \mathrm{mV}_1 \times F_1, \tag{6.15}$$

where

I_1	current through the span (amperes)
mV_1	voltage across the pipe span (millivolts)
F_1	calibration factor of the pipe span (amperes per millivolt)

Note: The voltage must be in volts if using the resistance but in millivolts when using the calibration factor.

6.9.1.8 Record the current direction.

6.9.2 Clamp-On Ammeter

6.9.2.1 Average the current taken with the coil in both directions.

6.9.2.2 Record the current direction.

6.10 Coating Conductance[7.3]

6.10.1 Equation (6.16) gives the coating conductance relationship to coating resistance:

$$G = \frac{1}{R}, \tag{6.16}$$

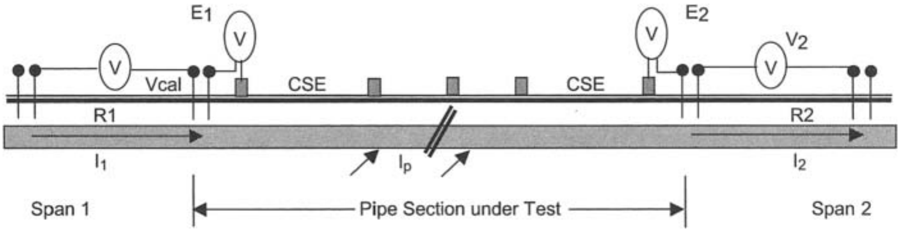

Figure 6.3 Coating conductance test is shown.

where

G	conductance (siemans)
R	resistance (ohms)

6.10.2 Note that conductance is the inverse of resistance. Either calculating the resistance and taking the inverse or calculating directly from the data can determine the coating conductance. The latter approach is described subsequently.

6.10.3 Determine the current applied only to the section in question.

6.10.4 Calculate the average potential change (ΔE) through the pipe section as a result of the applied current (Figure 6.3).

6.10.5 The current applied is then calculated as follows:

- Current for an isolated section is equal to the current applied.
- Current pickup to the pipeline coating conductance section (see Figure 6.3) is determined by Equation (6.17) from the current at each end of the section:

$$\Delta I_p = [(I_{\text{on}\,1} - I_{\text{off}\,1}) - (I_{\text{on}\,2} - I_{\text{off}\,2})], \tag{6.17}$$

where

ΔI_p	net current to the section (amperes)
$I_{\text{on}\,1}$	current at span 1 with test current on (amperes)
$I_{\text{off}\,1}$	current at span 1 with test current off (amperes)
$I_{\text{on}\,2}$	current at span 2 with test current on (amperes)
$I_{\text{off}\,2}$	current at span 2 with test current off (amperes)

6.10.6 The coating conductance is normally calculated as specific coating conductance, that is, the conductance of a specific unit area of the pipe surface. The specific coating conductance in siemans per meter squared of a given pipe section is calculated by Equation (6.18):

$$g' = \frac{\Delta I_p}{\Delta E \times A} \tag{6.18}$$

where

g'	specific coating conductance of pipe section (siemans per meter squared)
ΔI_p	net current to pipe section (amperes)
ΔE	average difference in ON and OFF pipe-to-electrolyte potentials throughout the pipe section (volts)
A	surface area of pipe section picking up current (meters squared); $A = \pi dL$, where π is the constant 3.141593, d is diameter (meters), and L is length (meters)

6.11 Soil Resistivity

6.11.1 Calculate the soil resistivity(19) from the four-pin test using Equation (6.19):

$$\rho = 2\pi aR, \tag{6.19}$$

where

ρ	resistivity (ohm-centimeters)
π	constant 3.141593
a	inside pin spacing and average depth of measurement (centimeters)
R	resistance measured or calculated (ohms)

6.11.2 Calculate the resistivity from a soil (water) box using Equation (6.20):

$$\rho = \frac{RA}{L}, \tag{6.20}$$

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(19) Four-pin calculations described in more detail in "Cathodic Protection Procedure No. 12: Soil Resistivity Measurement."

where

ρ resistivity (ohm-centimeters)
A cross-sectional area of soil box (centimeters squared)
L distance between potential pins, that is, P1 and P2 (centimeters)
R resistance measured or calculated (ohms)

Note: If the soil box is constructed where $A = L$, then Equation (6.20) becomes Equation (6.21):

$$\rho = R, \tag{6.21}$$

where

ρ resistivity (ohm-centimeters)
R resistance measured or calculated (ohms)

Although in Equation (6.21), the value of the resistivity is equal to the resistance, the resistivity is in ohm-centimeters, and the resistance is in ohms.

6.11.3 Soil resistivity layers can be predicted by the Barnes layer method.(20) Figure 6.4 illustrates three layers of soil resistivity that are to be predicted based on the average soil resistivity measured to three different depths (a_1, a_2, and a_3).

The Barnes layer analysis(21) assumes that the layers are uniform and in parallel. A_{Layer} is the thickness of each layer, which is the difference between the two depths measured. The resistance R_{Layer} of each layer can be calculated by the parallel resistance formula described for each layer in Figure 6.4. With the spacing and the resistance known, the resistivity (ρ_{Layer}) can be calculated from Equation (6.19) or as shown in Figure 6.4.

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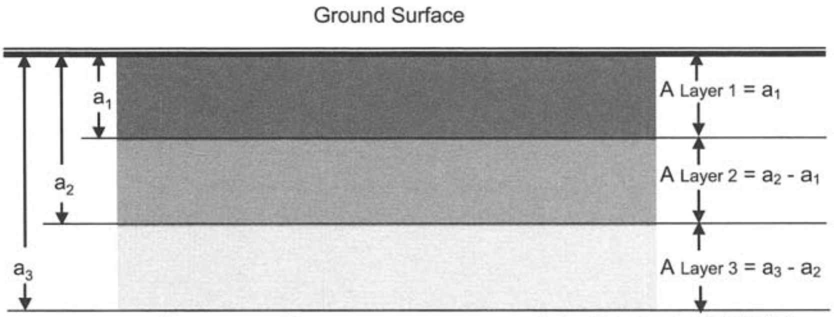
[20] The Barnes layer method is described in more detail in "Cathodic Protection Procedure No. 12: Soil Resistivity Measurement."

[21] *See* Cathodic Protection Procedure No. 12: Soil Resistivity Measurement.



$\rho_1 = 2 \times \pi \times a_1 \times R_1$

$\rho_2 = 2 \times \pi \times a_2 \times R_2$

$\rho_3 = 2 \times \pi \times a_3 \times R_3$

$R_{\text{Layer 1}} = R_1$

$R_{\text{Layer 2}} = R_1 \times R_2 / (R_1 - R_2)$

$R_{\text{Layer 3}} = R_2 \times R_3 / (R_2 - R_3)$

R - Resistance (Ω)

π (pi) - Constant = 3.141593

$\rho_{\text{Layer 1}} = 2 \times \pi \times a_1 \times R_1$ OR

$\rho_{\text{Layer 1}} = 2 \times \pi \times A_{\text{Layer 1}} \times R_{\text{Layer 1}}$

$\rho_{\text{Layer 2}} = 2 \times \pi \times A_{\text{Layer 2}} \times R_{\text{Layer 2}}$

$\rho_{\text{Layer 3}} = 2 \times \pi \times A_{\text{Layer 3}} \times R_{\text{Layer 3}}$

ρ - Resistivity (Ω-cm)

Figure 6.4 Soil resistivity layers with calculations are shown.

6.12 Additional Cathodic Protection Design Information

6.12.1 This section is only intended to explain how the field information will be used in a CP design, rather than to describe how to prepare a CP design.

6.12.2 The configuration of the temporary anode bed will be compared to that anticipated in the new anode bed design to decide how the distribution of current will change.

6.12.3 Details of the proposed anode bed locations are required to prepare the design and a list of materials and to acquire land. Anodes are to be placed in the following:

6.12.3.1 The lowest soil resistivity

6.12.3.2 Uniform soil resistivity

6.12.3.3 Permanent moisture

6.12.3.4 A layer below the maximum frost depth

6.12.4 Normally, the most suitable locations for anode beds are in geographically low areas, providing the soil resistivity is suitable.

6.12.5 In addition to deciding if an AC voltage supply is practical, the possibility of future hazardous AC voltages has to be considered.

6.12.6 Anode beds are to be installed away from foreign structures to avoid interference effects on them. Also, details of the foreign CP systems are needed to make certain that they will not interfere either.

6.12.7 Any sources of AC or DC stray current need to be addressed as they will not only affect the design but also the commissioning survey.

6.12.8 Photographs of the proposed anode bed area(s) and unusual features of the structure or terrain can prove invaluable in the preparation of a design.

7.0 REFERENCES

7.1 NACE Standard SP0177-2007, "Mitigation of Alternating Current and Lightning Effects on Metallic Structures and Corrosion Control Systems" (Houston, TX: NACE International, 2007).

7.2 NACE Standard TM0497-2002, "Measurement Techniques Related to Criteria for Cathodic Protection on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE International, 2002).

7.3 NACE SP0169-2007, "Control of External Corrosion on Underground or Submerged Metallic Piping Systems" (Houston, TX: NACE International, 2007).

7.4 NACE Standard TM0102-2002, "Measurement of Protective Coating Electrical Conductance on Underground Pipelines" (Houston, TX: NACE International, 2002).