# Basic Chapter 6
## Resistance and Current Measurements

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# Introduction to Resistance

- The electrical resistance of an object is a measure of its opposition to the flow of electric current.
- It is typically expressed in units of ohms.
- The Greek letter "omega" (Ω) is the symbol for ohms.

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# Values of Resistance We Might Want to Know

- The resistance across a wire, a reel of wire, a bond, a shunt or a resistor
- The resistance across an electrical isolation device
- The resistance across a pipeline span
- The resistance between a pipeline and earth
- The resistance between an anode bed and earth
- The resistance or resistivity of soil

# Measuring a Simple Resistance

- Measuring the resistance across an object that has been temporarily isolated electrically, is often referred to as a “Simple Resistance” measurement.
- Examples include the resistance across a wire, a reel of wire, a bond, a shunt or a resistor
- These resistance measurements are simple applications of the basic electric circuit as was discussed in Chapter 1.
- All that is needed for this measurement is a battery, a voltmeter, an ammeter and test leads.
- See Figure 6-1 for an example.

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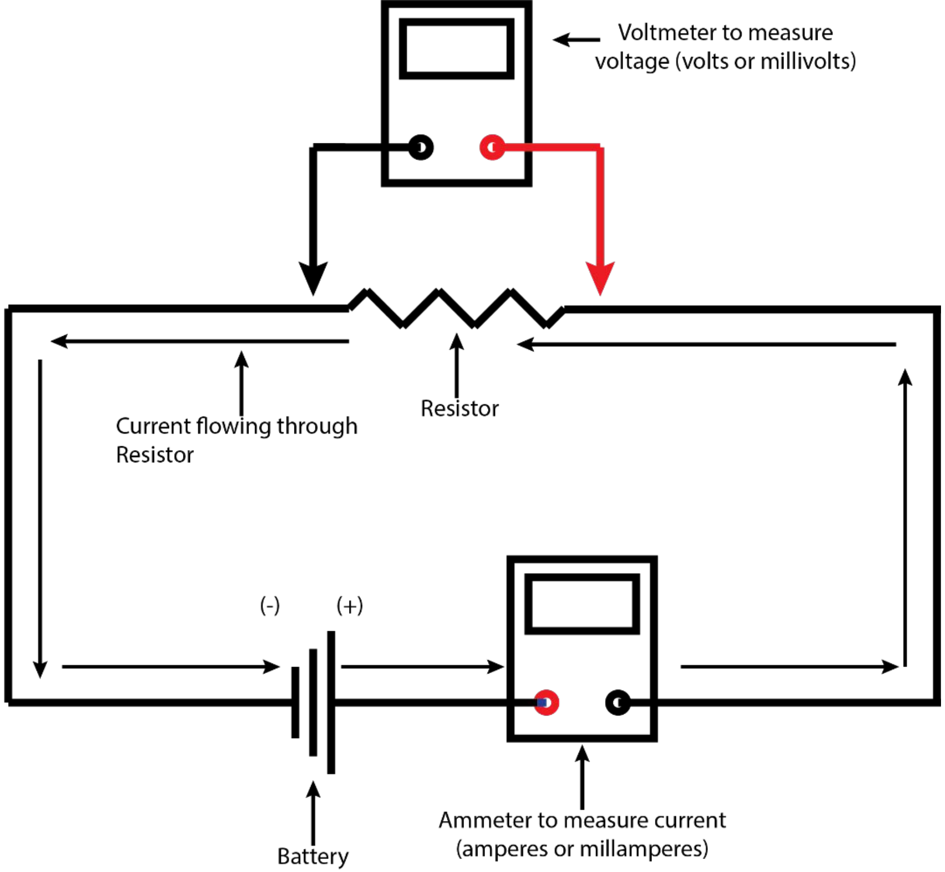



$$R = \frac{E}{I} = \frac{1.21\ V}{0.0676\ A} = 17.899\ \Omega$$

**Measuring a Simple Resistance**
**Figure 6-1**

# Delta Values in Resistance Tests

- The symbol Δ means "change in" and is normally read as “delta”.
- Delta is the “On” value minus the “Off” value.
- $\Delta E$ = E-On – E-Off and $\Delta I$ = I-On – I-Off
- Delta calculations must include the polarities of the measurements.
- In the previous example, E-Off and I-Off were both zero so considering the Δ was not necessary.

# Delta Values in Resistance Tests

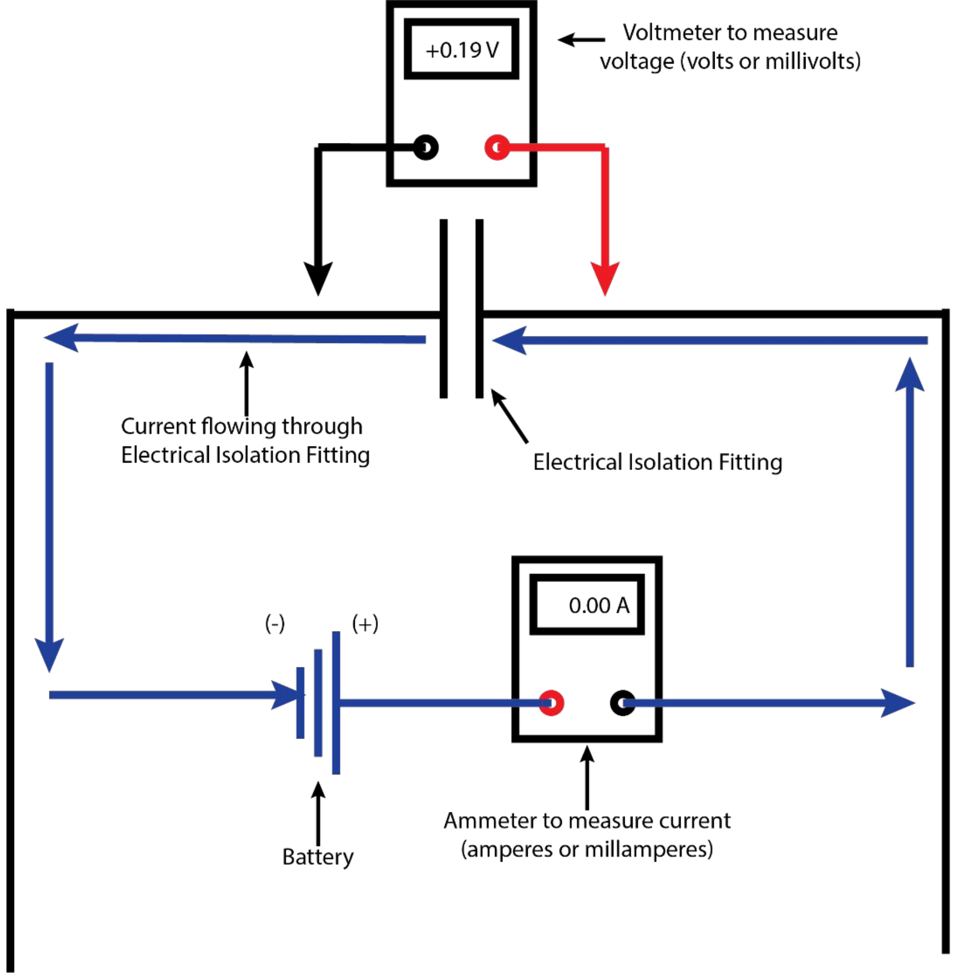
- In most cases in the field, E-Off will not be zero and $\Delta E$ must be used.
- In most cases when we use a test current, I-Off will be 0 since our test circuit is open and I-On = $\Delta I$.

# Resistance of Electrical Isolation Devices

- An effective electrical isolation device must have a very high resistance through it.
- Can we measure the resistance across it to determine if it is effective?
- For an installed device, unlike with a simple resistance, we cannot temporarily isolate the device electrically since the two sides of the device are in the earth.

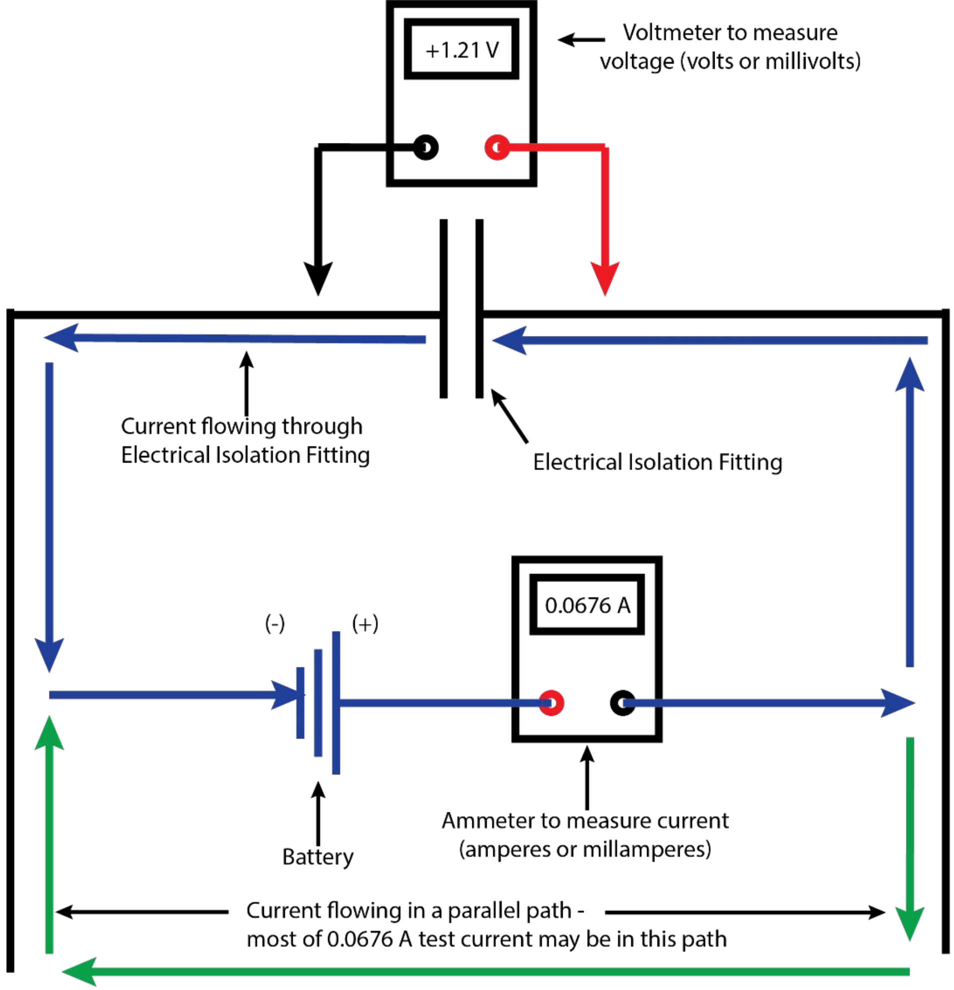
# Resistance of Electrical Isolation Devices

- If we connect as shown previously, there are two parallel paths for the test current to flow: through the device (the path we care about) and through the earth.
- See Figures 6-2 and 6-3.




$$R = \frac{\Delta E}{I} = \frac{E_{ON} - E_{OFF}}{I} = \frac{1.21\,V - 0.19\,V}{0.0676\,A} = 15.809\,\Omega$$

**Measuring Resistance Across an Electrical Isolation Fitting**
**Figure 6-2**




$$R = \frac{\Delta E}{I} = \frac{E_{ON} - E_{OFF}}{I} = \frac{1.21\ \text{V} - 0.19\ \text{V}}{0.0676\ \text{A}} = 15.809\ \Omega$$

**Measuring Resistance Across an Isolating Fitting - Parallel Paths**
**Figure 6-3**

# Resistance of Electrical Isolation Devices

- In Figure 2, note that voltage across the device is 0.19 V.
- The fact that the voltage across the device is not zero indicates that there is some resistance across it.
- This also demonstrates why we need to use Δ values.
- The resistance measured tells us nothing about the effectiveness of the electrical isolation device since some (most?) of the test current is flowing in a parallel path, not through the device.

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# Resistance-to-Earth of Pipelines

- Knowing the resistance-to-earth of a pipeline can help us evaluate its coating quality, determine its cathodic protection current requirements and determine if it is electrically isolated.
- The higher the resistance-to-earth of a pipeline, the better the coating and the lower the current requirements.
- If the resistance-to-earth of a pipeline is unusually low, it may not be electrically isolated, and troubleshooting may be needed.

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# Resistance-to-Earth of Anode Beds

- Knowing the resistance-to-earth of an anode bed can help us evaluate the anode bed.
- The lower the resistance-to-earth of an anode bed the better.
- If the resistance-to-earth of an anode bed has increased from previous values, it may indicate depleted anodes or a cable break.

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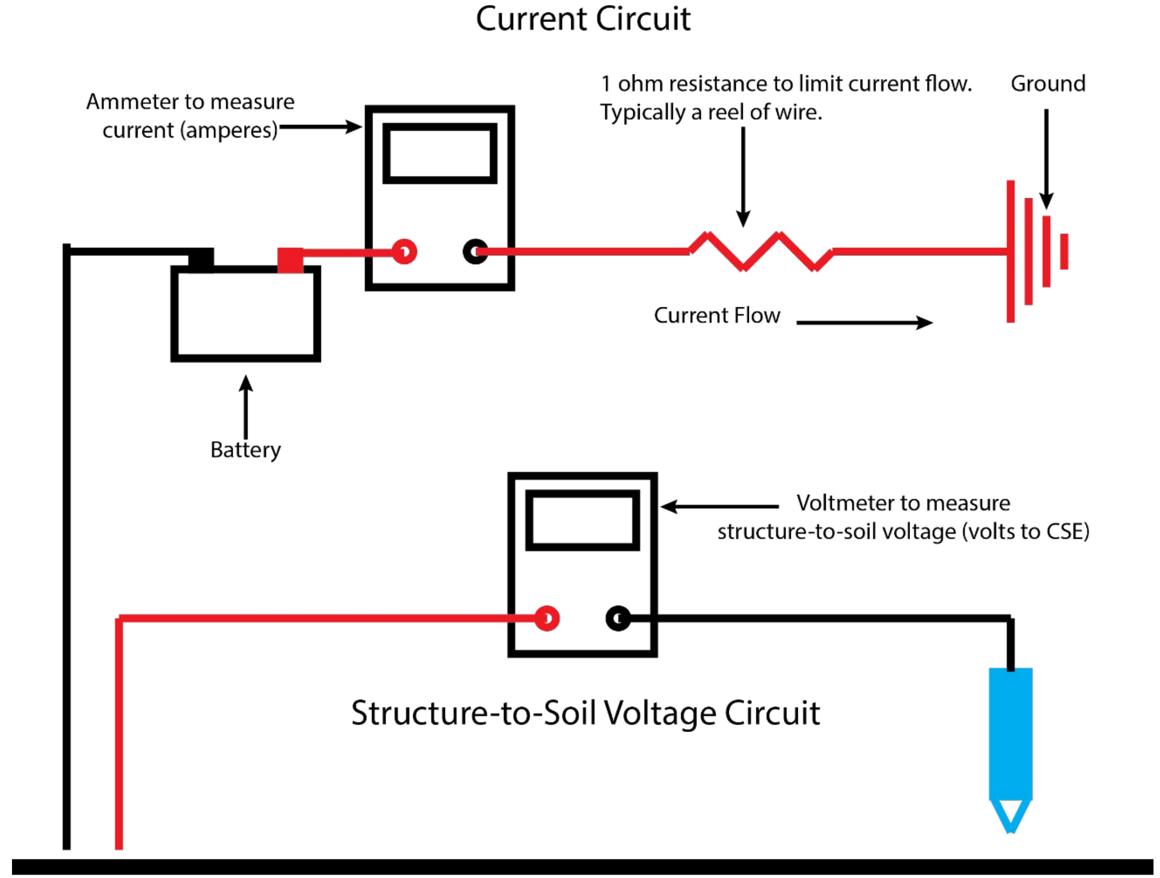
# Measuring the Resistance-to-Earth of Pipelines and Anode Beds

- Measuring the resistance-to-earth of a pipeline or an anode bed can be done using the same test set up. See Figure 6-4.
- A current circuit and a voltage circuit are set up.
- In the current circuit, a DC current source such as a battery is connected between the structure and an earth ground.
- The earth ground can be any metal that is in the earth. A low resistance ground works best.
- An ammeter is placed in the current circuit so that the test current can be measured.

# Measuring the Resistance-to-Earth of Pipelines and Anode Beds

- In the voltage circuit, a voltmeter is used to measure the structure-to-soil voltage to a reference electrode like a CSE.
- When the current circuit is closed, current will flow through the earth between the structure and the ground and the structure-to-soil voltage will change.
- The resistance-to-earth of the structure can be calculated using Ohm’s Law.




$$R = \frac{V_{ON} - V_{OFF}}{I} = \frac{9.80\ V - 1.00\ V}{2.20\ A} = 4.00\ \Omega$$

**Measuring the Resistance-to-Earth of a Buried Structure**
**Figure 6-4**

# Soil Resistivity Measurements

- Resistivity is a property that quantifies how strongly a material opposes the flow of electric current.
- A low resistivity indicates a material that readily allows the flow of electric current.
- A high resistivity indicates a material that resists the flow of electric current.
- Soil resistivity values are used in the evaluation of soils as to their corrosivity and in the design of anode beds.

# Soil Resistivity Measurements

- Soil resistivity is typically expressed in units of ohm-cm.
- The Greek letter "rho" ($\rho$) is commonly used to designate resistivity.

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# Soil Resistivity and Soil Corrosivity

- As was discussed in Chapter 2, low soil resistivities result in low circuit resistances for galvanic corrosion cells.
- This means higher current flow for a given cell potential and the higher current means more corrosion.
- There are various rating systems for soil corrosivity as a function of soil resistivity. The following is one example.

| Resistivity | Corrosivity |
|---|---|
| 0 to 1000 ohm-cm | Very corrosive |
| 1000 to 2000 ohm-cm | Corrosive |
| 2000 to 10,000 ohm-cm | Mildly corrosive |
| 10,000 ohm-cm and above | Progressively less corrosive |

# Methods for Measuring Soil Resistivity

- Soil Box Procedure
- Single Rod Test Procedure
- Wenner Four Pin Method

# Soil Box Procedure

- Used to measure the resistivity of soil samples removed from excavations or auger holes.
- The resistivity may be measured on site or the samples may be placed in sealed plastic bags (to preserve moisture content), tagged as to location, date of removal, and other pertinent information and tested later in the laboratory.

# Soil Box Procedure

- Figure 6-5 shows the soil box procedure.
- The potential pins are removed, and the box filled with the soil sample.
- The soil is compacted to the same degree as it was in the location from which it was taken.
- The potential pins are then inserted and the soil recompacted to ensure solid contact between the soil and the pins.
- The soil in the box is struck off flush with the top of the box so that the cross-sectional area of the soil sample is equal to that of the box.

# Soil Box Procedure

- The resistance is measured with an AC soil resistivity meter.
- The "C" terminals (current) of the meter are connected to the end plates of the soil box.
- The "P" terminals (potential) of the meter are connected to the potential pins of the soil box.
- With an AC soil resistivity meter, AC current passes between the end plates of the soil box.

# Soil Box Procedure

- The AC current causes an AC voltage drop between the potential pins with the amount of the voltage being proportional to the soil resistivity.
- To make a measurement, the energizing button is pressed, and the dial rotated until the galvanometer reads zero.
- The range selector switch may have to be adjusted in the process.

# Soil Box Procedure

- The ohms reading indicated on the resistance scale is multiplied by the factor indicated by the range selector switch to give the measured resistance value in ohms.
- The resistance value is multiplied by the soil box factor to give the soil resistivity in ohm-cm.
- For the most common commercially available soil boxes the factor is 1, so the resistance measured in ohms is equal to the soil resistivity in ohm-cm.

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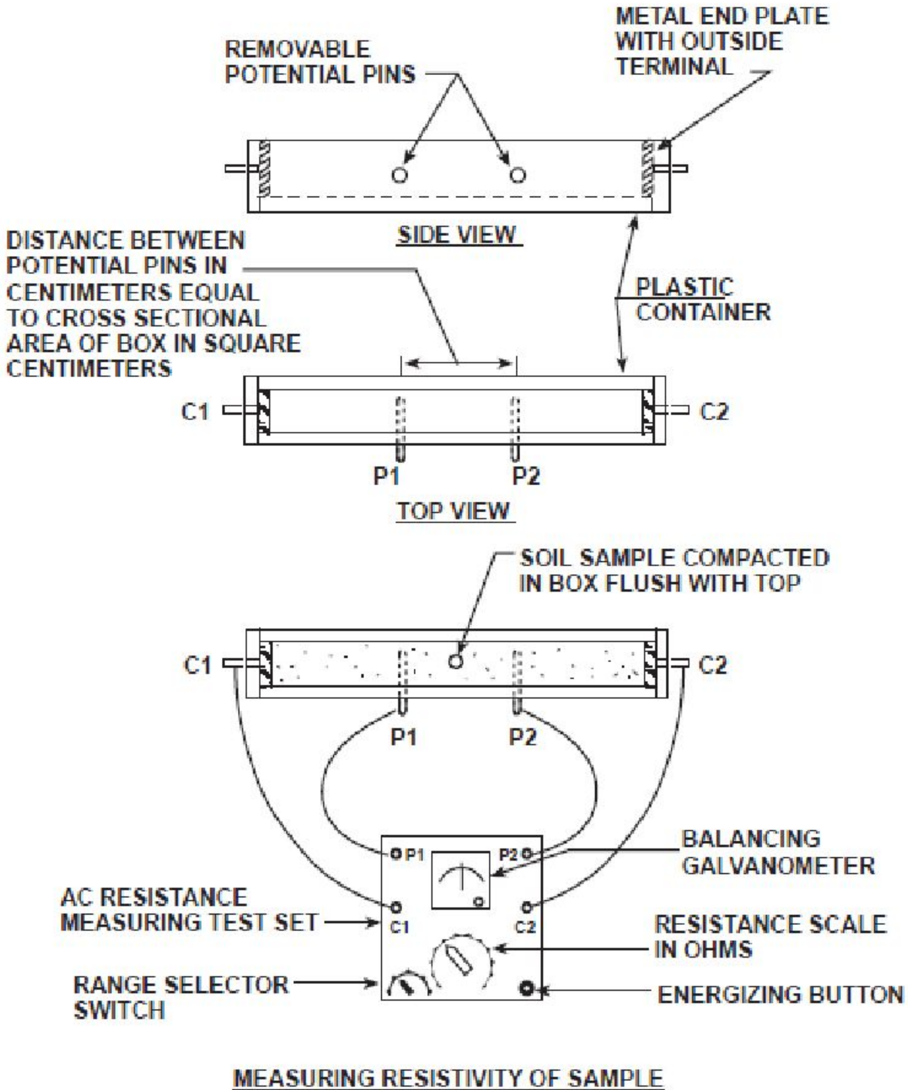
# Soil Box Procedure

- The resistance can also be measured using the voltmeter-ammeter-battery method.
- In the case of very high soil resistivities, resistance values may be beyond the range of an AC soil resistivity meter. The DC method may then be used.
- The soil box may be used for measuring the resistivity of water samples in the same fashion.
- The soil box should be cleaned thoroughly between tests to avoid contamination of the next sample.

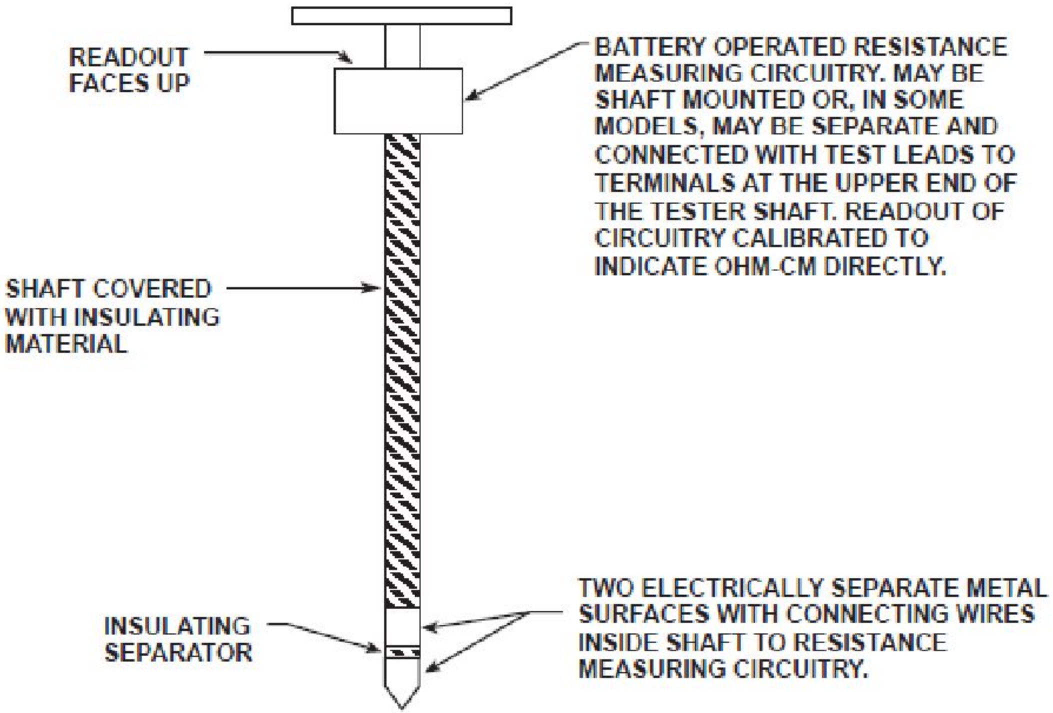



**SOIL BOX MEASUREMENT
OF SOIL RESISTIVITY**

**FIGURE 6-5**

# Single Rod Test Procedure

- For rapid accumulation of spot soil resistivity data along an underground structure such as a pipeline, the single rod resistivity equipment can be used.
- See Figure 6-6.
- The two exposed metal surfaces at the lower end of the tester shaft, when pushed into the ground, will have a resistance between them which is proportional to the resistivity of the soil immediately surrounding these tips.




SINGLE ROD
SOIL RESISTIVITY TESTER

FIGURE 6-6

# Single Rod Test Procedure

- The rod is pushed into the ground to the desired depth (up to three or four feet), the test circuit actuating button depressed, and the soil resistivity read directly from the calibrated read-out.
- The single rod tester only measures the soil resistivity in a small local area, which was also true of the soil box technique.

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# Single Rod Test Procedure

- This method is useful in screening prospective sites for anode bed installations and then using mass soil resistivity techniques to explore the more promising locations indicated by the single rod equipment.
- It can also be used to measure the resistivity of soil at the edge of an excavation.

# Wenner Four Pin Method

- This method measures mass soil resistivities to various depths without having to go below the surface.
- This procedure is used widely for selection of cathodic protection anode bed locations and to accumulate the data necessary for their design.
- The Wenner Four Pin or Four Point method is named for Dr. Frank Wenner who developed the theory and application of the procedure in 1915.
- The arrangement of a 4-pin test setup is shown in Figure 6-7.

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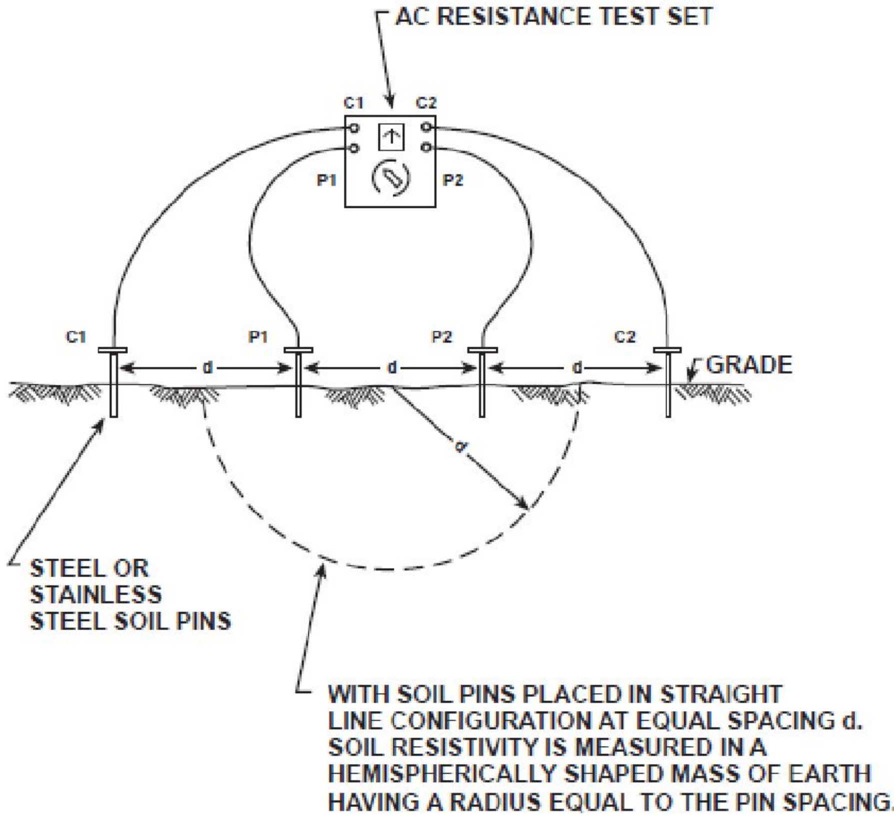


**SOIL RESISTIVITY MEASUREMENT BY WENNER 4-PIN METHOD**

**FIGURE 6-7**

# Wenner Four Pin Method

- Four pins are pushed or driven into the ground (to a depth no more than 5% of the pin spacing) along a straight line with spacing between pins equal to the depth to which the average soil resistivity is to be measured.
- The size of the soil pins is not critical but can be ¼-inch or ⅜-inch rod two to three feet long and fitted with tee handles to facilitate handling.
- An AC soil resistivity meter can be used to measure the resistance.

# Wenner Four Pin Method

- The “C” terminals (current) of the meter are connected to the outside pins.
- The “P” terminals (potential) of the meter are connected to the inside pins.
- The voltmeter-ammeter-battery method may also be used.
- The measured resistance value is not the soil resistivity.
- The resistivity is a function of both the measured resistance and the pin spacing.

# Wenner Four Pin Method

- For any pin spacing, the soil resistivity is determined by the following formula:

$$\rho = 191.5 \times D \times R$$

- Where:
- $\rho$ = soil resistivity in ohm-cm
- d = pin spacing in feet
- R = measured resistance between P1 and P2 in ohms

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# Wenner Four Pin Method - Example

- We perform a Wenner Four Pin test with the pins spaced 2.5 ft apart (d) and the measured resistance is 18 ohms (R).
- The soil resistivity will then be:

$\rho$ = 191.5 x d x R = 191.5 x 2.5 x 18 = 8617.5 ohm-cm

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# Wenner Four Pin Method

- The soil resistivity in this example is a weighted average to the 2.5 ft depth.
- As indicated on Figure 6-7, the mass of earth "seen" by the measurement is a hemispherically shaped mass with the flat cross-sectional area of the hemisphere flush with the earth surface, and with the radius equal to the pin spacing and centered at a point midway between soil pins P1 and P2.
- The average will be affected more by the substantially greater volume of earth in the top half of the hemisphere than by the bottom half.

# Introduction to Current

- Electrical current is the flow of electrons in a conductor.
- It is typically expressed in units of amperes.
- The letter "I" is commonly used to designate current. The letter “I” originated from the term “current intensity”.
- Wires and pipes are examples of conductors in corrosion control testing.

# Values of Current We Might Want to Know

- Current output from a rectifier
- Current output from a galvanic anode bed
- Current flow through an interference bond
- Current flow across a bonded electrical isolation device
- Current flow on a pipeline
- Test current for performing tests like a resistance test

# Methods to Measure Current

- Measuring the voltage across a shunt and calculating current using Ohm's Law
- Measuring the voltage across a pipeline span and calculating current using Ohm's Law
- Using an ammeter
- Using a clamp-on ammeter

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# Measuring Current with a Shunt

- The most common way that corrosion testers measure current is by using a shunt.
- A shunt is a resistor that has a known, constant resistance value.
- Shunts are installed at rectifiers, bonds and other locations so that current can be measured without opening the circuit.
- To determine current flow through a shunt, the voltage across the shunt is measured and the current is calculated using Ohm’s Law or a “Shunt Factor”.

# Measuring Current with a Shunt

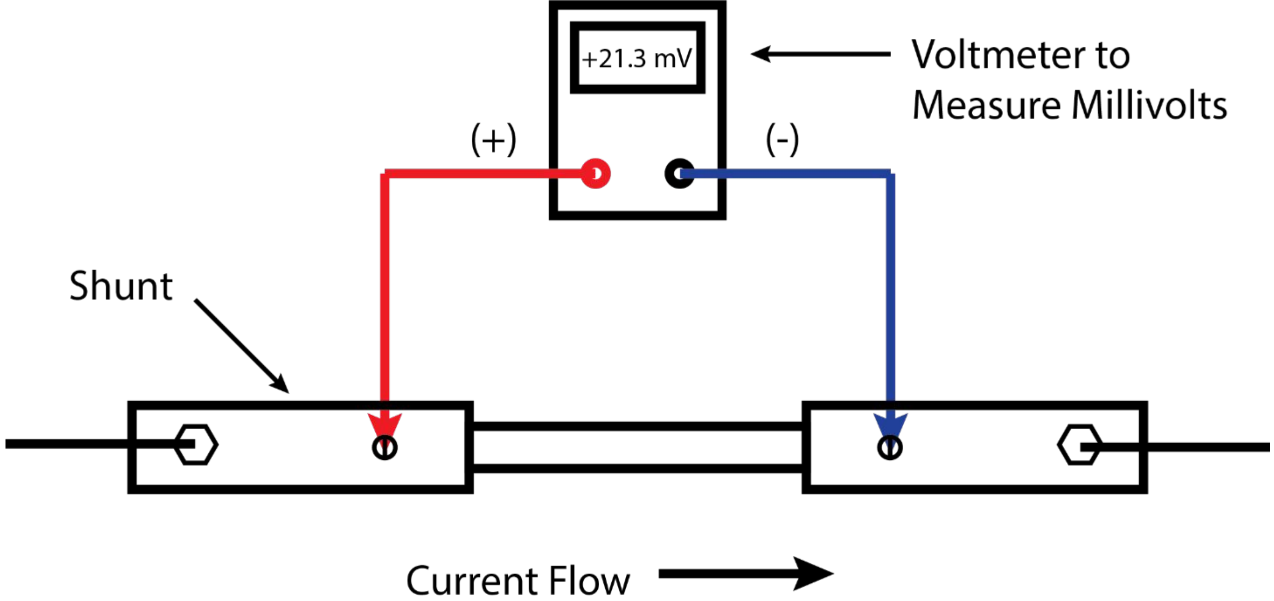
- A Shunt Factor is a rearrangement of Ohm's Law which simplifies the calculation of current.
- The current direction is determined by the polarity of the measurement.
- Current flows from + to -.
- If the measurement is positive, the current is flowing from the positive meter connection toward the negative meter connection.
- Figure 6-8 shows some common shunts.


**Cathodic Protection Shunts**
**Figure 6-8**

# Calculating Current Through a Shunt Using Ohm's Law

- Measure the voltage across the shunt, typically in millivolts.
- Convert the voltage from millivolts to volts.
- Calculate the current using this form of Ohm's Law:

  I = E/R - where R is the resistance of the shunt in ohms
- For example, see Figure 6-9.




If resistance of shunt = 0.005 Ω:

$$I = \frac{E}{R} = \frac{0.0213\ V}{0.005\ \Omega} = 4.26\ A$$

**Measuring Current with a Shunt Using the Shunt Resistance**
**Figure 6-9**

# Calculating Current Through a Shunt Using a Shunt Factor

- A simpler way to calculate current through a shunt is to use a shunt factor.
- A shunt factor is a rearrangement of Ohm's Law that simplifies calculating current from the millivolt reading.
- A shunt factor is in units of A/mV.
- It is calculated by dividing the current rating of the shunt by its millivolt value.
- Most cathodic protection shunts have a millivolt value of 50 mV.

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# Calculating Current Through a Shunt Using a Shunt Factor

- Some shunts have their rating and value stamped on them.
- For example, see Figure 6-10.

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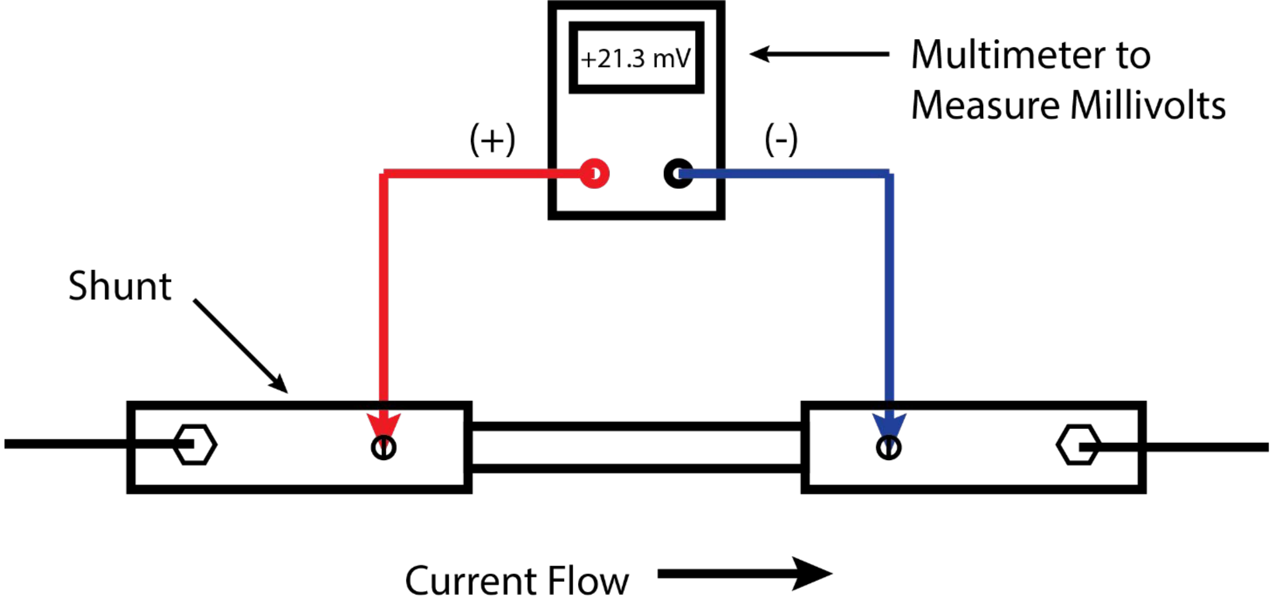


Current rating of shunt = 10 A
Millivolt value of shunt = 50 mV
Shunt factor = 10A/50 mV = 0.2 A/mV

I = E x Shunt Factor = 21.3 mV x 0.2 A/mV = 4.26 A

**Measuring Current with a Shunt Using a Shunt Factor**
**Figure 6-10**

# Measuring Current Flow on a Pipeline

- Current flow on a pipeline can be determined by measuring the voltage drop across a pipe span and calculating the current using Ohm’s Law. In effect, we are using the pipe as a shunt.
- In order to determine the resistance of the pipe span we can either estimate it using a pipe resistance table or by measuring it directly.

# Estimating Resistance of a Pipe Span

In order to estimate the resistance of a pipe span using a pipe resistance table we need to know:

- The length of the pipe span
- The size of the pipe
- The wall thickness of the pipe
- Table 6-1 shows the resistance per foot for various steel pipes.

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## TABLE 6-1

### RESISTANCE OF STEEL PIPE[1]

| Nominal Pipe Size (in) | Outside Diameter (in) | Wall Thickness (in) | Weight per Linear Foot[2] (lbs) | Resistance per Linear Foot[3] (μΩ) |
|---|---|---|---|---|
| 2 | 2.375 | 0.154 | 3.65 | 79.2 |
| 4 | 4.5 | 0.237 | 10.8 | 26.8 |
| 6 | 6.625 | 0.280 | 19 | 15.2 |
| 8 | 8.625 | 0.322 | 28.6 | 10.1 |
| 10 | 10.75 | 0.365 | 40.5 | 7.13 |
| 12 | 12.75 | 0.375 | 49.6 | 5.82 |
| 14 | 14 | 0.375 | 54.6 | 5.29 |
| 16 | 16 | 0.375 | 62.6 | 4.61 |
| 18 | 18 | 0.375 | 70.6 | 4.09 |
| 20 | 20 | 0.375 | 78.6 | 3.68 |
| 22 | 22 | 0.375 | 86.6 | 3.34 |
| 24 | 24 | 0.375 | 94.6 | 3.06 |
| 26 | 26 | 0.375 | 102.6 | 2.82 |
| 28 | 28 | 0.375 | 110.6 | 2.62 |
| 30 | 30 | 0.375 | 118.7 | 2.44 |
| 32 | 32 | 0.375 | 126.6 | 2.28 |
| 34 | 34 | 0.375 | 134.6 | 2.15 |
| 36 | 36 | 0.375 | 142.6 | 2.03 |

(1) From "Control of Pipeline Corrosion", NACE, 1967, Peabody.

(2) Based on steel density of 489 lbs/$ft^3$.

(3) Using 18 μΩ -cm resistivity for steel:

R = (16.061 x 18 μΩ -cm ) / weight per foot in pounds
= 289.1 / weight per foot
= resistance of one foot of pipe in μΩ

# Measuring Current Flow on a Pipeline - Example

- See Figure 6-11.
- We measure 2.36 mV across a 100-ft. span of 12-inch, 0.375” WT (wall thickness) pipe.
- First, we need to calculate the resistance of the span. Looking at Table 6-1, a 12-inch, 0.375” WT pipe has a resistance of 5.82 micro-ohms per foot. For a 100 ft. span:

  R = 100 ft. x 5.82 micro-ohms/ft = 582 micro-ohms

  582 micro-ohms = 0.000582 ohms

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# Measuring Current Flow on a Pipeline - Example

- 2.36 mV = 0.00236 V
- Apply Ohm's Law:

  I=E/R = 0.00236 V/0.000582 ohms = 4.055 A

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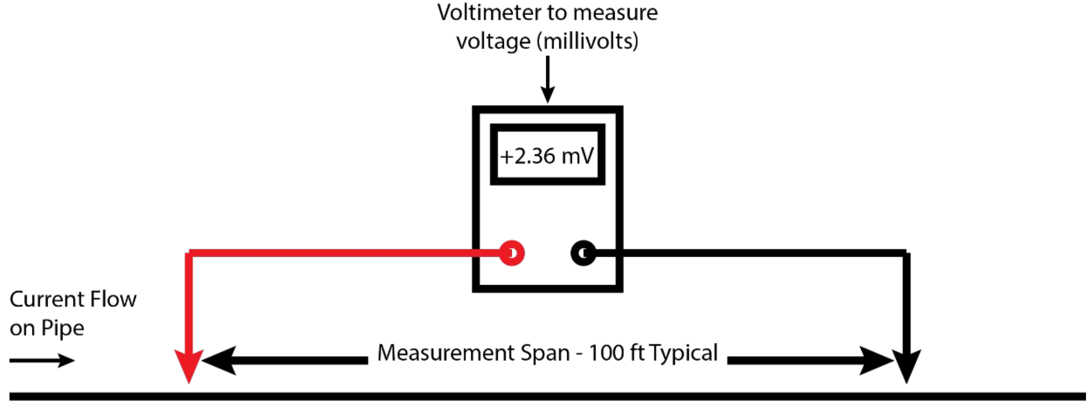



$$I = \frac{E}{R} = \frac{0.00236\ \text{V}}{0.000582\ \Omega} = 4.055\ \text{A}$$

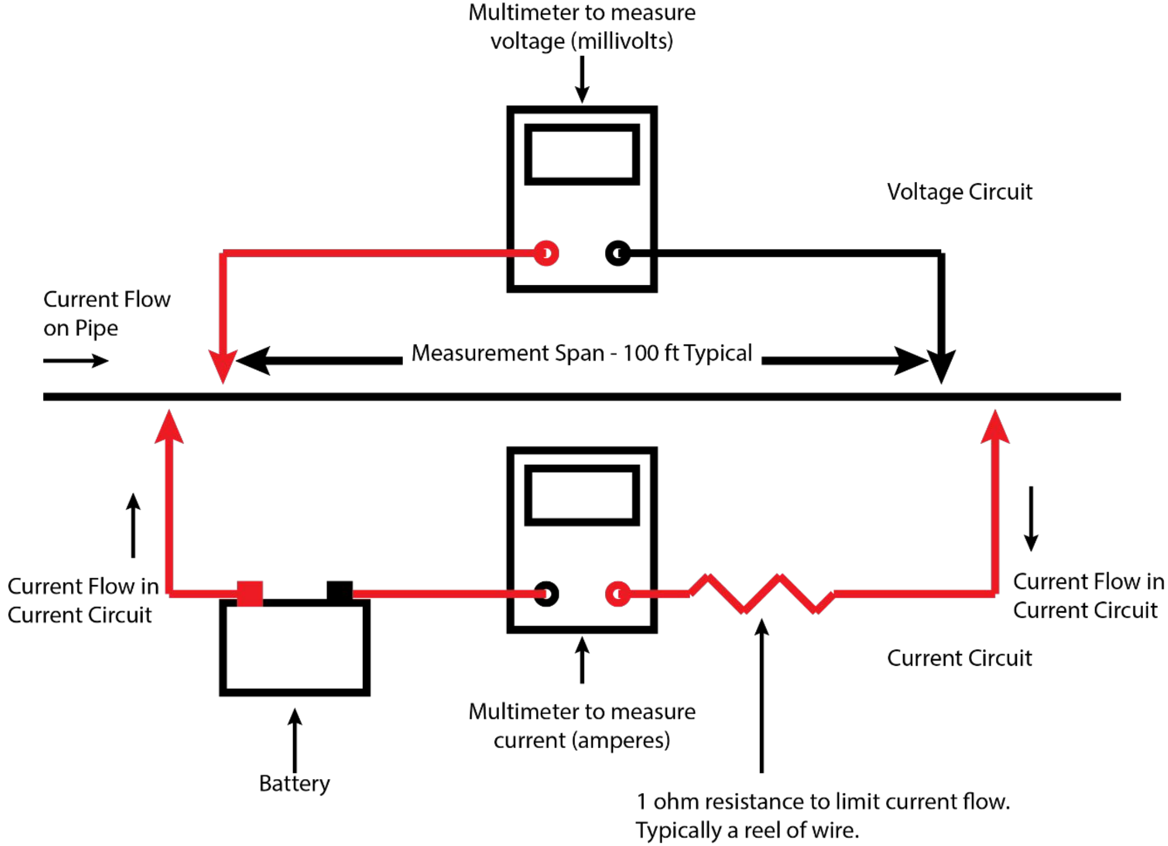
**Measuring Current Flow on a Pipeline**
**Figure 6-11**

# Measuring Resistance of a Pipe Span

- A more accurate way to determine the resistance of a pipe span is to measure it.
- In order to measure the resistance across a pipe span there must be 4 wires with 2 wires at each end of the span.
- Figure 6-12 shows the connections for measuring the resistance of a pipe span.
- A voltmeter is connected to measure the voltage across the span.
- A current circuit is set up across the span with a battery and ammeter.

# Measuring Resistance of a Pipe Span

- When the current circuit is closed the test current will flow through the span and cause the voltage across the span to change.
- Rather than calculating the span resistance in ohms, it is simpler to determine a calibration factor (K factor) in units of amps per millivolt (A/mV) like we do with shunts.
- A shown on Figure 6-12, a test current of 10.8 amperes is connected across the span and changes the voltage across the span from 2.36 millivolts to 7.31 millivolts.
- $K = I/\Delta E = 10.8\ A/(7.31\ mV – 2.36\ mV) = 2.182\ A/mV$
- .




$$K = \frac{I}{E_{ON} - E_{OFF}} = \frac{10.8 \text{ A}}{7.31 \text{ mV} - 2.36 \text{ mV}} = 2.182 \text{ A/mV}$$

$$I \text{ as found} = 2.36 \text{ mV} \times 2.182 \text{ A/mV} = 5.15 \text{ A}$$

**Calibrating a Current Measurement Pipe Span**
**Figure 6-12**

# Measuring Resistance of a Pipe Span

- When calibrating a pipe span it is critical that there be 2 wires at each end of the span so that the voltage and current connections to the pipe are separate. Using the same test wire for voltage and current will create a significant voltage across the wire which will be included in the voltage measurement rendering it invalid.
- Pipe spans used to measure current can be any length, but the resistance of the span needs to be high enough to allow measurement of the pipeline current with acceptable accuracy. A small amount of current flowing across a short span may not be measurable.
- .

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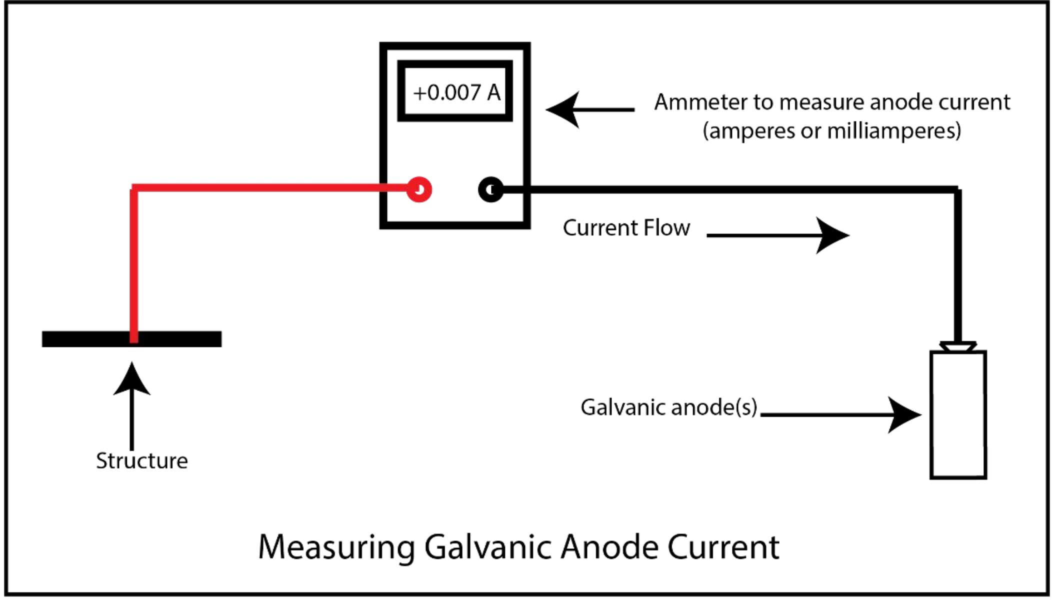
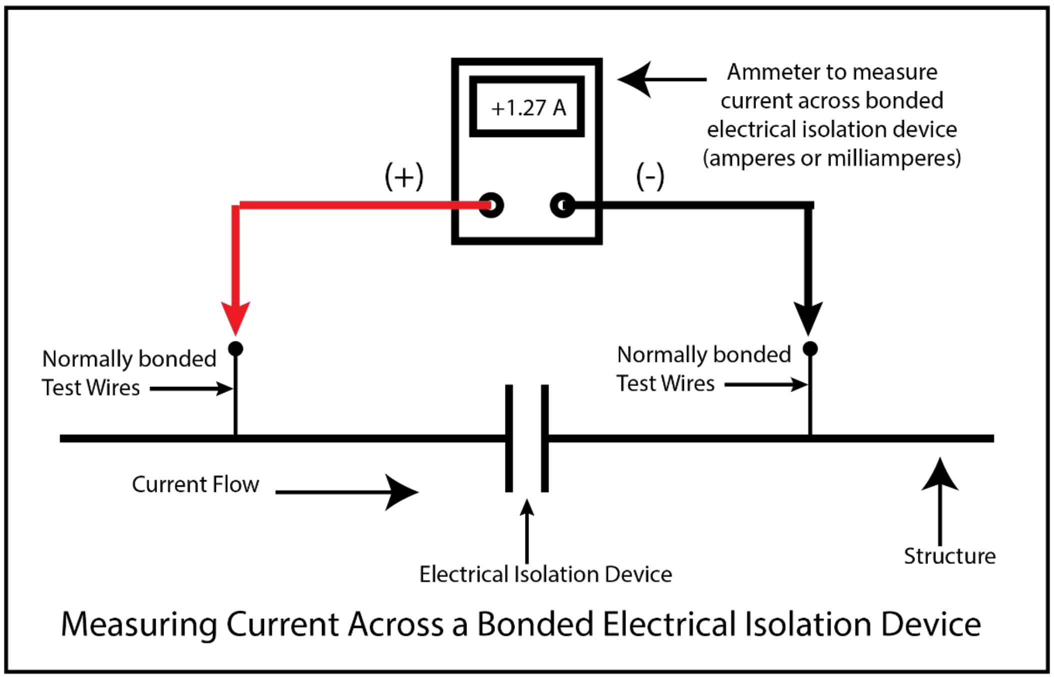
# Measuring Current with an Ammeter

- An ammeter can also be used to measure current. Most multimeters include an ammeter.
- In order to measure current with an ammeter you must break the circuit and install the ammeter in the circuit so that the current to be measured flows though the ammeter.
- Within the ammeter, the current is flowing through an internal shunt. The meter measures the voltage across the shunt and displays current.
- The primary drawback of this method is that the circuit must be opened, and the ammeter inserted in it.

# Measuring Current with an Ammeter

- An ammeter is used to measure current in circuits where a shunt has not been installed such as galvanic anode beds or bonded electrical isolation devices.
- Figure 6-13 shows an ammeter being used to measure galvanic anode current and current across a bonded electrical isolation device.




**Measuring Current with an Ammeter**
**Figure 6-13**

# Clamp-On Ammeters

- Another way to measure current flow on a conductor such as a pipe or cable is with a clamp-on ammeter.
- A clamp-on ammeter has a sensor in the form of a clip or clamp.
- When the sensor is placed around a conductor, the ammeter will indicate the current flow on it.
- Current quantity and direction will be indicated.
- Small sensors are in the form of clips or “jaws”.

# Clamp-On Ammeters

- The clips are squeezed open and placed around the conductor. The clips are then released so that they close.
- The ammeter will then indicate the current flow on the conductor within the sensor.
- The sensor may be integrated into the ammeter or may be separate from the ammeter and connected to it with test leads.
- Sensors in the form of clips are available for use on conductors up to 6 inches in diameter.

# Clamp-On Ammeters

- Large sensors are in the form of 2- or 4-piece clamps that are assembled around the conductor. The assembled sensor is connected to the ammeter with test leads. The ammeter will then indicate the current flow on the conductor within the sensor. Large sensors are available for use on conductors up to 82 inches in diameter.
- The sensors may be permanently installed around a buried or submerged pipeline and their test leads terminated in a test station so that current flow can be monitored.

# Clamp-On Ammeters

- It is important to note that clamp-on ammeters measure the net current within the sensor. If 2 conductors are placed within the sensor, the ammeter will indicate the sum of the current flow on the 2 conductors. For example, if the sensor is placed around both the positive and negative leads from a rectifier, the ammeter will indicate 0, since the current on the 2 cables is in opposite directions.
- Figure 6-14 shows a clamp-on ammeter measuring current flow on a stainless steel tubing line. In this example, the tubing line was installed across an isolating flange.


**CLAMP-ON AMMETER MEASURING CURRENT ON STAINLESS STEEL TUBING**

**FIGURE 6-14**