6th Edition

Low Level Measurements Handbook

Precision DC Current, Voltage, and Resistance Measurements

KEITHLEY

SECTION 2

Measurements from High Resistance Sources

2.1 Introduction

As described in Section 1 of this handbook, measurements made from high resistance sources include low DC voltage, low DC current, high resistance, and charge measurements. The instruments used to make these high impedance measurements include electrometers, picoammeters, and source-measure units (SMUs). While Section 1 described the basic circuits of these instruments and their measurement functions, Section 2 offers more detailed information about these functions, various interferences and error sources, and ways to maximize the accuracy of measurements made from high resistance sources. For easier reference, the information in Section 2 is organized into these subsections:

2.2 High Impedance Voltage Measurements: A discussion of loading errors and the use of guarding to minimize these errors, as well as information on insulating materials used for making high impedance measurements.

2.3 Low Current Measurements: Information about making successful low current measurements is described with such topics as leakage current and guarding, noise and source impedance, zero drift, generated currents, voltage burden, overload protection, and using a coulombmeter to measure low current.

2.4 High Resistance Measurements: Describes the constant-voltage and constant-current methods for measuring high resistance. It also includes information on high valued resistors.

2.5 Charge Measurements: A discussion of the error sources and ways to minimize them, zero check, and extending the range of the charge function.

2.6 General Electrometer Considerations: A discussion of techniques and error sources that affect high impedance measurements in general. Some of the topics include measurement connections, electrostatic interference and shielding, environmental factors, speed considerations, etc.

2.2 Voltage Measurements from High Resistance Sources

Measurements from voltage sources with high internal resistance are subject to a number of errors, such as loading errors from the voltmeter's input resistance and input bias current, as well as from external shunt resistance and capacitance. The following paragraphs discuss these error sources and ways to minimize their effects. For a discussion of errors due to improper connections and electrostatic interference, see Section 2.6.

2.2.1 Loading Errors and Guarding

Input Resistance Loading

Voltage measurements from high resistance sources are subject to loading errors from the meter input resistance, as well as the leakage resistance of the connecting cable. A practical voltmeter may be represented by an ideal infinite input-resistance voltmeter (V_M) in parallel with a resistor equal to the specified input resistance (R_{IN}), as shown in **Figure 2-1**. When a source whose Thevenin equivalent is V_S in series with R_S is connected to the input, the voltage (V_M) appearing across the meter input terminals is reduced by the voltage divider action of R_S and R_{IN} as follows:

$$V_M = V_S\left(\frac{R_{IN}}{R_S + R_{IN}}\right)$$

For example, assume R_S = 100kΩ and R_{IN} = 10MΩ. If V_S = 5V, the actual voltage measured by the meter is:

$$V_M = 5\left(\frac{10^7}{10^5 + 10^7}\right)$$

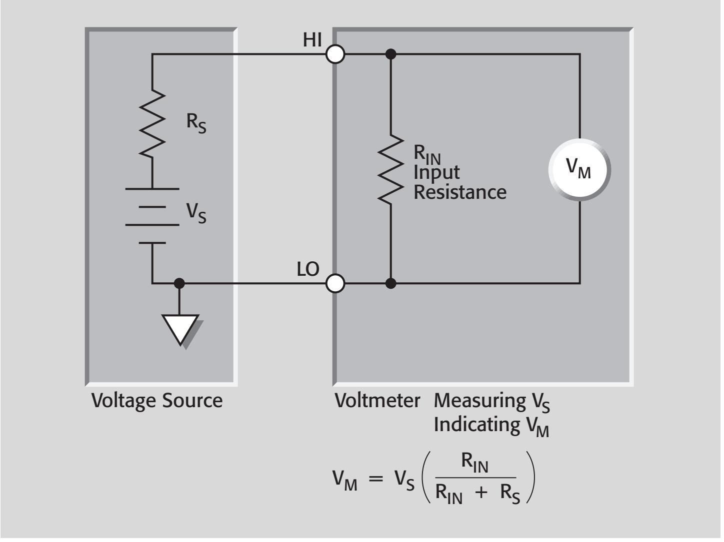
$$V_M = 4.95V$$

Thus, input resistance loading would result in an error of 1% in this example.

The meter input resistance should be much higher than the source resistance. For example, if the desired accuracy is 1%, then the meter resistance must be more than 100 times the source resistance. For higher accuracy, this ratio must be correspondingly higher.

The connecting cable ordinarily isn't a factor, but with very high source resistances (>10GΩ) or under extreme environmental conditions, it can

FIGURE 2-1: Effects of Input Resistance Loading on Voltage Measurement Accuracy



cause significant loading errors. It may be possible to guard the cable and thus reduce its loading on the measurement. This is discussed in the paragraphs on Shunt Resistance Loading and Guarding.

Input Bias Current Loading

Another consideration when measuring voltages from high resistance sources is the input bias current of the voltmeter. The input bias current flows at the instrument input due to internal instrument circuitry and the internal bias voltage. As shown in **Figure 2-2**, the input bias current (I_{BIAS}) develops an error voltage across the source resistance (R_S). Thus, the actual measured voltage (V_M) differs from the source voltage (V_S) as follows:

$$V_M = V_S \pm I_{OFFSET} R_S$$

For example, assume the following parameters:

$$I_{OFFSET} = 1\text{pA} \qquad R_S = 10\text{G}\Omega \qquad V_S = 10\text{V}$$

The actual voltage measured by the meter is:

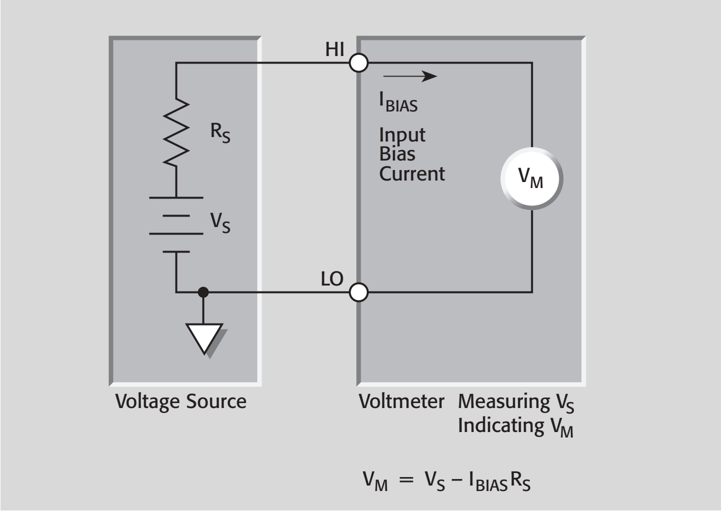
$$V_M = 10 \pm (10^{-12} \cdot 10^{10})$$

$$V_M = 10 \pm 0.01$$

$$V_M = 9.99\text{V or } 10.01\text{V (depending on the offset current polarity)}$$

Thus, the error caused by input offset current would be about 0.1% in this example.

Figure 2-2: Effects of Input Bias Current on Voltage Measurement Accuracy



DMMs and nanovoltmeters have bias currents from 1pA to 1nA, although DMM bias currents are not always specified. Electrometers are known for their low input bias current, which is usually a few femtoamps. Picoammeters and SMUs also have very low input bias currents, although usually not as low as an electrometer's.

Although input bias current is a common source of this type of error, currents generated by external circuits can also result in errors due to voltage drops across the source resistance. Typical sources of such offset currents are insulators and cables.

Shunt Resistance Loading and Guarding

External shunt resistances, such as leaky cables and dirty insulators, may also cause loading errors.

Any external shunt resistance across the voltage source will attenuate the measured voltage, as shown in **Figure 2-3**. As in the case of input resistance voltage loading, the shunt resistance (R_{SHUNT}) and the source resistance (R_S) form a voltage divider that reduces the measured voltage (V_M) as follows:

$$V_M = V_S \left(\frac{R_{SHUNT}}{R_{SHUNT} + R_S} \right)$$

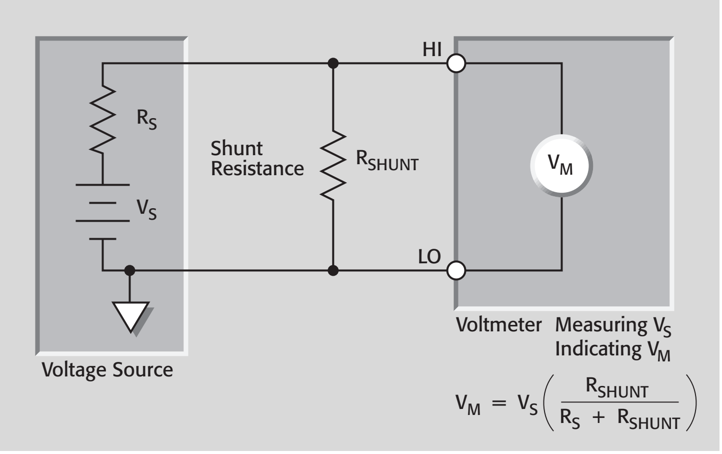
For example, assume $R_S = 10G\Omega$ and $R_{SHUNT} = 100G\Omega$. If V_S has a value of 10V, the measured voltage (V_M) is:

$$V_M = 10 \left(\frac{10^{11}}{10^{11} + 10^{10}} \right)$$

$$V_M = 9.09V$$

In this instance, the error due to shunt loading is approximately 9%.

FIGURE 2-3: Effects of Shunt Resistance on Voltage Measurement Accuracy

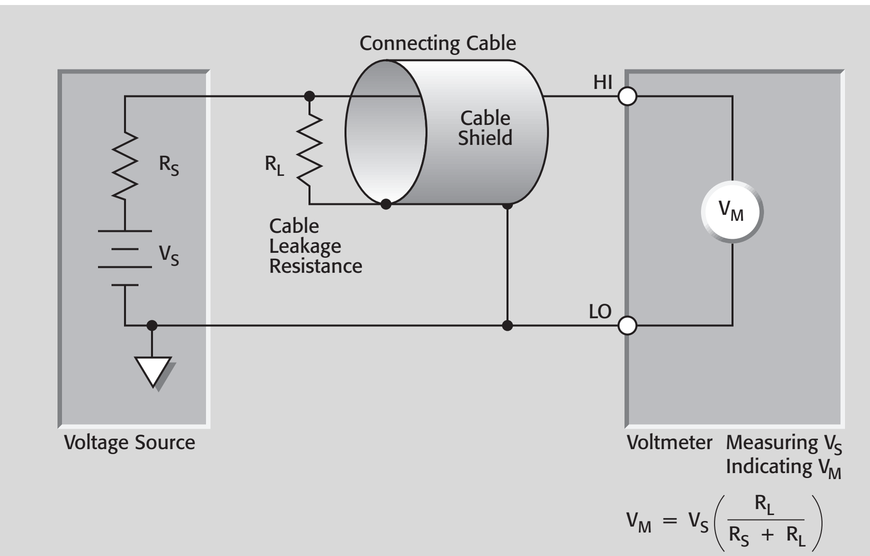


Cable leakage resistance is a common source of shunt resistance loading, as shown in **Figure 2-4**. In this case, the measured voltage (V_M) is attenuated by the voltage divider formed by R_S and the cable resistance (R_L):

$$V_M = V_S \left(\frac{R_L}{R_S + R_L} \right)$$

To reduce errors due to shunt resistance, use cables, connectors, and test fixturing with the highest possible insulation resistance. In addition, the use of guarding will eliminate any residual errors.

FIGURE 2-4: Effect of Cable Leakage Resistance on Voltage Measurement Accuracy

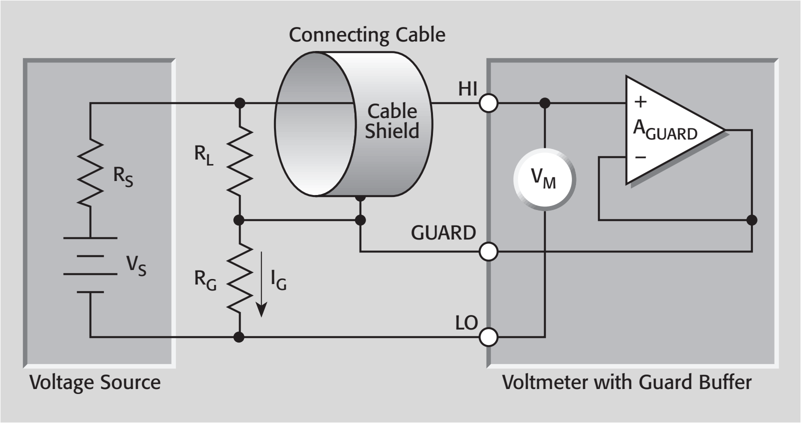


The error due to cable leakage can be greatly reduced by the use of guarding, as shown in **Figure 2-5**. In the guarded configuration, the cable shield is now connected to the output of the guard buffer instead of the meter LO terminal. R_G represents the resistance from the cable shield to meter LO, and I_G is the current through R_G as a result of driving the shield to the same potential as the input HI terminal. This current is supplied by the guard buffer, not the voltage source. Since the voltage across R_L is now many decades lower, the leakage current will be negligible in most cases.

By definition, a guard is a low impedance point in the circuit that's at nearly the same potential as the high impedance input terminal.

In modern electrometers, the preamplifier output terminal is such a point, and can be used to reduce the effect of cable leakage, as shown in **Figure 2-5**. An additional benefit is that the effective cable capacitance is

FIGURE 2-5: Guarded Configuration



also reduced, making the response speed of the circuit much faster. This is discussed in detail in the paragraphs on Shunt Capacitance Loading and Guarding.

The source-measure unit (SMU) can also be used to measure voltages from a high resistance source and the Guard terminal will make a similar improvement.

The circuit of the electrometer when used as a voltmeter is actually as shown in **Figure 2-6**. The guard amplifier is a unity-gain amplifier with very high input impedance. The open-loop gain, A_{GUARD}, ranges from 10^4 to 10^6. The leakage resistance (R_L) is multiplied by this gain and the measured voltage becomes:

$$V_M = V_S \left(\frac{A_{GUARD} R_L}{R_S + A_{GUARD} R_L} \right)$$

Example: Assume R_S has a value of 10GΩ and R_L is 100GΩ. If we assume a mid-range value of 10^5 for A_{GUARD} and a value of 10V for V_S, the voltage measured by the meter is:

$$V_M = 10 \left(\frac{10^{16}}{1.000001 \times 10^{16}} \right)$$

$$V_M = 9.99999\text{V}$$

Thus, we see the loading error with guarding is less than 0.001%. In contrast, the unguarded error voltage with this combination of source and shunt resistances would be about 9%.

Shunt Capacitance Loading and Guarding

The settling time of a voltage measurement depends both on the equivalent source resistance and the effective capacitance at the input of the voltmeter;

FIGURE 2-6: Guarding Leakage Resistance

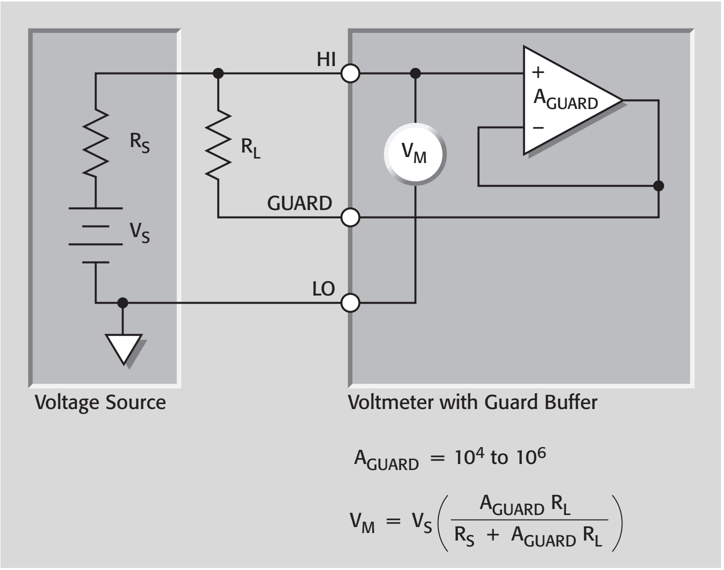
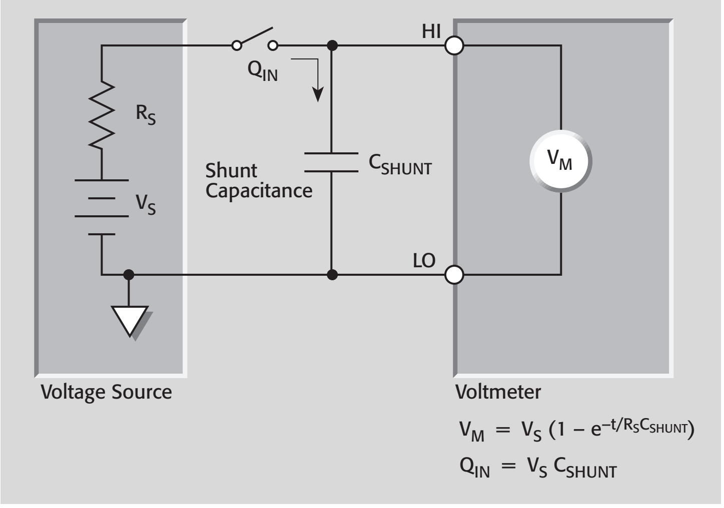


FIGURE 2-7: Shunt Capacitance Loading



this input capacitance consists of the meter input capacitance in parallel with the input cable capacitance. Even a small amount of shunt capacitance can result in long settling times if the source resistance is high. For example, a shunt capacitance of 100pF (including the input cable) and a source resistance of 20GΩ will result in an RC time constant of two seconds. Ten seconds must be allowed for the measurement to settle to within 1% of the final value.

Figure 2-7 demonstrates the effects of shunt capacitance loading on the input of a typical high impedance voltmeter. The signal source is represented by V_S and R_S, the shunt capacitance is C_{SHUNT}, and the measured voltage is V_M. Initially, the switch is open, and C_{SHUNT} holds zero charge.

When the switch is closed, the source voltage (V_S) is applied to the input, but the measured voltage across C_{SHUNT} doesn't rise instantaneously to its final value. Instead, the voltage rises exponentially as follows:

$$V_M = V_S\,(1 - e^{t/R_S C_{SHUNT}})$$

Also, the charge (Q_{IN}) transferred to the capacitor is:

$$Q_{IN} = V_S C_{SHUNT}$$

The charging of C_{SHUNT} yields the familiar exponential curve shown in **Figure 2-8**. After one time constant (τ = RC), the measured voltage rises to within 63% of its final value; final values for various time constants are summarized in **Table 2-1**.

FIGURE 2-8: Exponential Response of Voltage Across Shunt Capacitance

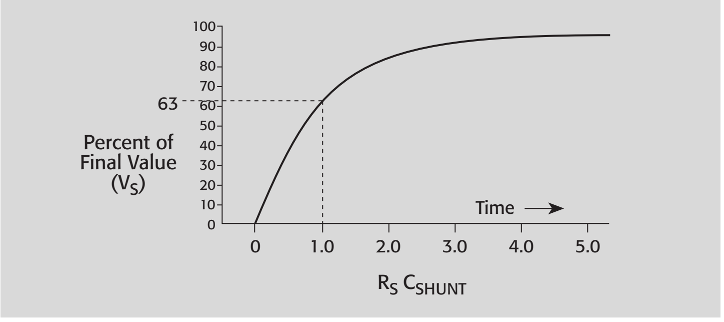


TABLE 2-1: Settling Times to Percent of Final Value

Time Constant (τ*)	Percent of Final Value
1	63 %
2	86 %
3	95 %
4	98 %
5	99.3 %

*τ = RC, where R = resistance (ohms), C = capacitance (farads)

Example: Assume R_S = 10GΩ and C_{SHUNT} = 100pF. This combination results in an RC time constant of one second. Thus, it would take five seconds for the circuit to settle to within less than 1% of final value. With a 10V change in V_S, a total of 1nC of charge would be transferred to C_{SHUNT}.

While the primary advantage of guarding is a reduction in the effects of shunt resistance, another important aspect is the reduction in the effects of shunt capacitance. As shown in **Figure 2-9**, the guard buffer significantly reduces the charging time of C_{SHUNT} because of the open-loop gain (A_{GUARD}), which is typically 10^4 to 10^6.

With guarding, the rise time of the measured voltage (V_M) now becomes:

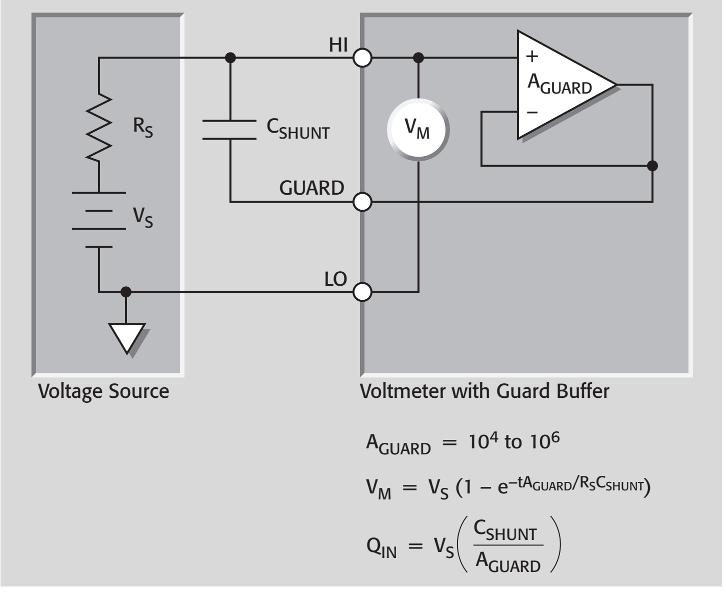
$$V_M = V_S\,(1 - e^{-tA_{GUARD}/R_SC_{SHUNT}})$$

and the charge transferred to C_{SHUNT} is:

$$Q_{IN} = \left(\frac{V_SC_{SHUNT}}{A_{GUARD}}\right)$$

Example: Assume R_S = 10GΩ and C_{SHUNT} = 100pF, as in the unguarded example given previously. With a nominal value of 10^5 for A_{GUARD}, we can see the guarded RC settling time is reduced to approximately $5s/10^5 = 50\mu s$, an insignificant period of time compared to the time it typically takes an instrument to process a single reading. Note that with a 10V change in V_S, the charge transferred (Q_{IN}) is only 10fC, a reduction of 10^5:1.

FIGURE 2-9: Guarding Shunt Capacitance



2.2.2 Insulation Resistance

Electrometers and some SMUs as voltmeters are characterized by high input resistance. High resistance insulation in the test circuits is one of the first requirements of making successful electrometer measurements. Thus, a knowledge of the various types of insulating materials and how to apply them properly is important. To measure voltages from high resistance sources accurately, the insulation leakage resistance of the test fixtures, test leads, and measuring voltmeter must be several orders of magnitude higher than the Thevenin equivalent resistance of the circuit under test, depending on the number of decades of precision, resolution, or accuracy required. If the insulation resistances aren't decades higher, the shunting effects of the insulation will reduce the source voltage being measured, as discussed previously.

Detecting inferior insulation in test setups is difficult because the erroneous reading can appear well-behaved and steady. Therefore, it's prudent to measure the insulation resistance of the test fixtures and cables periodically with an electrometer ohmmeter to ensure their integrity. If deficiencies are discovered, either cleaning or replacement of the defective insulator is in order.

Choosing the Best Insulator

In evaluating an insulating material, consider these material properties:

- **Volume resistivity:** leakage of current directly through the material.
- **Surface resistivity:** leakage across the surface, a function primarily of surface contaminants.
- **Water absorption:** leakage dependent on the amount of water that has been absorbed by the insulator.
- **Piezoelectric or stored charge effects:** the creation of charge unbalances (and thus current flow or voltage shift) due to mechanical stress.
- **Triboelectric effects:** the creation of charge unbalance due to frictional effects when materials rub against each other.
- **Dielectric absorption:** the tendency of an insulator to store/release charge over long periods.

Table 2-2 summarizes important characteristics of insulators, while **Figure 2-10** shows their resistivity ranges. Insulator characteristics are described further in the following paragraphs.

Teflon®

Teflon is the most satisfactory and commonly used insulator for the impedance levels encountered in measurements of currents greater than 10^{-14}A. It has high volume resistivity and water vapor films don't form readily on its surface. Its insulating properties, therefore, aren't severely impaired by humid air. Teflon is chemically inert, is easily machined, and can be readily

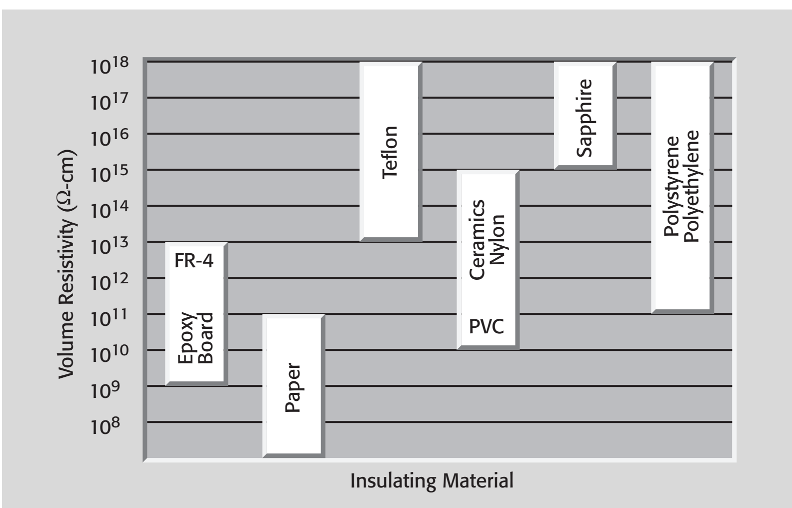
TABLE 2-2: Properties of Various Insulating Materials

Material	Volume Resistivity (Ohm-cm)	Resistance to Water Absorption	Minimal Piezoelectric Effects[1]	Minimal Triboelectric Effects	Minimal Dielectric Absorption
Sapphire	$>10^{18}$	+	+	0	+
Teflon® PTFE	$>10^{18}$	+	–	–	+
Polyethylene	10^{16}	0	+	0	+
Polystyrene	$>10^{16}$	0	0	–	+
Kel-F®	$>10^{18}$	+	0	–	0
Ceramic	10^{14}–10^{15}	–	0	+	+
Nylon	10^{13}–10^{14}	–	0	–	–
Glass Epoxy	10^{13}	–	0	–	–
PVC	5×10^{13}	+	0	0	–

KEY: + Material very
0 Material mo
– Material wea

[1] Stored charge ef

FIGURE 2-10: Approximate Resistivity of Various Insulating Materials



cleaned. Teflon PTFE is the type of Teflon most commonly used in electronics.

Teflon's principal shortcoming is that charges appear internally when it's deformed, causing spurious voltages and currents. With ordinary care, however, these characteristics aren't serious for currents greater than 10^{-13}A.

Polystyrene

Polystyrene is much less expensive than Teflon, and was the general purpose standard before Teflon was available. It machines easily, but internal crazing often develops. This characteristic doesn't impair its insulating properties unless the cracks reach the surface. The volume resistivity of polystyrene is similar to that of Teflon, but water vapor films form on its surface when humidity becomes high, significantly reducing its surface resistance.

Kel-F®

Kel-F has volume and surface characteristics nearly as good as Teflon, it machines easily, and it doesn't craze.

Polyethylene

Polyethylene has excellent volume resistivity and surface characteristics similar to polystyrene. Because it's flexible, it's used extensively for insulating coaxial and triaxial cable. These cables are excellent for general-purpose electrometer work because the surface leakage in this application is relatively unimportant. However, polyethylene melts at a relatively low temperature, so leads into ovens should use Teflon insulation rather than polyethylene.

Glass and Ceramics

Glass and ceramics also have high volume resistivity, but poor surface properties at high humidity and often-poor piezoelectric properties. Glass or ceramic cleaned with methanol and dipped in boiling paraffin has a good, but not durable, insulating surface. Various silicone varnishes can also be baked or air-dried onto glass or ceramic surfaces, but even after this treatment, handling can easily spoil the insulators. Glass and ceramics are difficult to machine, although they can be molded. They are used principally when their mechanical properties are mandatory.

Sapphire

Sapphire is one of the best insulators. Very little charge is generated in it when it's stressed mechanically. It's used most often in measuring currents in the 10^{-18}A to 10^{-15}A range. The use of sapphire is restricted by its cost and because the material is difficult to machine and form.

Quartz

Quartz has properties similar to sapphire, but considerably higher piezoelectric output, so it's rarely used in electrometer circuits.

Other Insulating Materials

Practically all other insulating materials have unacceptably low volume resistivity or unsatisfactory surface characteristics for electrometer use. Vinyl, nylon, and Lucite® are markedly inferior to Teflon, polystyrene, polyethylene, sapphire, or quartz.

Keeping Insulators Clean

As with any high resistance device, mishandling can destroy the integrity of insulators. Oils and salts from the skin can degrade insulator performance, and contaminants in the air can be deposited on the insulator surface, reducing its resistance. Therefore, insulator handling should be minimized; under no circumstances should the insulator be touched with the hand or with any material that might contaminate the surface.

If the insulator becomes contaminated, either through careless handling or from deposits, it can be cleaned with a foam tipped swab dipped in methanol. After cleaning, the insulator should be allowed to dry for several hours at low humidity before use or be dried using dry nitrogen.

2.3 Low Current Measurements

A number of error sources can have serious impacts on low current measurement accuracy. For example, the ammeter may cause measurement errors if not connected properly. (Refer to Sections 2.6.1 and 2.6.2 for more information on how to make properly shielded connections.) The ammeter's voltage burden and input offset current may also affect measurement accuracy. The source resistance of the device under test will affect the noise performance of a feedback ammeter. External sources of error can include leakage current from cables and fixtures, as well as currents generated by triboelectric or piezoelectric effects. Section 2.3 addresses low current measurement considerations in detail and outlines methods for minimizing the effects of error sources. It also includes information on using the electrometer's coulomb function to make very low current measurements.

2.3.1 Leakage Currents and Guarding

Leakage currents are generated by stray resistance paths between the measurement circuit and nearby voltage sources. These currents can degrade the accuracy of low current measurements considerably. To reduce leakage currents, use good quality insulators, reduce the level of humidity in the test environment, and use guarding. Guarding will also reduce the effect of shunt capacitance in the measurement circuit.

Using good quality insulators when building the test circuit is one way to reduce leakage currents. Teflon, polyethylene, and sapphire are examples of good quality insulators, but avoid materials like phenolics and nylon. Refer to Section 2.2.2 for further discussion on choosing the best insulating materials.

Humidity may also degrade low current measurements. Different types of insulators will absorb varying amounts of water from the air, so it's best to choose an insulator on which water vapor doesn't readily form a continuous film. Sometimes, this is unavoidable if the material being measured absorbs water easily, so it's best to make the measurements in an environmentally controlled room. In some cases, an insulator may have ionic contaminants, which can generate a spurious current, especially in high humidity.

Guarding is a very effective way to reduce leakage currents. A guard is a low impedance point in the circuit that's at nearly the same potential as the high impedance lead being guarded. The guard on the electrometer ammeter and picoammeter differs from the guard on the SMU ammeter. The use of guarding can best be explained through examples.

The Use of Guarding Using an Electrometer Ammeter or Picoammeter

The guard terminal of the electrometer ammeter or picoammeter is the LO input terminal. The guard can be used to isolate the high impedance input lead of the ammeter from leakage current due to voltage sources. **Figures 2-11** and **2-12** illustrate examples of guarding.

Figure 2-11 illustrates guarding as applied to measuring the ion current (I_C) from an ionization chamber. An unguarded ionization chamber and the corresponding equivalent circuit are shown in **Figure 2-11a**. The equivalent circuit shows that the full bias voltage appears across the insulator leakage resistance (R_L), therefore, a leakage current (I_L) will be added to the measured ion current ($I_M = I_C + I_L$). The leakage resistance is due to the insulator of the ionization chamber and the coax cable.

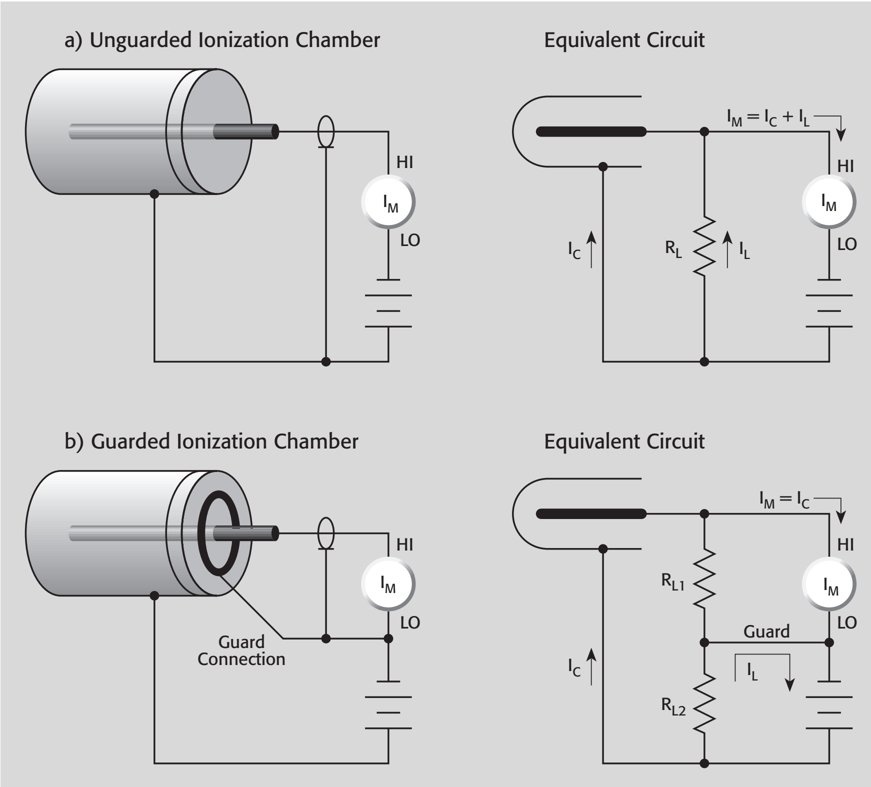
In **Figure 2-11b**, a metal guard ring is added to the ionization chamber. This guard circuit splits the leakage resistance into two parts. The voltage across R_{L1} is the picoammeter voltage burden, normally less than one millivolt, so the resulting current will be quite small. The full bias voltage appears across R_{L2}. A leakage current will flow around this loop, but won't affect the measurement.

Guarding may also be necessary to prevent leakage current due to test fixturing. **Figure 2-12** shows a high mega-ohm resistor (R_{DUT}) supported on two insulators mounted in a metal test fixture.

Figure 2-12a is the unguarded circuit. The leakage current (I_L) through the stand-off insulators will be added to the measured current (I_M).

As illustrated in **Figure 2-12b**, this circuit is guarded by connecting the LO of the picoammeter (I_M) to the metal mounting plate. This will put the bottom of the right insulator at almost the same potential as the top. The

FIGURE 2-11: Guarding as Applied to an Ionization Chamber



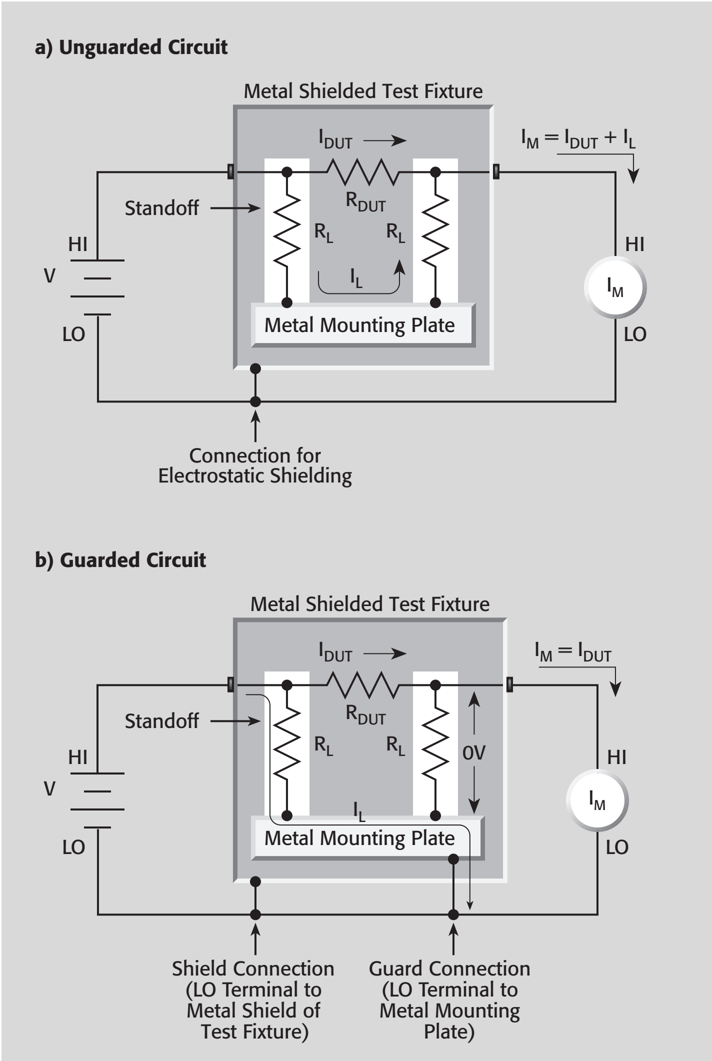
voltage difference is equal to the voltage burden of the picoammeter. The voltage burden is small, less than 200µV. The top and bottom of the insulator are at nearly the same potential, so no significant current will flow through it, and nearly all the current from the device under test will flow through the ammeter as desired.

The Use of Guarding with an SMU Ammeter

The guard terminal of an SMU is usually the inside shield of the triax connector. This guard is driven by a unity-gain, low impedance amplifier. By definition, the guard terminal is nearly at the same potential as the high impedance terminal, so the guard terminal will be at the same potential as the magnitude of the voltage source.

Figure 2-13 illustrates how a driven guard prevents the leakage resistance of a cable from degrading the low current measurements. In the unguarded circuit of **Figure 2-13a**, the leakage resistance of the coax cable

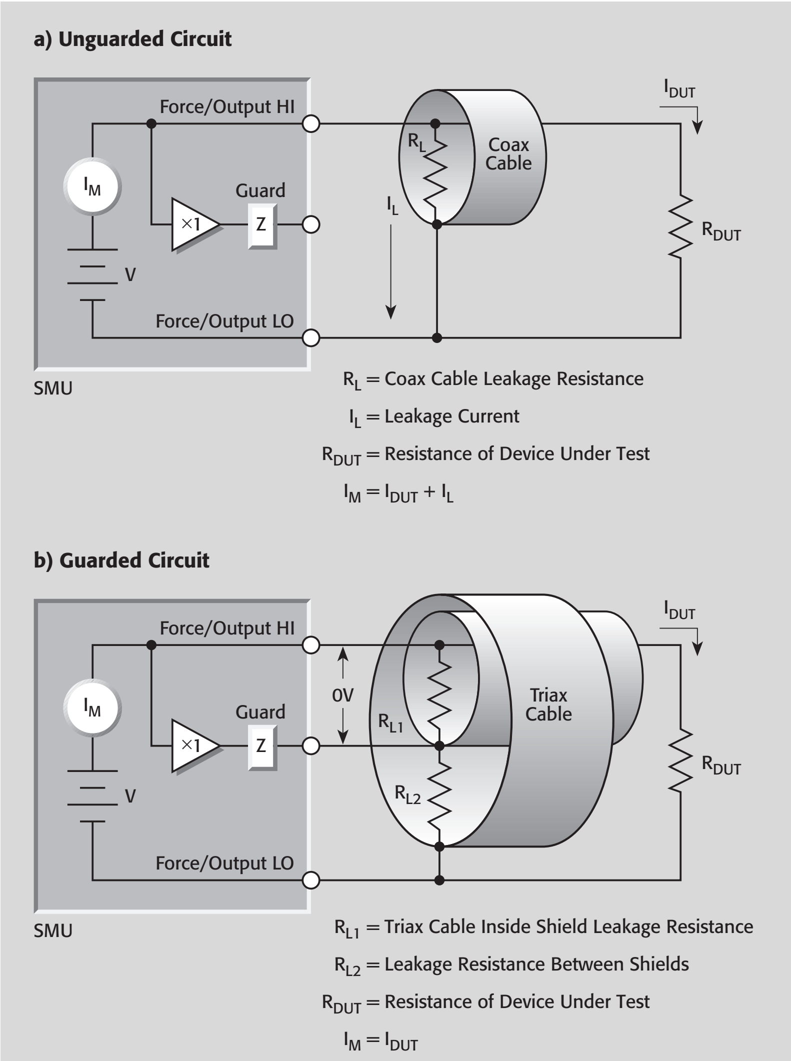
FIGURE 2-12: Guarding to Reduce Leakage Currents



is in parallel with the DUT (R_{DUT}), creating an unwanted leakage current (I_L). This leakage current will degrade very low current measurements.

In the guarded circuit shown in **Figure 2-13b**, the inside shield of the triax cable is connected to the guard terminal of the SMU. Now this shield is driven by a unity-gain, low impedance amplifier (Guard). The difference

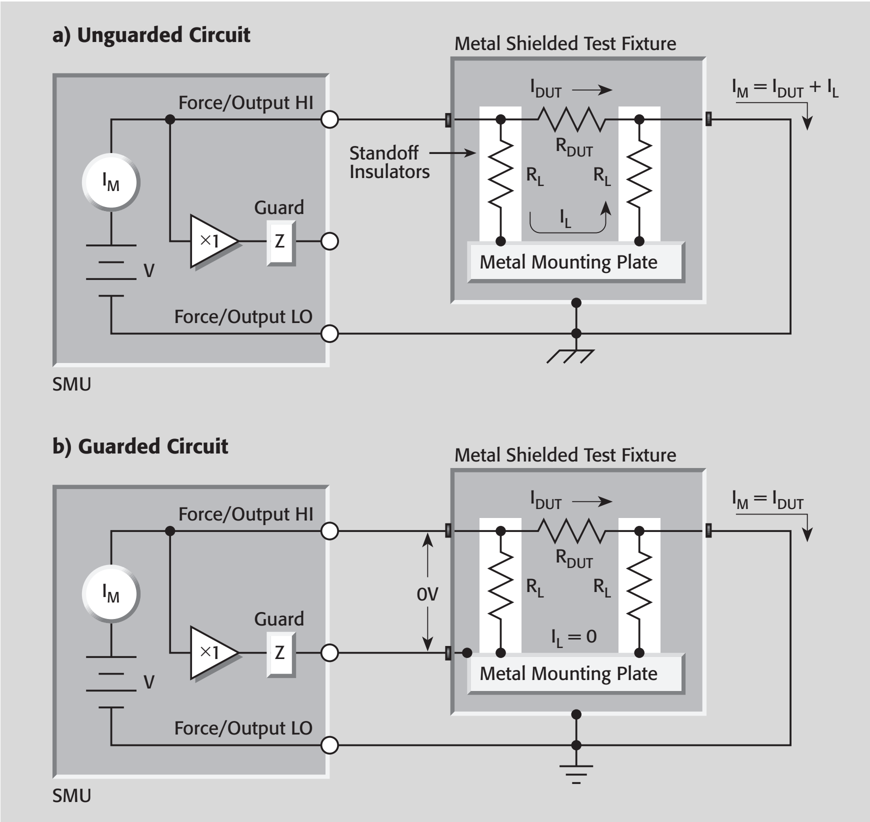
FIGURE 2-13: Guarding the Leakage Resistance of a Cable with an SMU



in potential between the Force/Output HI terminal and the Guard terminal is nearly 0V, so the leakage current (I_L) is eliminated.

Figure 2-14 shows how the guard can eliminate the leakage current that may flow through the stand-off insulators in a test fixture. In **Figure 2-14a**, leakage current (I_L) flows through the stand-off insulators (R_L). This

FIGURE 2-14: Test Fixture Guarding with an SMU



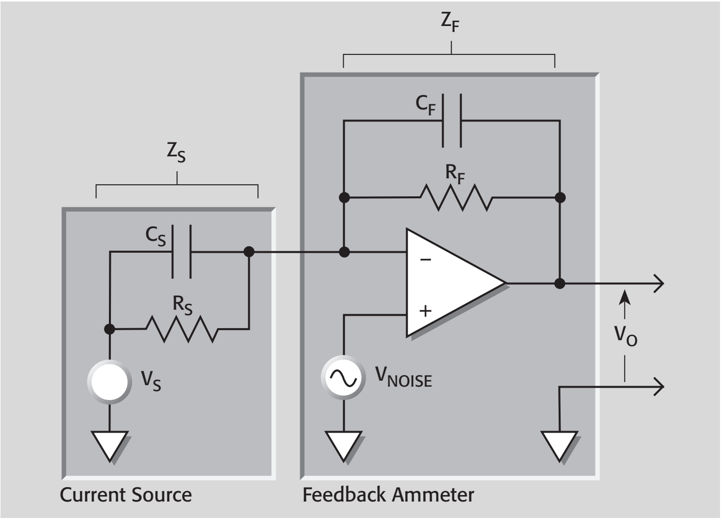
leakage current is added to the current from the DUT (I_{DUT}) and is measured by the SMU ammeter (I_M), adversely affecting the accuracy of the low current measurement.

In **Figure 2-14b**, the metal mounting plate is connected to the guard terminal of the SMU. The voltages at the top and the bottom of the standoff insulator are nearly at the same potential (0V drop), so no leakage current will flow through the standoffs and affect the measurement accuracy. For safety purposes, the metal shield must be connected to earth ground because the metal mounting plate will be at the guard potential.

2.3.2 Noise and Source Impedance

Noise can seriously affect sensitive current measurements. This section discusses how source resistance and source capacitance affect noise performance.

FIGURE 2-15: Simplified Model of a Feedback Ammeter



Source Resistance

The source resistance of the DUT will affect the noise performance of a feedback ammeter. As the source resistance is reduced, the noise gain of the ammeter will increase.

Figure 2-15 shows a simplified model of a feedback ammeter. R_S and C_S represent the source resistance and source capacitance, V_S is the source voltage, and V_{NOISE} is the noise voltage of the ammeter. Finally, R_F and C_F are the feedback resistance and capacitance respectively.

The noise gain of the circuit can be given by the following equation:

$$\text{Output } V_{NOISE} = \text{Input } V_{NOISE} \ (1 + R_F/R_S)$$

Note that as R_S decreases in value, the output noise increases. For example, when $R_F = R_S$, the input noise is multiplied by a factor of two. Too low a source resistance can have a detrimental effect on noise performance, so there are usually minimum recommended source resistance values based on the measurement range. **Table 2-3** summarizes minimum recommended source resistance values for various measurement ranges for a typical feedback ammeter. Note that the recommended source resistance varies by measurement range because the R_F value also depends on the measurement range. Refer to the instruction manual for the instrument to be used for the appropriate minimum recommended source resistances.

TABLE 2-3: Minimum Recommended Source Resistance Values for a Typical Feedback Ammeter

Range	Minimum Recommended Source Resistance
pA	1 GΩ
nA	1 MΩ
μA	1 kΩ
mA	1 Ω

Source Capacitance

DUT source capacitance will also affect the noise performance of a feedback type ammeter. In general, as source capacitance increases, so does the noise gain.

To see how changes in source capacitance can affect noise gain, let's again refer to the simplified ammeter model in **Figure 2-15**. The elements of interest for this discussion are the source capacitance (C_S) and the feedback capacitance (C_F). Taking into account the capacitive reactance of these two elements, our previous noise gain formula must be modified as follows:

$$\text{Output } V_{NOISE} = \text{Input } V_{NOISE} \, (Z_F/Z_S)$$

Here, Z_F represents the feedback impedance made up of C_F and R_F, while Z_S is the source impedance formed by R_S and C_S. Furthermore,

$$Z_F = \frac{R_F}{\sqrt{(2\pi f \, R_F C_F)^2 + 1}}$$

and

$$Z_S = \frac{R_S}{\sqrt{(2\pi f \, R_S C_S)^2 + 1}}$$

Note that as C_S increases in value, Z_S *decreases* in value, thereby increasing the noise gain. Again, at the point where $Z_S = Z_F$, the input noise is amplified by a factor of two.

Most picoammeters will have a maximum recommended value for C_S. Although it is usually possible to measure at higher source capacitance values by inserting a resistor in series with the ammeter input, remember that any series resistance will increase the voltage burden by a factor of $I_{IN} \cdot R_{SERIES}$. Any series resistance will also increase the RC time constant of the measurement. A series diode, or two diodes in parallel back-to-back, can serve as a useful alternative to a series resistor for this purpose. The diodes can be small-signal types and should be in a light-tight enclosure. See Section 4.3.1 for a further discussion of the use of a series diode.

2.3.3 Zero Drift

Zero drift is a gradual change of the indicated zero offset with no input signal. Unless it's corrected by "zeroing," the resulting offset produces an error by adding to the input signal. Drift is normally specified as a function of time and/or temperature. Zero offset over a time period and temperature range will stay within the specified limits. Offset due to step changes in temperatures may exceed the specification before settling. Typical room temperature rates of change (1°C/15 minutes) won't usually cause overshoot.

Most electrometers include a means to correct for zero drift. A ZERO CHECK switch is used to configure most electrometers and picoammeters to display any internal voltage offsets. This feature allows fast checking and adjustment of the amplifier zero. Typically, the instrument is zero corrected while zero check is enabled. This procedure may need to be performed periodically, depending on ambient conditions. Electrometers perform this function with the touch of a button or upon command from the computer.

In a picoammeter or electrometer ammeter, note that ZERO CHECK and ZERO CORRECT functions are used to correct for internal voltage offsets. SUPPRESS or REL controls are used to correct for external current offsets. For optimum accuracy, zero the instrument on the range to be used for measurement. Refer to Section 2.3.4 for a discussion of correcting for internal offset current.

2.3.4 Generated Currents

Any extraneous generated currents in the test system will add to the desired current, causing errors. Currents can be internally generated, as in the case of instrument input offset current, or they can come from external sources such as insulators and cables. The following paragraphs discuss the various types of generated currents.

Figure 2-16 summarizes the magnitudes of a number of generated currents discussed in this section.

Offset Currents

Offset currents can be generated within an instrument (input offset current) or can be generated from external circuitry (external offset current).

Input Offset Current

The ideal ammeter should read zero when its input terminals are left open. Practical ammeters, however, do have some small current that flows when the input is open. This current is known as the input offset current, and it's caused by bias currents of active devices as well as by leakage currents through insulators within the instrument. Offset currents generated within picoammeters, electrometers, and SMUs are included in the instrument's specifications. As shown in **Figure 2-17**, the input offset current adds to the measured current so the meter measures the sum of the two currents:

$$I_M = I_S + I_{OFFSET}$$

Input offset current can be determined by capping the input connector and selecting the lowest current range. Allow about five minutes for the instrument to settle, then take a reading. This value should be within the instrument's specification.

FIGURE 2-16: Typical Magnitudes of Generated Currents

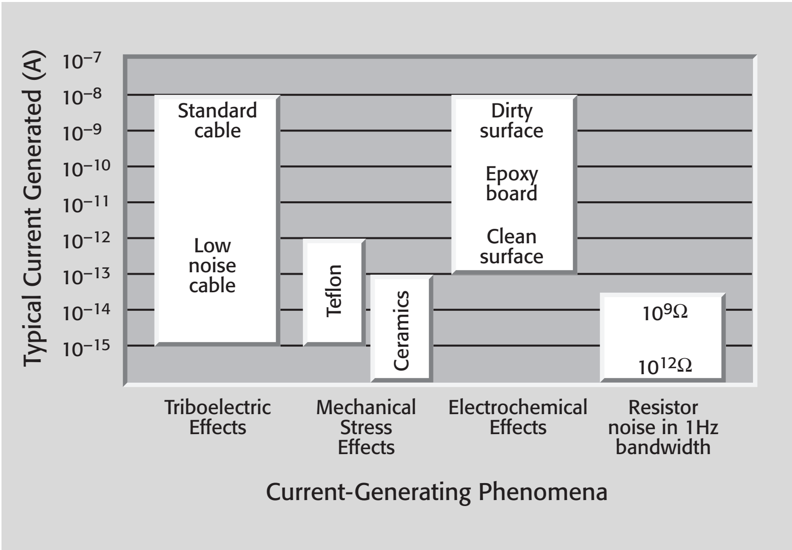
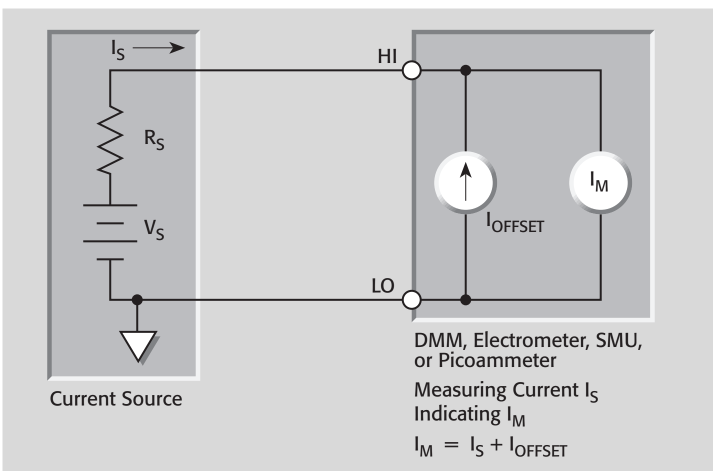


FIGURE 2-17: Effects of Input Offset Current on Current Measurement Accuracy



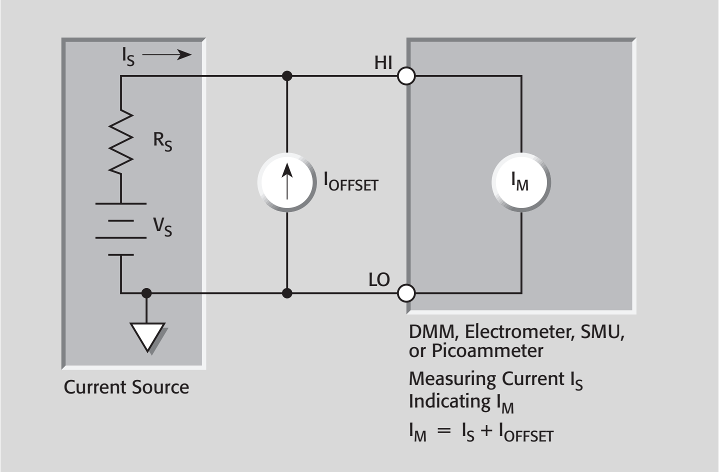
If an instrument has current suppression, the input offset current can be partially nulled by enabling the current suppress function with the input terminals disconnected and ZERO CHECK open.

Another way to subtract the input offset current from measurements is to use the relative (REL or zero) function of the ammeter. With the input open-circuited, allow the reading to settle and then enable thr REL function. Once the REL value is established, subsequent readings will be the difference between the actual input value and the REL value.

External Offset Current

External offset currents can be generated by ionic contamination in the insulators connected to the ammeter. Offset currents can also be generated externally from such sources as triboelectric and piezoelectric effects. As shown in **Figure 2-18**, the external offset current also adds to the source current, and the meter again measures the sum of the two.

FIGURE 2-18: Effects of External Offset Current on Current Measurement Accuracy



External offset currents can be suppressed with the current suppression feature (if available) of the instrument or they can be nulled by using a suitably stable and quiet external current source, as shown in **Figure 2-19**. With this arrangement, the current measured by the meter is:

$$I_M = I_S + I_{OFFSET} - I_{SUPPRESS}$$

Assuming I_{OFFSET} and $I_{SUPPRESS}$ are equal in magnitude but opposite in polarity,

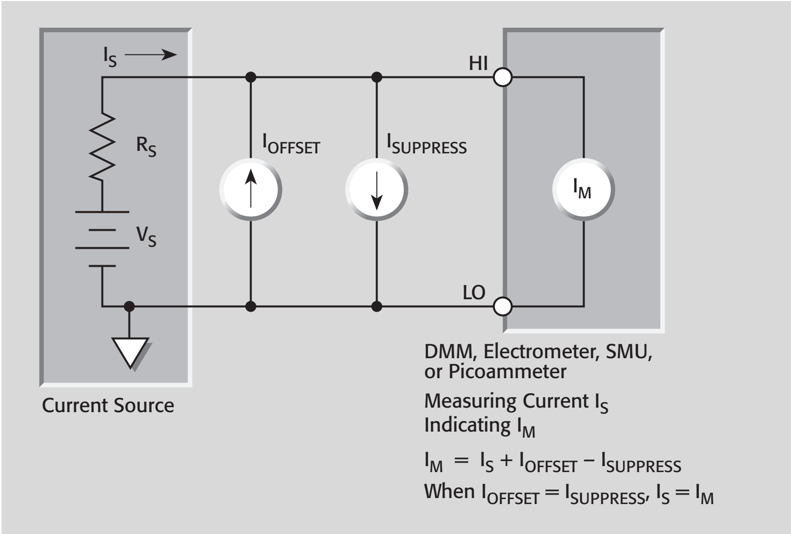
$$I_M = I_S$$

The advantage of using an external current source is that I_{OFFSET} can be as large or larger than the full-range value, and only $I_{OFFSET} - I_{SUPPRESS}$ need be small.

Triboelectric Effects

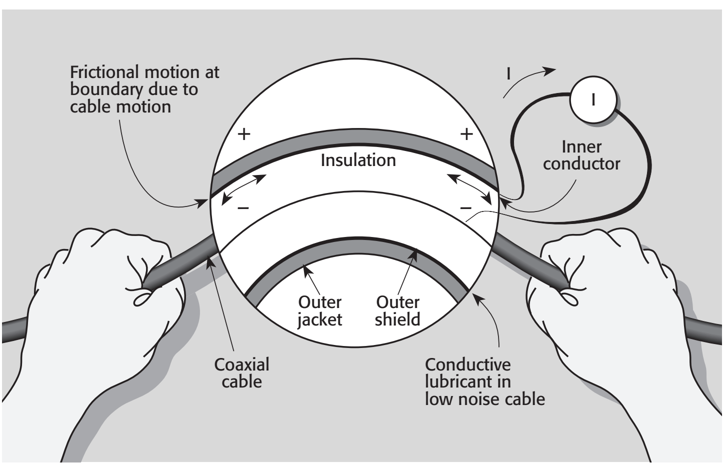
Triboelectric currents are generated by charges created between a conductor and an insulator due to friction. Here, free electrons rub off the con-

FIGURE 2-19: Using External Current Source to Suppress Offset Current



ductor and create a charge imbalance that causes the current flow. A typical example would be electrical currents generated by insulators and conductors rubbing together in a coaxial cable, as shown in **Figure 2-20**.

FIGURE 2-20: Triboelectric Effect



"Low noise" cable greatly reduces this effect. It typically uses an inner insulator of polyethylene coated with graphite underneath the outer shield. The graphite provides lubrication and a conducting equipotential cylinder to equalize charges and minimize charge generated by frictional effects of cable movement. However, even low noise cable creates some noise when subjected to vibration and expansion or contraction, so all connections should be kept short, away from temperature changes (which would create thermal expansion forces), and preferably supported by taping or tying the cable to a non-vibrating surface such as a wall, bench, or other rigid structure.

There are a variety of other solutions to movement and vibration problems:

- Removal or mechanical decoupling of the source of vibration. Motors, pumps, and other electromechanical devices are the usual sources.
- Stabilization of the test hookup. Securely mount or tie down electronic components, wires, and cables. Shielding should be sturdy.

Triboelectric effects can also occur in other insulators and conductors that touch each other. Therefore, it's important to minimize contact between insulators as well as conductors in constructing test fixtures and connections for low current and high impedance.

Table 2-2 in Section 2.2.2 summarizes the triboelectric effects of various insulating materials.

Piezoelectric and Stored Charge Effects

Piezoelectric currents are generated when mechanical stress is applied to certain crystalline materials when used for insulated terminals and interconnecting hardware. In some plastics, pockets of stored charge cause the material to behave in a manner similar to piezoelectric materials. An example of a terminal with a piezoelectric insulator is shown in **Figure 2-21**.

To minimize the current due to this effect, it's important to remove mechanical stresses from the insulator and use insulating materials with minimal piezoelectric and stored charge effects. Section 2.2.2 and **Table 2-2** summarize the piezoelectric properties of various insulating materials.

This effect is independent of the capacitance change between the plate and terminals. Charges are moved around, resulting in current flow.

In practice, it may be quite difficult to distinguish stored charge effects (in insulators) from piezoelectric effects. Regardless of the phenomenon involved, it's important to choose good insulating materials and make connecting structures as rigid as possible.

Contamination and Humidity

Error currents also arise from electrochemical effects when ionic chemicals create weak batteries between two conductors on a circuit board. For example, commonly used epoxy printed circuit boards, when not thoroughly cleaned of etching solution, flux or other contamination, can generate currents of a few nanoamps between conductors (see **Figure 2-22**).

FIGURE 2-21: Piezoelectric Effect

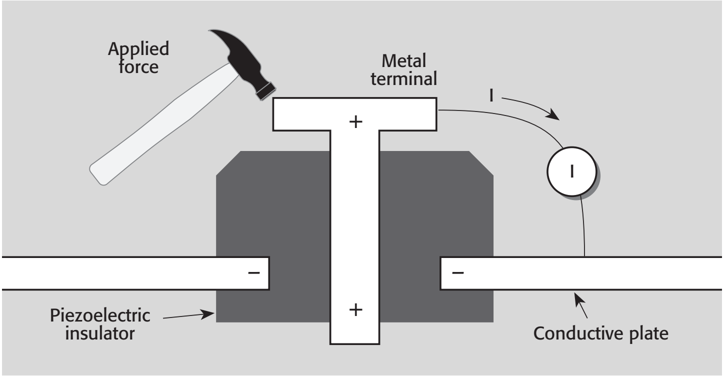
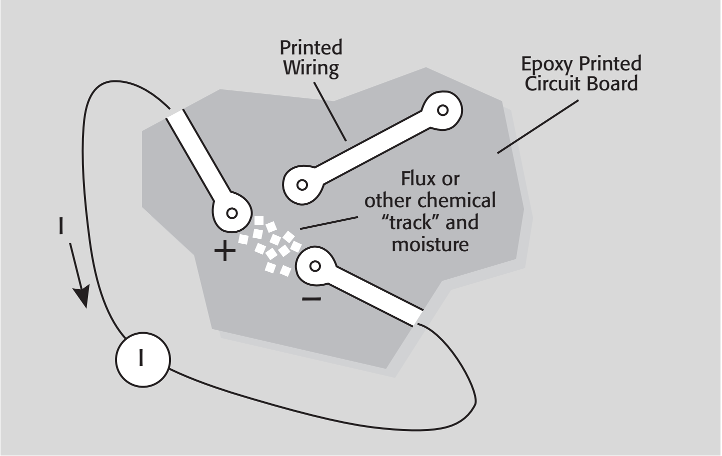


FIGURE 2-22: Electrochemical Effects



Insulation resistance can be dramatically reduced by high humidity or ionic contamination. High humidity conditions occur with condensation or water absorption, while ionic contamination may be the result of body oils, salts, or solder flux.

While the primary result of these contaminants is the reduction of insulation resistance, the combination of both high humidity and ionic contamination can form a conductive path, or they may even act as an electrochemical cell with high series resistance. A cell formed in this manner can source picoamps or nanoamps of current for long periods of time.

To avoid the effects of contamination and humidity, select insulators that resist water absorption, and keep humidity to moderate levels. Also, be sure all insulators are kept clean and free of contamination.

If insulators become contaminated, apply a cleaning agent such as methanol to all interconnecting circuitry. It's important to flush away all contaminants once they're dissolved in the solvent, so they won't be redeposited. Use only very pure solvents for cleaning; lower grades may contain contaminants that leave an electrochemical film.

Dielectric Absorption

Dielectric absorption in an insulator can occur when a voltage across that insulator causes positive and negative charges within the insulator to polarize because various polar molecules relax at different rates. When the voltage is removed, the separated charges generate a decaying current through circuits connected to the insulator as they recombine.

To minimize the effects of dielectric absorption on current measurements, avoid applying voltages greater than a few volts to insulators being used for sensitive current measurements. In cases where this practice is unavoidable, it may take minutes or even hours in some cases for the current caused by dielectric absorption to dissipate.

Table 2-2 in Section 2.2.2 summarizes the relative dielectric absorption of various insulating materials.

2.3.5 Voltage Burden

An ammeter may be represented by an ideal ammeter (I_M) with zero internal resistance, in series with a resistance (R_M), as shown in **Figure 2-23**. When a current source whose Thevenin equivalent circuit is a voltage (V_S) in series with a source resistance (R_S) is connected to the input of the ammeter, the current is reduced from what it would be with the ideal ammeter ($R_M = 0\Omega$). This reduction is caused by the internal resistance (R_M), which creates an additional voltage drop called the voltage burden (V_B).

The voltage burden is specified for a full-scale input. Therefore, the voltage burden at a given current can be calculated by:

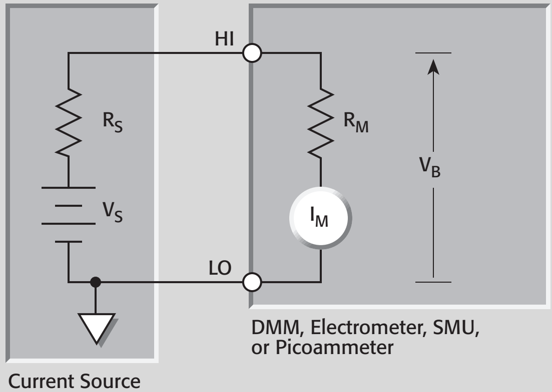
$$V_{B(I)} = V_B\left(\frac{I_S}{I_{FS}}\right)$$

where I_{FS} is full scale current and I_S is the magnitude of the current source.

Taking into account the voltage burden, the measurement error can be calculated as follows:

$$I_M = \frac{V_S - V_B\left(\frac{I_S}{I_{FS}}\right)}{R_S}$$

FIGURE 2-23: Effects of Voltage Burden on Current Measurement Accuracy



$$I_M = \frac{V_S - V_B}{R_S} \quad \text{or} \quad I_M = \frac{V_S}{R_S}\left(1 - \frac{V_B}{V_S}\right)$$

The percent error in the measured reading due to voltage burden is:

$$\%\ \text{error} = \frac{V_B\left(\frac{I_S}{I_{FS}}\right)}{V_S} \times 100\%$$

Example: In this circuit, $V_S = 0.7V$, $I_S = 100\mu A$, and $I_{FS} = 200\mu A$. Assuming $R_S = 10k\Omega$ and the voltage burden at full scale is 200mV:

$$I_M = \frac{0.7V - 0.2V\left(\frac{100\mu A}{200\mu A}\right)}{10k\Omega} = 60\mu A$$

compared to the ideal case,

$$I_M = \frac{0.7V}{10k\Omega} = 70\mu A$$

Thus, the ammeter reading is 60μA vs. the ideal case of 70μA—an error of 14%.

In comparison, if a picoammeter is used and the voltage burden is 200μV:

$$I_M = \frac{0.7V - 0.0002V\left(\frac{100\mu A}{200\mu A}\right)}{10k\Omega} = 69.99\mu A$$

Thus, the picoammeter reading is 69.99μA vs. the ideal measurement of 70μA—an error of only 0.01%.

The input resistance of a feedback picoammeter or electrometer ammeter is less than the ratio of the specified voltage burden to the full-scale current:

$$\text{Input Resistance} < \frac{\text{Voltage Burden}}{\text{Full Scale Current}}$$

When determining the voltage burden of an SMU, the offset voltage on the voltage source range being used must be included. Therefore, it's best to use the lowest possible voltage source range in order to minimize error.

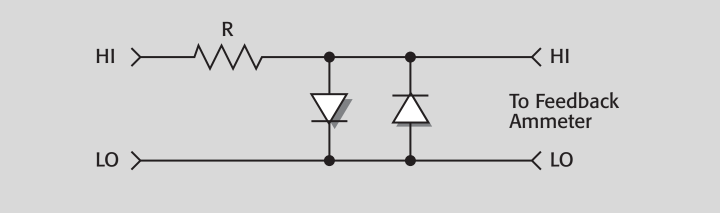
2.3.6 Overload Protection

Electrometers, picoammeters, and SMUs may be damaged if excessive voltage is applied to the input. Most instruments have a specification for the maximum allowable voltage input. In some applications, this maximum voltage may be unavoidably exceeded. Some of these applications may include leakage current of capacitors, reverse diode leakage, or insulation resistance of cables or films. If the component or material breaks down, all the voltage would be applied to the ammeter's input, possibly destroying it. In these cases, additional overload protection is required to avoid damaging the input circuitry of the instrument.

Electrometer or Picoammeter Overload Protection

Figure 2-24 shows a protection circuit for an electrometer ammeter or picoammeter, consisting of a resistor and two diodes (1N3595). The leakage of the 1N3595 diode is generally less than one picoampere even with 1mV of forward bias, so the circuit won't interfere with measurements of 10pA or more. This diode is rated to carry 225mA (450mA repeated surge). Since the voltage burden of the electrometer ammeter or picoammeter is less than 1mV, the diodes won't conduct. With two diodes in parallel back to back, the circuit will provide protection regardless of the signal polarity.

FIGURE 2-24: Overload Protection Circuit for Electrometers and Picoammeters



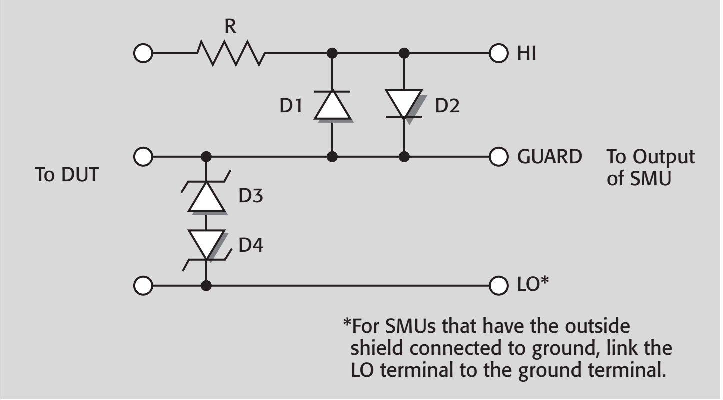
The resistor (R) must be large enough to limit the current through the diodes to prevent damage to the diodes. It also must be large enough to withstand the supply voltage. A good rule of thumb is to use a large enough resistor to cause a 1V drop at the maximum current to be measured.

The protection circuit should be enclosed in a light-tight shield because the diodes are photosensitive. The shield should be connected to the low of the ammeter.

SMU Overload Protection (in Force Voltage, Measure Current Mode)

Figure 2-25 illustrates an overload protection circuit for an SMU in the ammeter mode. This circuit consists of two zener diodes (D3 and D4) connected between the Guard and LO (or Common) terminals, a current limiting resistor (R) in series with the HI terminal, and two low leakage diodes (D1 and D2) between the HI and Guard terminals.

FIGURE 2-25: Overload Protection Circuit for the SMU in Force Voltage, Measure Current Mode



The two zener diodes are used to clamp the guard to LO (or the Common terminal). These should be rated slightly higher than the SMU's maximum measurable voltage. Since the leakage current through the zener diodes results in a voltage drop across the resistor, low leakage zener devices are desirable.

The resistor (R) is used to limit the current through the diodes (D1 and D2). The resistance value should be large enough to limit the current flowing through the diodes to one-tenth of their forward current rating, thereby preventing diode damage. The resistor must also be rated high enough to meet the power dissipation requirements while the zeners are conducting.

If an overload occurs, one of the diodes (D1 or D2) will conduct and prevent the input from being damaged. The 1N3595 diode is a good choice for this function because it has low leakage current, typically less than 1pA, even with a forward bias of 1mV.

High impedance circuit construction, such as Teflon standoffs, must be used. The protection circuit should be built into a light-tight, metal-shielded enclosure with the shield connected to the LO terminal of the SMU.

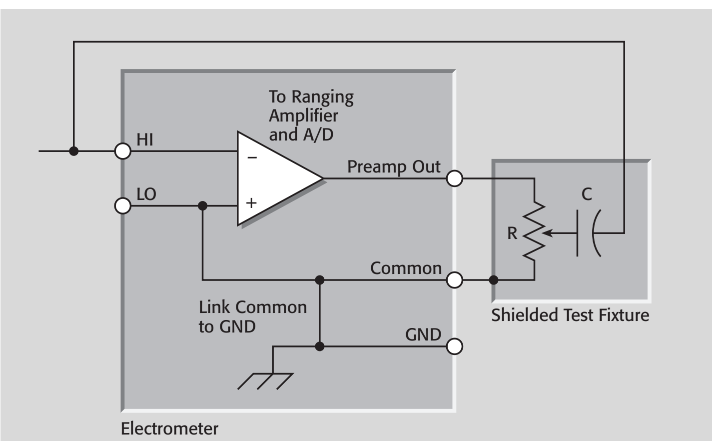
2.3.7 AC Interference and Damping

When measuring low current, electrostatic shielding (as discussed in Section 2.6.2) is the most common way to reduce noise due to AC interference. However, in some cases, shielding the device under test or the connecting cabling isn't practical. For these applications, a variable damping control may reduce the AC pickup enough to make meaningful measurements.

A damping circuit is a type of low pass filter that reduces the electrometer's AC response so the low DC current can be measured accurately. The damping circuit may already be built into the electrometer or may be an external circuit. Refer to the instrument's instruction manual for information on a particular electrometer's internal damping feature. However, it may be necessary to increase the damping with an external circuit.

Figure 2-26 illustrates an example of an external damping circuit. This circuit consists of a low leakage polystyrene or polyester capacitor (C) and a potentiometer (R). The potentiometer is connected between the preamp output and the common (or LO) terminal of the ammeter. The capacitor is connected between the HI input terminal of the ammeter and the moving arm of the potentiometer. The value of the capacitor depends on the current range of the ammeter. Higher ranges require the use of higher magnitude capacitors. However, typical values of the capacitor are in the range of hundreds of picofarads. The value of the potentiometer should be chosen to be high enough (>50kΩ) to avoid loading the preamp output, but still reduce noise effectively.

FIGURE 2-26: External Damping Circuit



Some experimentation will be needed to choose the best values for the capacitor and the resistance. Connect an oscilloscope to the analog output and observe the AC waveform on the scope. Adjust the potentiometer to make the AC signal as small as possible. If the noise can't be suppressed enough with the potentiometer, use a bigger capacitor.

The damping circuit should be built into a shielded enclosure.

2.3.8 Using a Coulombmeter to Measure Low Current

In most cases, an ammeter or picoammeter is used to measure current. However, for femtoamp-level currents, it may be better to use the coulombs function of an electrometer to measure the change in charge over time, then use those charge measurements to determine the current. A further discussion of charge measurements can be found in Section 2.5.

Basic Charge Measurement Methods

Charge is difficult to measure directly; it must be related to an easily measured quantity. One commonly used method of making this type of measurement is to measure the voltage across a capacitor of known value. The charge is related to capacitor voltage as follows:

$$Q = CV$$

where: Q = capacitor charge (coulombs)
C = capacitor value (farads)
V = voltage across capacitor (volts)

Once the rate of change in charge is known, the current can easily be determined from the charge measurement. The instantaneous current (i) is simply:

$$i = \frac{dQ}{dt}$$

while the long-term average current is defined as:

$$I_{AVG} = \frac{\Delta Q}{\Delta t}$$

Thus, we see that charge can be measured and current can be determined simply by making a series of voltage measurements.

Using a Feedback Coulombmeter to Measure Current

Charge can be measured directly with a feedback coulombmeter. **Figure 2-27** shows a simplified model of a feedback type coulombmeter. The input current to the circuit is I_S, the output voltage is V_{OUT}, and the feedback capacitor is C_F.

The current (I_S) is applied to the input of the feedback coulombmeter. The circuit is an integrator, so the charge is determined by integrating the current:

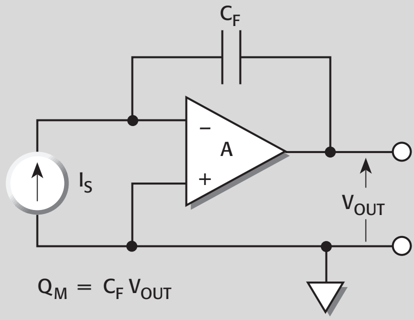
$$Q_M = \int i \, dt$$

The coulombmeter determines charge from the output voltage and the value of the feedback capacitor:

$$Q_M = C_F V_{OUT}$$

From the measured charge (Q_M), the user can calculate current:

FIGURE 2-27: Feedback Coulombmeter Equivalent Circuit



$$Q_M = C_F V_{OUT}$$

$$i_M = C_F (dV_{OUT}/dt) = dQ_M/dt$$

$$I_{AVG} = \frac{\Delta V_{OUT} C_F}{\Delta t} = \frac{\Delta Q_M}{\Delta t}$$

$$i_M = C_F(dV_{OUT}/dt) = dQ_M/dt$$

The long-term average current (I_{AVG}) can be calculated from the change in output voltage over a specific time period:

$$I_{AVG} = \frac{\Delta V_{OUT} C_F}{\Delta t} = \frac{\Delta Q}{\Delta t}$$

To make calculations easier, set a one-second measurement interval time in the one-shot trigger mode. The "REL" or zero function of the electrometer may be used to reset the readings.

Fixed Integration Time Period Method

The fixed integration time method shown in **Figure 2-28** can be used to determine current and is a variation of the feedback coulombmeter technique. In this instance, the increasing charge value is measured at specific time intervals of equal length. The average current (I_{AVG}) during a given period can be determined from the slope of the line and is calculated as follows:

$$I_{AVG} = \frac{\Delta Q}{\Delta t}$$

This method gives the average current during the time interval and produces readings at a steady rate determined by the integration period. This method can be accomplished automatically in software by determining the difference between successive readings.

Fixed Threshold Method

The fixed threshold method, which is shown in **Figure 2-29**, is somewhat similar to the fixed integration time method just described. In this case,

FIGURE 2-28: Fixed Integration Time Method of Determining Current from Charge

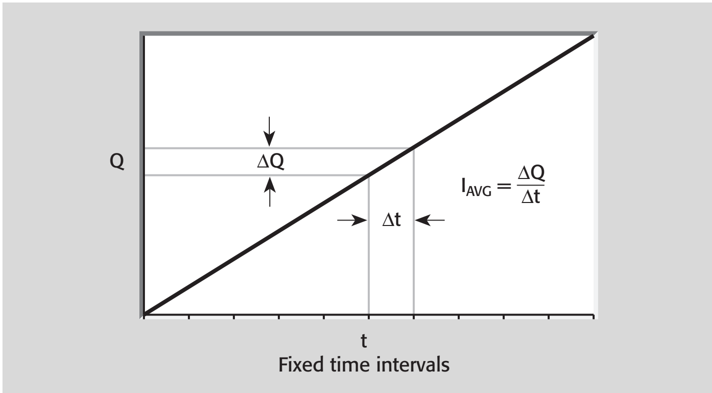
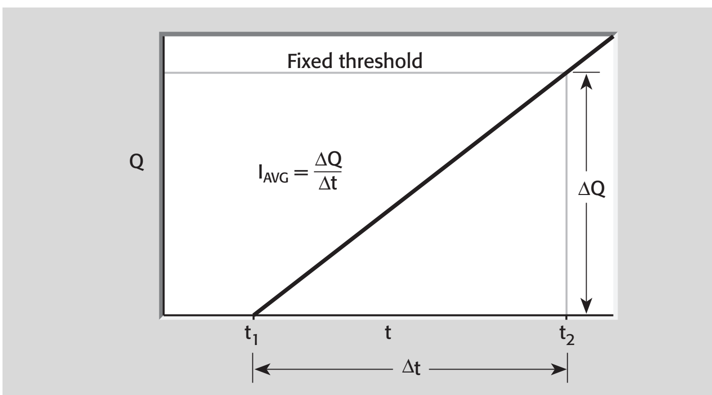


FIGURE 2-29: Fixed Threshold Method of Determining Current from Charge



however, the charge measurement begins at time t_1 and continues until the charge value reaches some predetermined threshold value at time t_2. The current is then calculated as follows:

$$I_{AVG} = \frac{\Delta Q}{\Delta t} \quad \text{where } \Delta t = t_2 - t_1$$

Note that the voltage coefficient of the coulombmeter capacitor has little effect on overall current measurement accuracy. As long as the threshold point and time periods are accurately known, current measurement accuracy will be quite good. However, readings won't be evenly spaced when current levels vary, and the interval between readings can be quite long when the average current for a given time period is small.

Advantages of Using a Coulombmeter to Measure Current

There are several advantages to using a coulombmeter instead of an ammeter for measuring current in certain situations:

- **Lower Current Noise:** The ammeter uses a feedback resistor, which will have significant Johnson noise. For charge measurement, this resistor is replaced by a capacitor, which theoretically has no Johnson noise. Consequently, the charge method of current measurement results in lower noise than measuring currents directly with a feedback ammeter. Thus, the charge method is preferable when current noise performance less than 1fA p-p is required. (Refer to **Figure 2-52** in Section 2.6.5 and note that feedback resistances higher than $10^{12}\Omega$ aren't very practical.)
- **Faster Settling Times:** The speed of a feedback ammeter is limited by the time constant of its feedback circuit ($R_F C_F$). For example, for feedback resistances greater than 10GΩ, stray capacitance limits response times to tens of milliseconds. In contrast, a feedback integrator will respond immediately and is limited only by the speed of the operational amplifier.
- **Random Pulses Can Be Integrated:** The average charge transferred per unit time of random pulse trains can be evaluated by integrating the current pulse train for a given period of time. The average current amplitudes can then be expressed as the total charge divided by the time period involved in the measurement. This technique is especially useful when averaging very small, unsteady currents. If the duty cycle is known, the pulse height can also be determined.
- **The Noise Effects of Input Shunt Capacitance are Minimized:** Noise gain is mainly determined by C_{IN}/C_F, and C_F is much larger in a coulombmeter than in an ammeter, so much larger input capacitance values can be tolerated. This characteristic is beneficial when measuring from high capacitance sources or when long connecting cables are used.

2.4 High Resistance Measurements

When resistances greater than 1GΩ must be measured, an electrometer, SMU, or picoammeter/voltage source are usually required. An electrometer may measure high resistance by either the constant-voltage or the constant-current method. Some electrometers allow the user to choose either method. The constant-voltage method uses an ammeter and a voltage source, while the constant-current method uses an electrometer voltmeter and a current source. A description of these techniques follows.

2.4.1 Constant-Voltage Method

To make high resistance measurements using the constant-voltage method, an instrument that can measure low current and a constant DC voltage source are required. Some electrometers and picoammeters have voltage sources built into the instrument and automatically can calculate the unknown resistance.

The basic configuration of the constant-voltage method using an electrometer or picoammeter is shown in **Figure 2-30a**. As shown in **Figure 2-30b**, an SMU can also be used for making high resistance measurements using the constant voltage method.

In this method, a constant voltage source (V) is placed in series with the unknown resistor (R) and an ammeter (I_M). Since the voltage drop across the ammeter is negligible, essentially all the test voltage appears across R. The resulting current is measured by the ammeter and the resistance is calculated using Ohm's Law (R= V/I).

High resistance is often a function of the applied voltage, which makes the constant-voltage method preferable to the constant-current method. By testing at selected voltages, a resistance vs. voltage curve can be developed and a "voltage coefficient of resistance" can be determined.

Some of the applications that use this method include testing two terminal high resistance devices, measuring insulation resistance, and determining the volume and surface resistivity of insulating materials. See Section 4 for descriptions of these applications.

The constant-voltage method requires measuring low current, so all the techniques and error sources described in Section 2.3 (Low Current Measurements) apply to this method. The two most common error sources when measuring high resistance are electrostatic interference and leakage current. As described in Section 2.6.2, electrostatic interference can be minimized by shielding the high impedance circuitry. Interferences due to leakage current can be controlled by guarding as described in Section 2.3.1.

2.4.2 Constant-Current Method

High resistance measurements using the constant-current method may be made using either an electrometer voltmeter and current source or just an electrometer ohmmeter. An SMU that has a voltmeter with high input impedance and low current source ranges may also be used. Using the electrometer voltmeter with a separate current source or an SMU allows the user to make a four-wire measurement and to control the amount of current through the sample. The electrometer ohmmeter makes a two-wire resistance measurement at a specific test current, depending on the measurement range.

Using The Electrometer Voltmeter and an External Current Source

The basic configuration for the constant-current method is shown in **Figure 2-31**. Current from the source (I) flows through the unknown resistance (R) and the voltage drop is measured by the electrometer voltmeter (V). Using this method, resistances up to about $10^{12}\Omega$ can be measured. Even though the basic procedure seems simple enough, some precautionary measures must be taken. The input impedance of the voltmeter must be high enough

FIGURE 2-30: Constant-Voltage Method for Measuring High Resistance

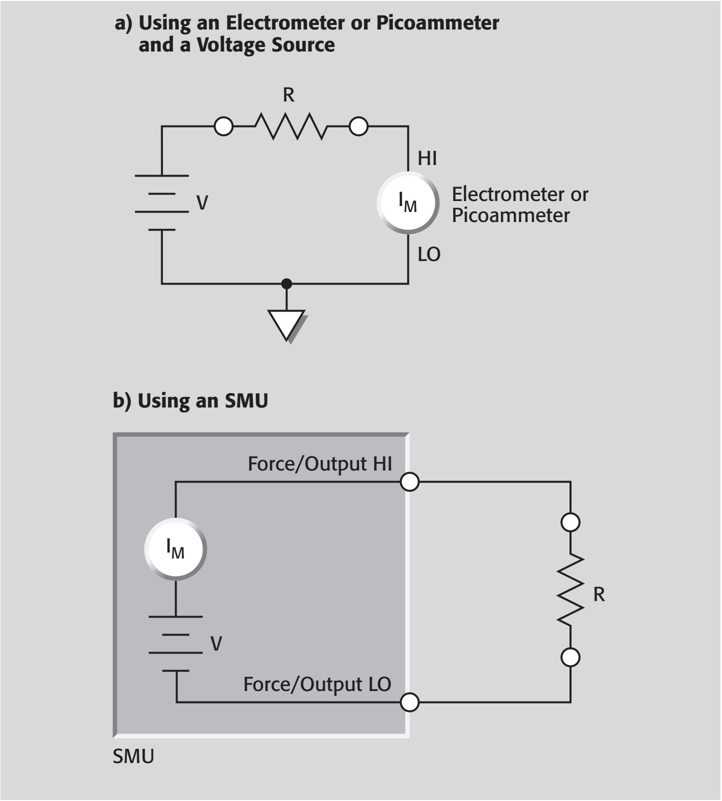
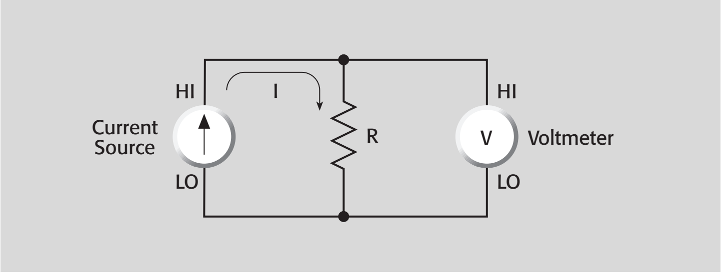


FIGURE 2-31: Constant-Current Method Using a Separate Current Source and Voltmeter

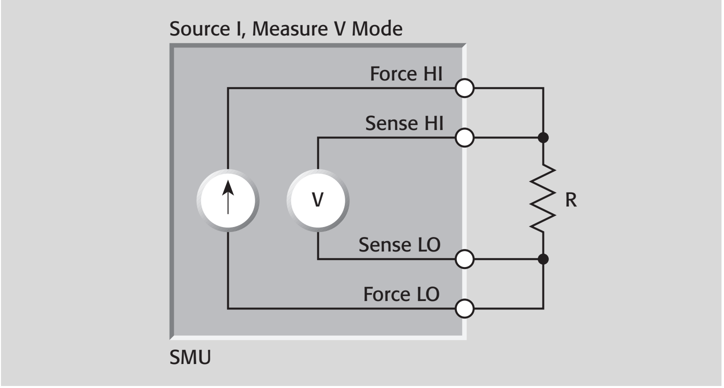


compared with a source resistance to keep the loading error within acceptable limits. Typically, the input impedance of an electrometer voltmeter is about $10^{14}\Omega$. Also, the output resistance of the current source must be much greater than the unknown resistance for the measurement to be linear. The voltage across the sample depends upon the sample resistance, which makes it difficult to account for voltage coefficient when using the constant-current method. If voltage coefficient is a concern, it's best to use the constant-voltage method. When using the electrometer voltmeter to make high resistance measurements, all the techniques and error sources described in Section 2.2 (Voltage Measurements from High Resistance Sources) apply to these measurements. The electrometer voltmeter and a separate current source are used when determining high resistivity of semiconductor materials using the four-point probe or van der Pauw technique. These methods of determining the resistivity of semiconductor materials are described in more detail in Section 4.4.3.

Using an SMU in the Source I, Measure V Mode

An SMU can measure high resistance in the source current/measure voltage mode by using either a two-wire (local sense) or four-wire (remote sense) method. **Figure 2-32** illustrates an SMU in four-wire mode.

FIGURE 2-32: Using the SMU in the Four-Wire Mode to Measure High Resistance



The four-wire method is used to eliminate contact and lead resistance, which is especially important when measuring resistivity of semiconductor materials. These measurements usually involve measuring low voltages. The resistance of the metal probe to semiconductor contact can be quite high.

When using remote sense, the voltage difference between high force and high sense, and between low force and low sense is usually limited to a specified value. Exceeding this voltage difference can result in erratic measurements. Check the instruction manual of the SMU for further information on this limitation.

In addition to the voltage drop limitation, some SMUs have automatic remote sensing resistors located between the HI Force and HI Sense terminals and between the LO Force and LO Sense terminals. This may further limit the use of a single SMU in remote mode for certain applications, such as semiconductor resistivity. If this is the case, use the SMU as a current source in the two-wire mode, and use a separate voltmeter(s) to measure the voltage difference. See Section 4.4.3 for further information.

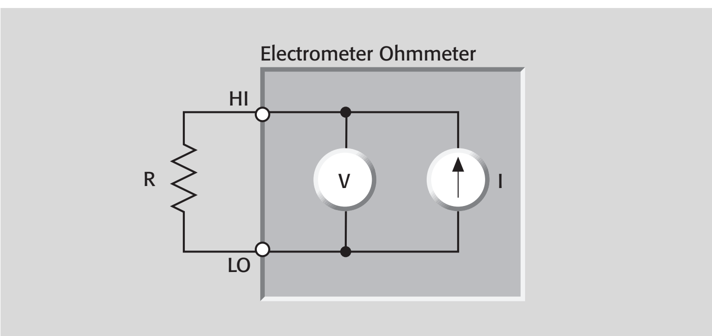
Using the Electrometer Ohmmeter

When using the electrometer ohmmeter, measurement accuracy can be affected by a variety of factors. In the following paragraphs, we will discuss the most important considerations for making accurate high resistance measurements.

Basic Configuration

Figure 2-33 shows the electrometer ohmmeter measuring a resistance (R). The ohmmeter uses an internal current source and electrometer voltmeter to make the measurement. It automatically calculates and displays the measured resistance. Notice that this is a two-wire resistance measurement compared to using the electrometer voltmeter and external current source, which can make a four-wire measurement. This is because the current source is internally connected to the voltmeter and cannot be used separately.

FIGURE 2-33: Electrometer Ohmmeter for Measuring High Resistance



Guarding

As with high impedance voltage measurements and current measurements, guarding high resistance test connections can significantly reduce the effects of leakage resistance and improve measurement accuracy.

Consider the unguarded resistance measurement setup shown in **Figure 2-34a**. Here, an electrometer ohmmeter is forcing a current (I_R) through the unknown resistance (R_S) and then measuring the voltage (V_M)

across the DUT. If we assume that the meter has infinite input resistance, the measured resistance is then computed from Ohm's Law:

$$R_M = \frac{V_M}{I_R}$$

However, since the cable leakage resistance (R_L) is in parallel with R_S, the actual measured resistance (R_M) is reduced, as shown in the parallel equivalent circuit of **Figure 2-34b**. The measured resistance now becomes:

$$R_M = R_S \left(\frac{R_L}{R_S + R_L} \right)$$

The loading effects of cable resistance (and other leakage resistances) can be virtually eliminated by driving the cable shield with a unity-gain amplifier, as shown in **Figure 2-34c**. Since the voltage across R_L is essentially zero, all the test current (I_R) now flows through R_S, and the source resistance value can be accurately determined. The leakage current (I_G) through the cable-to-ground leakage path (R_G) may be considerable, but that current is supplied by the low impedance output of the ×1 amplifier rather than by the current source (I_R).

Settling Time

The settling time of the circuit is particularly important when making high resistance measurements. The settling time of the measurement is affected by the shunt capacitance, which is due to the connecting cable, test fixturing, and the DUT. As shown in **Figure 2-35**, the shunt capacitance (C_{SHUNT}) must be charged to the test voltage by the current (I_S). The time period required for charging the capacitor is determined by the RC time constant (one time constant, $\tau = R_S C_{SHUNT}$), and the familiar exponential curve of **Figure 2-36** results. Thus, it becomes necessary to wait four or five time constants to achieve an accurate reading. When measuring very high resistance values, the settling time can range up to minutes, depending on the amount of shunt capacitance in the test system. For example, if C_{SHUNT} is only 10pF, a test resistance of 1TΩ will result in a time constant of 10 seconds. Thus, a settling time of 50 seconds would be required for the reading to settle to within 1% of final value.

In order to minimize settling times when measuring high resistance values, keep shunt capacitance in the system to an absolute minimum by keeping connecting cables as short as possible. Also, guarding may be used to decrease settling times substantially. Finally, the source voltage, measure current method of resistance measurement is generally faster because of reduced settling times.

FIGURE 2-34a: Effects of Cable Resistance on High Resistance Measurements

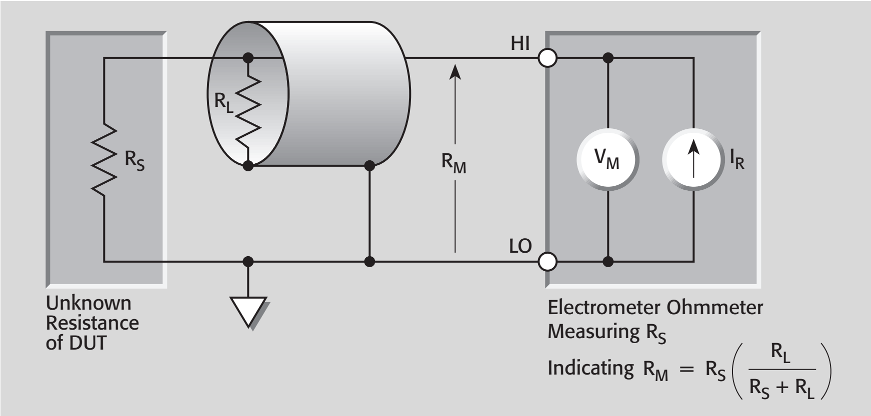


FIGURE 2-34b: Equivalent Circuit of Figure 2-34a Showing Loading Effect of Cable Leakage Resistance R_L.

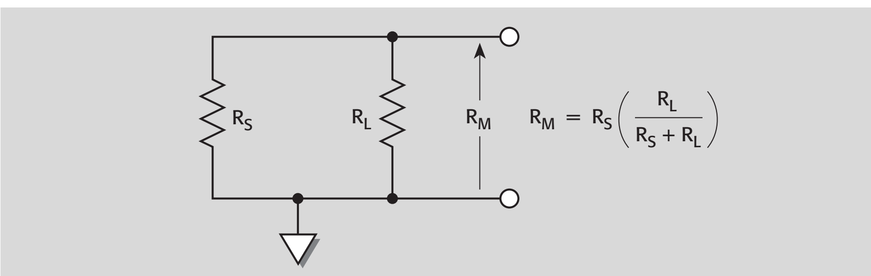


FIGURE 2-34c: Guarding Cable Shield to Eliminate Leakage Resistance

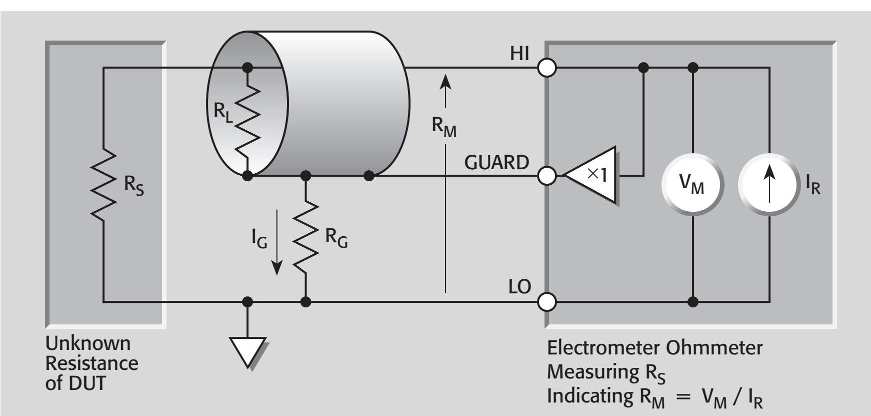


FIGURE 2-35: Settling Time is the Result of $R_S C_{SHUNT}$ Time Constant

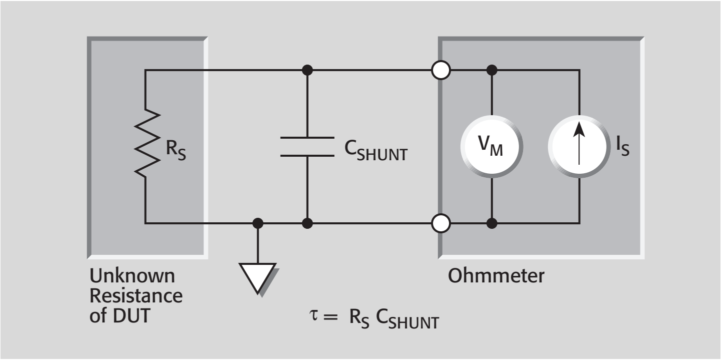
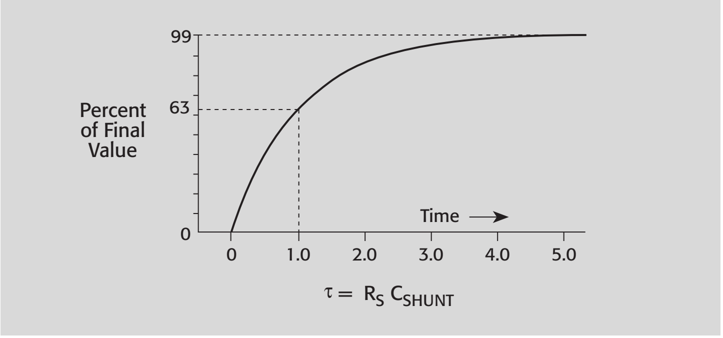


FIGURE 2-36: Exponential Settling Time Caused by Time Constant of Shunt Capacitance and Source Resistance



2.4.3 Characteristics of High Ohmic Valued Resistors

Resistors with values of 1GΩ or more are often referred to as high megohm resistors. Their high resistances make these components very unusual devices, so take several considerations into account when measuring them: voltage and temperature coefficients, the effects of mechanical shock, and contamination.

Two types of high megohm resistors are widely used: carbon-film and metal-oxide. When compared with conventional resistors, carbon-film high megohm resistors are noisy, unstable, have high temperature coefficients, display high voltage coefficients, and are very fragile. Recent developments in metal-oxide types have resulted in resistors with much lower voltage coefficients, as well as improved temperature and time stability. Modern devices exhibit voltage coefficients less than 5ppm/V and no significant drift after five years of tests. Temperature coefficients are on the order of 0.01%/°C at 100MΩ, 0.025%/°C at 100GΩ.

Such devices require extreme care in handling. Mechanical shock may significantly alter the resistance by dislodging particles of the conductive material. It's also important not to touch the resistance element or the glass envelope that surrounds it; doing so could change its resistance due to the creation of new current paths or small electrochemically generated currents.

The resistors are coated to prevent water films from forming on the surface. Therefore, if a resistor acquires surface films from careless handling or deposits from air contaminants, it should be cleaned with a foam-tipped swab and methanol. After cleaning, the resistor should be dried in a low humidity atmosphere for several hours to allow any static charges to dissipate.

2.5 Charge Measurements

Charge is the time integral of current, $q = \int idt$. Charge is often measured on a quantity of particles, on a surface, or on a component such as a capacitor. Sometimes, the charge is measured on a continuous basis, such as when using the coulombmeter to measure very low current, as discussed in Section 2.3.8.

An electrometer makes an ideal coulombmeter because it has very low input offset current and high input resistance. The coulombmeter function of the electrometer measures charge by integrating the input current. An integrating capacitor is used in the feedback loop of the input stage. Refer to Section 1.5.3 for a more detailed discussion of the coulombmeter circuit of the electrometer.

2.5.1 Error Sources

Charge measurements made with an electrometer are subject to a number of error sources, including input offset current, voltage burden, generated currents, and low source impedance.

Input Offset Current

With an electrometer, the input offset current is very low. However, at low charge levels, even this small current may be a significant error factor. Over long time periods, the instrument will integrate the offset current, which will be seen as a long-term drift in the charge measurement. Typical offset current is 4fA, which will cause a change in the charge measurement of 4fC per second. If the offset current is known, it's possible to compensate for this error simply by subtracting the charge drift due to offset current from the actual reading. However, determining the offset current of the entire system may be difficult.

Voltage Burden

The voltage burden of a feedback coulombmeter is generally quite low ($<100\mu V$), just as it is with a feedback picoammeter. However, if the instantaneous peak current is $>10\mu A$, the voltage burden can exceed this level momentarily. In an overload condition, the voltage burden can reach many volts, depending on the input value.

If the source voltage is at least 10mV, the typical electrometer in the coulombs mode will integrate the current accurately. If the source voltage is much lower, the voltage burden may become a problem, and the input stage noise will be amplified so much that accurate measurements aren't possible.

Generated Currents

Generated currents from the input cable or induced currents due to insufficient shielding can cause errors in charge measurements, especially with charge levels of 100pC or less. To minimize generated currents, use low noise cable and electrostatically shield all connections and the DUT.

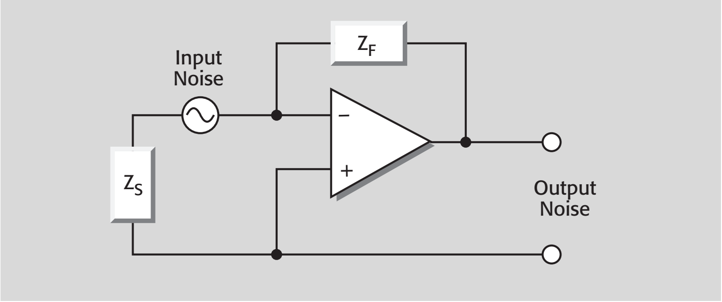
Source Impedance

The magnitude of the source impedance can affect the noise performance of the feedback coulombmeter. **Figure 2-37** shows a generalized feedback circuit connected to a source impedance. In a coulombmeter, the feedback impedance is a capacitor. From this diagram, the noise gain of the coulombmeter can be calculated from the following equation:

$$\text{Output Noise} = \text{Input Noise} \times (1 + Z_F/Z_S)$$

where: Z_S is the source impedance
Z_F is the feedback impedance of the coulombmeter
Input Noise is the noise of the input stage of the electrometer

FIGURE 2-37: Generalized Feedback Circuit



In general, as Z_F becomes larger, the noise gain becomes larger. Refer to the electrometer's manual or specifications for the value of the feedback impedance for a particular instrument.

2.5.2 Zero Check

Unlike a voltage measurement, a charge measurement can be a destructive measurement. In other words, the process of making the measurement may remove the charge stored in the device under test.

When measuring the charge on a device such as a capacitor, it's important to disable the zero check of the electrometer first, and then connect the capacitor to the high impedance input terminal. Otherwise, some of the charge will be lost through the zero check impedance and won't be measured by the electrometer. That's because when zero check is enabled, the input resistance of the electrometer is about 10MΩ.

Opening the zero check switch will produce a sudden change in charge reading known as "zero hop." To eliminate the effects of zero hop, take a reading just after the zero check is disabled, then subtract this value from all subsequent readings. An easy way to do this is to enable the REL function after zero check is disabled, which nulls out the charge reading caused by the hop.

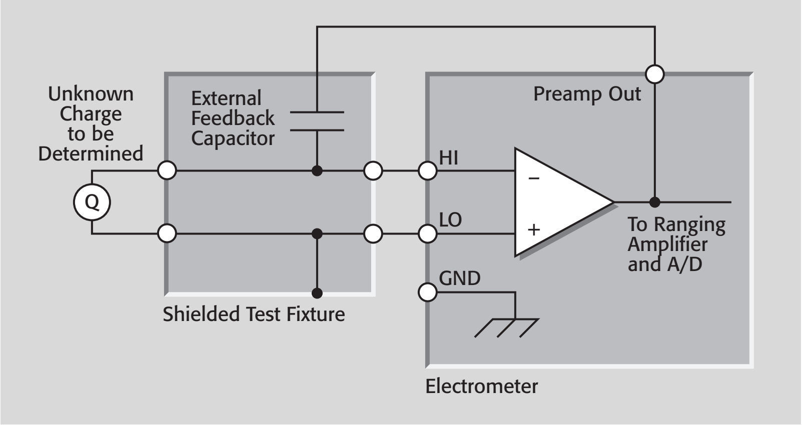
2.5.3 Extending the Charge Measurement Range of the Electrometer

The charge measurement range of most electrometers can be extended using external feedback. The external feedback mode allows an external device to be used as the feedback element of the electrometer. Placing the electrometer in the volts mode and then enabling external feedback switches the feedback circuit from an internal network to a feedback circuit connected to the preamp output.

To extend the coulombs ranges, an external capacitor is used as the feedback element.

As illustrated in **Figure 2-38**, an external feedback capacitor is placed between the preamp output terminal and the HI input terminal of the electrometer. To prevent electrostatic interference, the capacitor is placed in a shielded test fixture.

FIGURE 2-38: Connections for Using External Feedback Capacitor



When in the external feedback mode, the electrometer will display the voltage across the feedback element. The unknown charge can be calculated from the following formula:

$Q = CV$

where: Q = charge (coulombs)
C = capacitance of the external feedback capacitor (farads)
V = voltage on display of electrometer (volts)

For example, using an external feedback capacitor of 10μF and measuring 5V on the display of the electrometer, the calculated charge is 50μC.

The capacitance of the feedback element should be at least 10pF to avoid errors due to stray capacitance and noise gain.

To ensure low leakage current and low dielectric absorption, the feedback capacitor should be made of a suitable dielectric material such as polystyrene, polypropylene, or Teflon.

More information on the measurement procedure can be found in the instruction manual of the electrometer.

2.6 General Electrometer Considerations

So far, we have discussed considerations specific to voltage, current, resistance, and charge measurements. The following paragraphs examine considerations that apply to all types of electrometer and SMU measurements on high resistance sources.

2.6.1 Making Connections

To avoid measurement errors, it's critical to make proper connections from the electrometer, SMU, or picoammeter to the device under test. **Always connect the high resistance terminal of the meter to the highest resistance point of the circuit under test.**

Figure 2-39 shows an electrometer connected to a current source that consists of a voltage source in series with a resistor. An AC powered source usually has a significant level (often several volts) of line frequency common mode voltage. As shown in **Figure 2-40**, this will cause a current (i) to flow through the low to ground capacitance of the electrometer (I_M). This circuit

FIGURE 2-39: Connecting the HI Terminal of the Ammeter to High Resistance

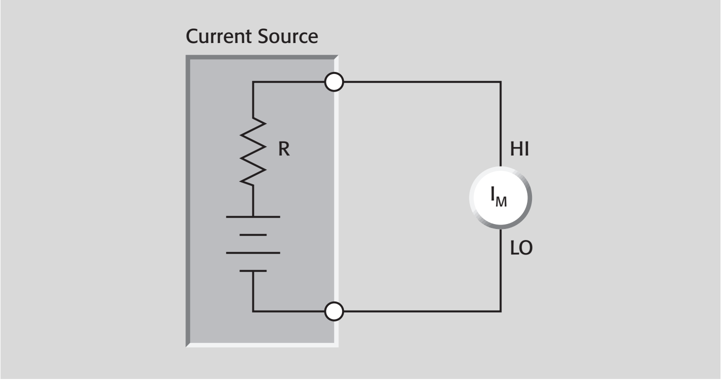


FIGURE 2-40: Proper Connection

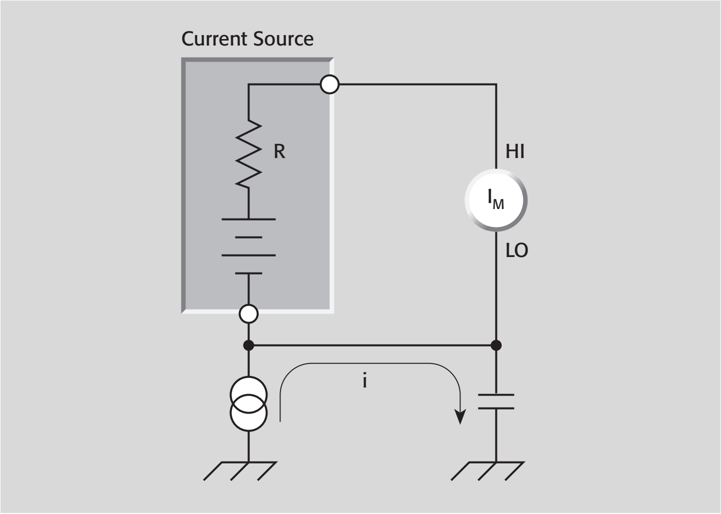
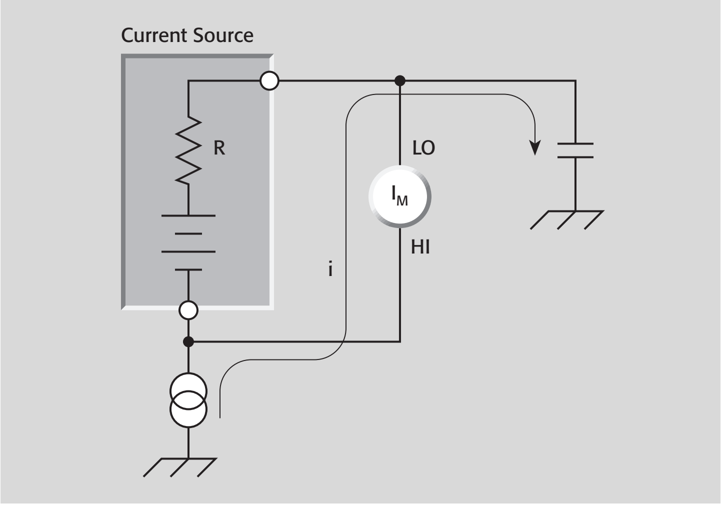


FIGURE 2-41: Improper Connection



is connected properly, so this current doesn't flow through the electrometer measurement circuitry and, therefore, doesn't cause any measurement errors. However, when the HI terminal of the electrometer is connected to the low impedance power supply, this AC current (i) flows through the electrometer (I_M), as illustrated in **Figure 2-41**. This current may affect the measurement accuracy, especially at low signal levels.

See Section 2.6.6 for details on appropriate cabling and connector types for electrometer measurements.

2.6.2 Electrostatic Interference and Shielding

Electrostatic coupling or interference occurs when an electrically charged object approaches the input circuit under test. At low impedance levels, the effects of the interference aren't noticeable because the charge dissipates rapidly. However, high resistance materials don't allow the charge to decay quickly, which may result in unstable measurements. The erroneous readings may be due to either DC or AC electrostatic fields, so electrostatic shielding will help minimize the effects of these fields.

DC fields can produce noisy readings or undetected errors. These fields can be detected when movement near an experiment (such as the movement of the person operating the instrument or others in the immediate vicinity) causes fluctuations on the electrometer's display. To perform a quick check for interference, place a piece of charged plastic, such as a comb, near the circuit. A large change in the meter reading indicates insufficient shielding.

AC fields can be equally troublesome. These are caused most often by power lines and RF fields. If the AC voltage at the input is large, part of this signal is rectified, producing an error in the DC signal being measured. This can be checked by observing the analog output of the electrometer or picoammeter with an oscilloscope. A clipped waveform indicates a need to improve electrostatic shielding. **Figure 2-42** illustrates a clipped waveform taken from the 2V analog output of an electrometer. In this example, the amount of clipping reduced the DC current reading by nearly 50%.

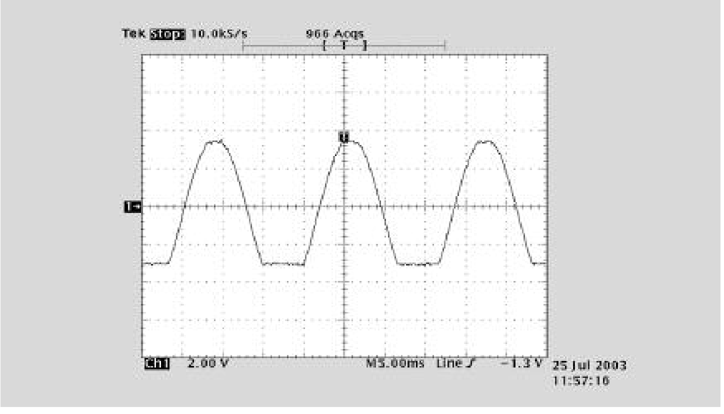


FIGURE 2-42: Clipped Waveform from the Analog Output of an Electrometer Caused by AC Pickup

For an SMU, check for AC pickup by connecting the oscilloscope between the guard terminal and common.

Figure 2-43 shows an example of AC electrostatic coupling. An electrostatic voltage source in the vicinity of a conductor, such as a cable or trace on a PC board, generates a current proportional to the rate of change of the voltage and of the coupling capacitance. This current can be calculated with the following equation:

$$i = C\,dV/dt + V\,dC/dt$$

For example, two conductors, each with $1cm^2$ area and spaced 1cm apart by air, will have almost 0.1pF of capacitance. With a voltage difference of 100V between the two conductors and a vibration causing a change of capacitance of 0.01pF/second (a 10% fluctuation between them), a current of 1pA AC will be generated.

To reduce the effects of the fields, a shield can be built to enclose the circuit being measured. The easiest type of shield to make is a simple metal box or meshed screen that encloses the test circuit. Shielded boxes are also available commercially.

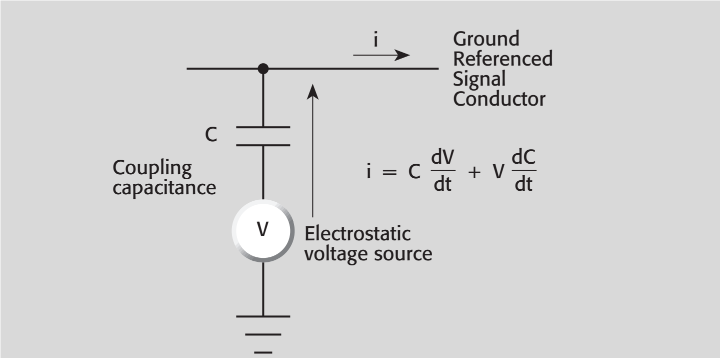


FIGURE 2-43: Electrostatic Coupling

Figure 2-44 illustrates an example of shielding. Made from a conductive material, the shield is always connected to the low impedance input of the electrometer or picoammeter or to the output LO (or common) terminal of the SMU. If circuit LO is floating above ground, observe special safety precautions to prevent anyone from touching the shield. These safety precautions are discussed in Section 2.6.8.

The cabling between the HI terminal of the meter and the device under test also requires shielding. Capacitive coupling between an electrostatic noise source and the signal conductors or cables can be greatly reduced by surrounding those conductors with a metal shield connected to LO, as shown in **Figure 2-45**. With this shield in place, the noise current generated by the electrostatic voltage source and the coupling capacitance flows through the shield to ground rather than through the signal conductors.

FIGURE 2-44: Shielding a High Impedance Device

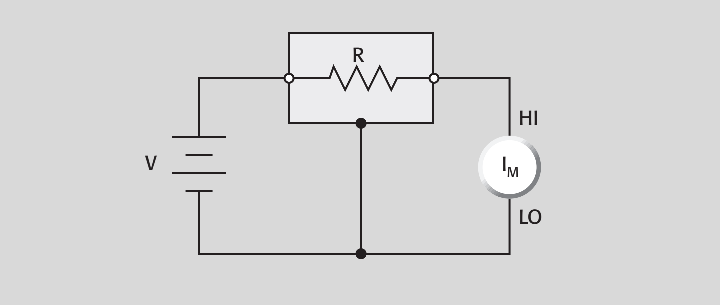
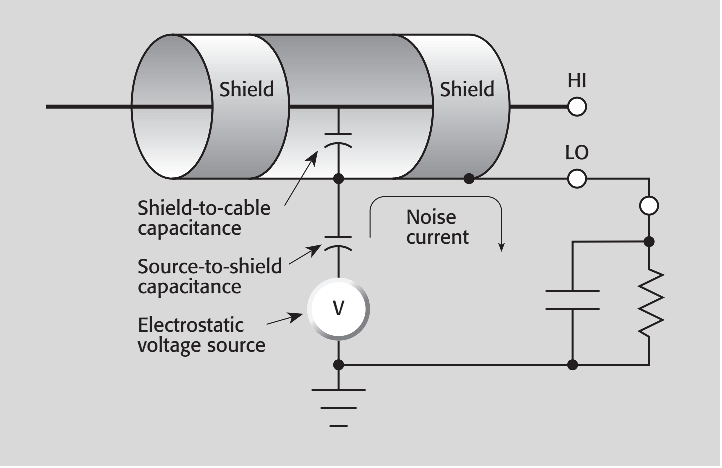


FIGURE 2-45: Electrostatic Shielding



To summarize, follow these guidelines to minimize error currents due to electrostatic coupling:

- Keep all charged objects (including people) and conductors away from sensitive areas of the test circuit.
- Avoid movement and vibration near the test area.
- When measuring currents <1nA, shield the device under test by surrounding it with a metal enclosure and connect the enclosure electrically to the test circuit common terminal.

Shielding vs. Guarding

Shielding usually implies the use of a metallic enclosure to prevent electrostatic interference from affecting a high impedance circuit. Guarding implies the use of an added low impedance conductor, maintained at the same potential as the high impedance circuit, which will intercept any interfering voltage or current. A guard doesn't necessarily provide shielding. Guarding is described further in Section 2.2.1 for voltmeters, Section 2.3.1 for ammeters, and Section 2.4.2 for ohmmeters.

2.6.3 Environmental Factors

A stable test environment is essential when making accurate low level measurements. This section addresses important environmental factors that may affect the accuracy of low level measurements.

Temperature and Temperature Stability

Varying temperatures can affect low level measurements in several ways, including causing thermal expansion or contraction of insulators and producing noise currents. Also, a temperature rise can cause an increase in the input bias current of the meter. As a general rule, JFET gate leakage current doubles for every 10°C increase in temperature, but most electrometers are temperature compensated to minimize input current variations over a wide temperature range.

To minimize errors due to temperature variations, operate the entire system in a thermally stable environment. Keep sensitive instruments away from hot locations (such as the top of a rack) and allow the complete system to achieve thermal stability before making measurements. Use the instrument's zero or suppress feature to null offsets once the system has achieved thermal stability. Repeat the zeroing process whenever the ambient temperature changes. To ensure optimum accuracy, zero the instrument on the same range as that to be used for the measurement.

Humidity

Excess humidity can reduce insulation resistance on PC boards and in test connection insulators. A reduction in insulation resistance can, of course, have a serious effect on high impedance measurements. In addition, humidity or moisture can combine with any contaminants present to create electrochemical effects that can produce offset currents.

To minimize the effects of moisture, reduce the humidity in the environment (ideally <50%). Be sure all components and connectors in the test system are clean and free of contamination. When cleaning, use only pure solvents to dissolve oils and other contaminants, then rinse the cleaned area with fresh methanol or deionized water. Allow cleaned areas to dry for several hours before use.

Light

Some components such as diodes and transistors are excellent light detectors. Consequently, these components must be tested in a light-free environment. To ensure measurement accuracy, check the test fixture for light leaks at doors and door hinges, tubing entry points, and connectors or connector panels.

Ionization Interference

Current measurements made at very low levels (<100fA) may be affected by ionization interference from sources such as alpha particles. A single alpha particle generates a track of from 30,000 to 70,000 positive and negative ions per cm, which may be polarized and moved about by ambient electric fields. Also, ions that strike a current-sensing node may generate a "charge hop" of about 10fC per ion.

There are several ways to minimize noise in the test system due to ionization interference. First, minimize the volume of air inside the shield around sensitive input nodes. Also, keep sensitive nodes away from high intensity electric fields.

RFI (Radio Frequency Interference)

Interference from radio frequency sources can affect any sensitive electrometer measurement. This type of interference may be indicated by a sudden change in the reading for no apparent reason.

A non-linear device or junction in the input circuit can rectify the RF energy and cause significant errors. Sources of such RFI are nearby transmitters, contactors, solenoid valves, and even cellular telephones and portable two-way radios.

Once the source is identified, the RF energy may be reduced or eliminated by shielding and adding snubber networks or filters at appropriate points. Consult Section 3.2.1 for further discussion of RFI.

2.6.4 Speed Considerations

Time and Frequency Relationships

Although this handbook stresses DC measurements, an analysis of noise and instrument response speed requires a brief discussion of time and frequency relationships in electronic circuits.

A steady-state DC signal applied to a voltmeter presents no conceptual difficulty. However, if the signal has a time-varying component such as an AC signal superimposed on the DC signal, the meter will tend to follow the varying signal and show the instantaneous magnitude of the input. As the frequency of the AC component increases, the DC meter response decreases, until at some frequency only the average input voltage will be displayed. The frequency at which the voltmeter's response to an AC signal drops to 70% is often denoted as the "3dB point" (f_{3dB}). Digital multimeters have a bandwidth of roughly half the conversion rate (readings per second) at the display. The analog output has a much wider bandwidth unless it's reconstructed from digital information.

Bandwidth describes the instrument's ability to respond to time varying signals over a range of frequencies. Another measure of the instrument's response is its ability to respond to a step function; the typical measure of response is the rise time of the instrument. Bandwidth or rise time may be used to describe the instrument's response to time-varying signals.

Rise time of an analog instrument (or analog output) is generally defined as the time necessary for the output to rise from 10% to 90% of the final value when the input signal rises instantaneously from zero to some fixed value. This relationship is shown in **Figure 2-46**. In **Figure 2-46a**, a step function with an assumed rise time of zero is shown, while **Figure 2-46b** shows the instrument's response and the associated rise time. Rise time, frequency response, and the RC time constant of a first order system are related. The 3dB point is given by the relationship:

$$f_{3dB} = \frac{1}{2\pi RC}$$

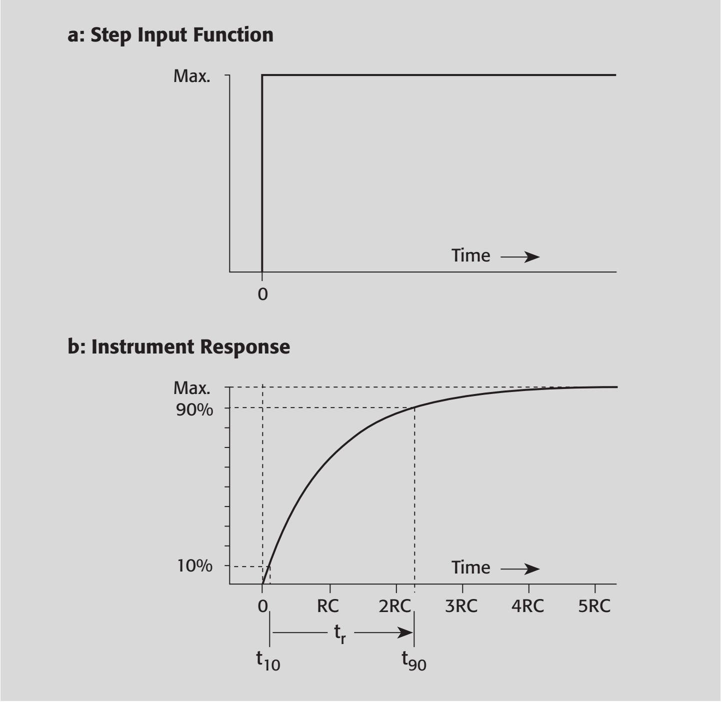
Rise time (t_r) is related to the RC time constant as follows:

$$t_r = t_{90} - t_{10}$$

where: $t_{90} = 2.3RC$
$t_{10} = 0.1RC$

Thus, $t_r = 2.2RC$.

FIGURE 2-46: Instrument Response to Step Input



For example, the rise time of a circuit with a source resistance of 1TΩ and capacitance of 100pF will be approximately:

$$t_r = (2.2)\ (10^{12})\ (100 \times 10^{-12}) = 220 \text{ seconds}$$

Using this with the above relationship between RC and f_{3dB}, we see that:

$$t_r = \frac{2.2}{2\pi f_{3dB}} \quad \text{or} \quad t_r = \frac{0.35}{f_{3dB}}$$

Thus, the 1TΩ source resistance and 100pF capacitance limit the bandwidth to:

$$f_{3dB} = \frac{0.35}{t_r} = \frac{0.35}{220} = 0.0016\text{Hz}$$

Rise time affects the accuracy of the measurement when it's of the same order of magnitude as the period of the measurement. If the length of time allowed before taking the reading is equal to the rise time, an error of approximately 10% will result, since the signal will have reached only 90% of its final value. To reduce the error, more time must be allowed. To reduce the error to 1%, about two rise times must be allowed, while reducing the error to 0.1% would require roughly three rise times (or nearly seven time constants).

Beyond the 0.1% error level (and occasionally the 1% level), second-order effects come into play. For example, more than four rise times are generally required to settle to within 0.01% of final value, due to dielectric absorption in insulators and other second-order effects.

In summary, an analog instrument's response (or the analog output response of most digital instruments) to a changing input signal is a function of its bandwidth, since frequency response and rise time are directly related. To ensure accurate measurements, sufficient settling time must be allowed for the source, the connection to the instrument, and the instrument itself to settle after the input signal is applied.

Effects of Input Capacitance on Rise Time and Noise

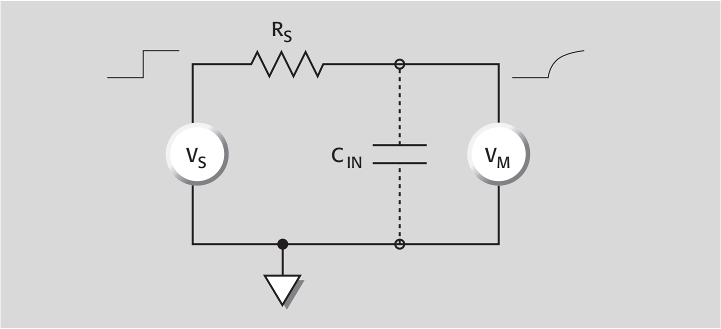
Voltage Measurements

In voltage measurements from high impedance sources (**Figure 2-47**), capacitance (C_{IN}) across the voltmeter (V_M) must be charged through R_S. The equation for the output voltage as a function of time is:

$$V_M = V_S\,(1 - e^{-t/R_S C})$$

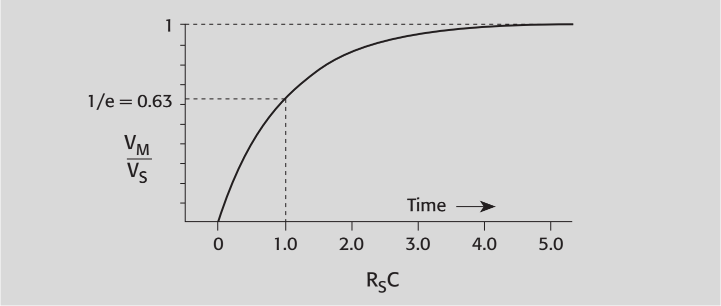
where: V_M = voltmeter reading at t seconds
V_S = step function source
t = time in seconds after step occurs
R_S = equivalent series resistance in ohms
C_{IN} = equivalent shunt capacitance in farads (instrument plus cable capacitance)

FIGURE 2-47: Shunt Capacitance Effect of High Impedance Voltage Measurement



Thus, the familiar exponential curve of **Figure 2-48** results, in which it becomes necessary to wait four or five time constants to achieve an accurate reading. In the case of large resistors and capacitance, the rise time can range up to minutes. While increased shunt capacitance causes rise time to increase, it does filter out noise produced in the source and interconnecting cable simply by reducing the effective bandwidth of the voltmeter.

FIGURE 2-48: Exponential Response to Step Input



Shunt Current Measurements

The effects of input capacitance on current measurements using a shunt type ammeter (**Figure 2-49**) are similar to those for voltage measurements. A shunt ammeter can be modeled as a voltmeter with a resistor across the input. The circuit shows that the input capacitance (C_{IN}) must be charged to $I_S R_S$ volts, at an exponential rate of the $R_S C$ time constant. Note that C_{IN} is the sum of the source, connecting cable, and meter capacitance.

Feedback Current Measurements

The effect of input capacitance on current meters employing negative feedback is different than the effect on the shunt ammeter. The circuit for this mode is shown in **Figure 2-50**.

FIGURE 2-49: Shunt Type Ammeter

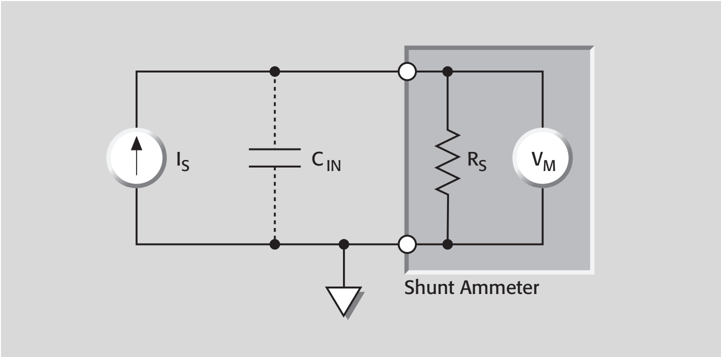
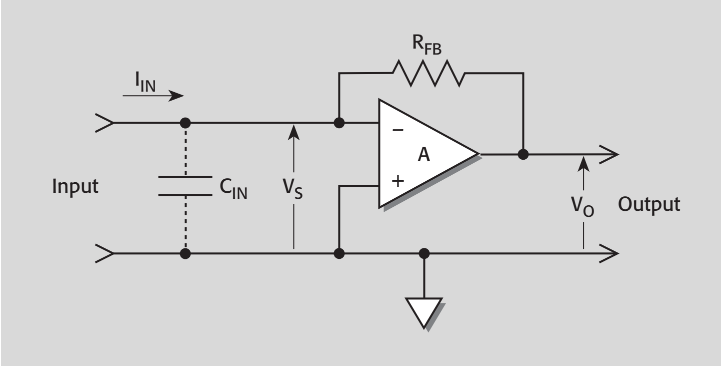


FIGURE 2-50: Feedback Electrometer Ammeter



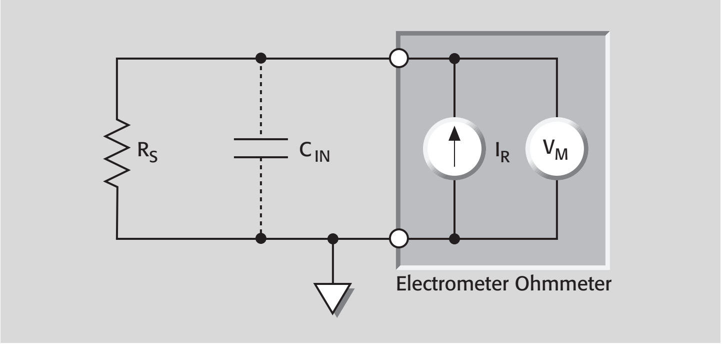
If A, the gain of the amplifier, is large, then $V_O = -I_{IN}R_{FB}$. In such an arrangement, C_{IN} doesn't shunt R_{FB}, and has only a fraction of the effect it would have with a shunt picoammeter. The resulting speed-up comes from the reduction of the input impedance of the picoammeter due to negative feedback. In other words, only $V_S = -V_O/A$ volts is developed across C_{IN} instead of the V_O that would occur in a shunt picoammeter. Thus, even large values of capacitance shunting the input will have negligible effect on rise time.

Rise time in a feedback picoammeter is a function of the physical or stray capacitance shunting the feedback resistance (R_{FB}). Electrometers, SMUs, and picoammeters can be used with relatively large values of source capacitance. It's important to realize that increasing values of input shunt capacitance (the parallel combination of source, cable and input capacitances) will degrade the signal-to-noise ratio of a given measurement. See Sections 2.3.2 and 4.3.1 for more information on noise and source impedance.

Resistance Measurements (Constant-Current Method)

Input capacitance also affects resistance measurements (**Figure 2-51**) in the same manner. Again, C_{IN} must be charged by the current (I_R), hence, the same equation applies. (See Section 2.4.2 for more information on the constant-current method.)

FIGURE 2-51: Constant-Current Resistance Measurement



Electrometer Rise Time Summary

For most measurements of high resistance sources, rise time considerations require minimizing the capacitance shunting the meter input. Earlier, it was shown that doing so also minimizes noise gain. In broader terms, the source impedance should be large compared to the feedback impedance of the meter.

The most effective method of minimizing input capacitance is to connect the electrometer, SMU, or picoammeter to the signal source with a shielded cable that is as short as possible. When measuring a voltage from a high source resistance, or when measuring high resistance, guarding can minimize the effects of input capacitance by driving the inner shield of a triax cable or an enclosure surrounding the input with a potential to minimize the effective capacitance, as discussed in Section 2.2.1.

2.6.5 Johnson Noise

The fundamental limit to measurement is Johnson noise in the source resistance. In any resistance, thermal energy produces motion of charged particles. This charge movement results in noise, which is often called Johnson or thermal noise. The power available from this motion is given by:

$$P = 4kTB$$

where: k = Boltzmann's constant (1.38×10^{-23}J/K)
T = absolute temperature in K
B = noise bandwidth in Hz

Metallic conductors approach this theoretical noise limit, while other materials produce somewhat higher noise. Johnson voltage noise (E) developed in a resistor (R) is:

$$E = \sqrt{4kTRB} \text{ volts, rms}$$

and Johnson current noise (I) developed by a resistor (R) is:

$$I = \frac{\sqrt{4kTRB}}{R} \text{ amperes, rms}$$

Statistical considerations show that peak-to-peak noise will be within five times the rms noise more than 99% of the time; therefore, the rms level is commonly multiplied by five to convert to peak-to-peak. At room temperature (300K), the previous equations become:

$$E_{p\text{-}p} = 6.4 \times 10^{-10} \sqrt{RB}$$

$$I_{p\text{-}p} = 6.4 \times 10^{-10} \sqrt{\frac{B}{R}}$$

All real voltage and current sources contain an internal resistance; therefore, they exhibit Johnson noise. **Figure 2-52** shows Johnson noise voltage versus source resistance for various bandwidths (or rise times) at room temperature.

For current measurements, **Figure 2-53** shows the current noise generated by various resistances at various bandwidths. Note that current noise decreases with increasing resistance, while voltage noise increases.

Johnson noise imposes a theoretical limit to achievable voltage or current resolution. The previous equations suggest several means for reducing Johnson noise. It might be possible to reduce the bandwidth, the source temperature, or the source resistance.

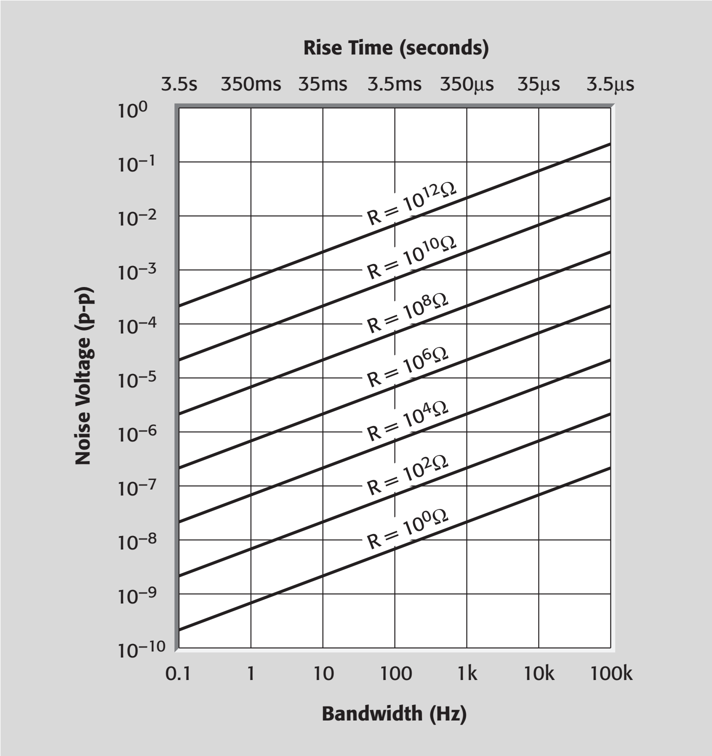
Bandwidth

Johnson noise is uniformly distributed over a wide frequency range, so reducing the noise bandwidth effectively decreases the noise in the measurement. Note that noise bandwidth isn't necessarily the same as signal bandwidth. The high frequency noise cutoff point is approximately equal to the smallest of:

- $\pi/2$ times the upper 3dB frequency limit of the analog DC measuring circuitry
- $0.35/t_r$ where t_r is the instrument's 10%–90% rise time
- 1Hz if an analog panel meter is used for readout or
- $0.314/t_{INT}$ where t_{INT} is the integration period of the A/D converter in a digital instrument.

In high resistance circuits, the noise bandwidth is often limited by the time constant of the source resistance and input capacitance, and this value

FIGURE 2-52: Noise Voltage vs. Bandwidth at Various Source Resistances

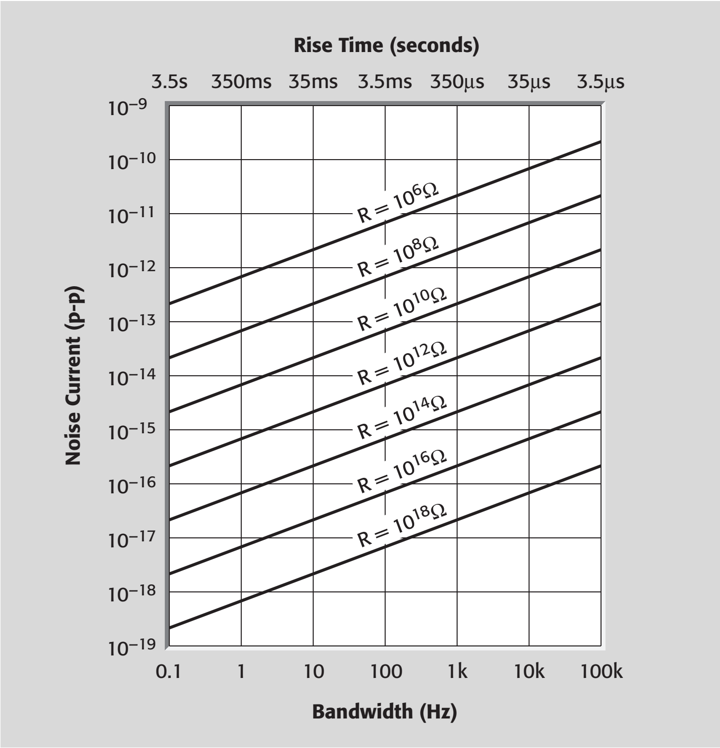


represents the smallest of the above alternative noise bandwidth calculations. In this case, noise bandwidth is:

$$
\begin{aligned}
B_{NOISE} &= \frac{\pi}{2}\,(f_{3dB}) \\
&= \frac{\pi}{2}\left(\frac{1}{2\pi R_{EFFECTIVE} C_{IN}}\right) \\
&= \frac{1}{4R_{EFFECTIVE} C_{IN}}
\end{aligned}
$$

where $R_{EFFECTIVE}$ is the source resistance in parallel with the input resistance of the measuring device, and C_{IN} is the sum of all capacitance shunting the input to the instrument (input capacitance, cable capacitance, etc.) Note that this analysis assumes a simple first-order system with one dominant time constant.

FIGURE 2-53: Noise Current vs. Bandwidth at Various Source Resistances



To reduce noise, the bandwidth (B) may be reduced artificially by averaging an analog meter reading by eye over an extended period, or by averaging a number of digital readings with a computer, or by internal digital filtering. Using low pass filters before the readout device may also reduce bandwidth. There is a practical limit to reducing bandwidth since very long-term measurements become susceptible to other errors, such as time and temperature drift.

Temperature

Reducing the temperature of the signal source from room temperature to –270°C (3K) decreases noise voltage by a factor of about ten. Similarly, a reduction from room temperature to liquid nitrogen levels (77K) reduces noise by a factor of two. In some applications, the inconvenience and expense of cryogenic operation may be justified and feasible. However, most experiments are designed to operate within a certain temperature range, which in turn determines the noise to be expected from the source.

Source Resistance

After the bandwidth and temperature, the remaining factor in determining the system noise is the effective source resistance. The effective source resistance includes the device under test as well as the measurement instrument. Changing the source resistance is usually impractical for noise reduction. However, if a change can be made, the equations show that R should be lowered to decrease voltage noise or raised to decrease current noise.

In voltage measurements, the voltage source resistance is in parallel with the voltmeter input resistance (see **Figure 2-1**). The input resistance is normally much larger than the source resistance; hence, the source resistance value usually determines the Johnson noise voltage.

In current measurements, the source resistance and the sensing resistance both contribute noise. The effective resistance is the parallel combination of the source resistance and the feedback (or shunt) sensing resistance. Feedback ammeters with high value sensing resistors in the feedback loop have lower Johnson current noise and thus greater sensitivity than shunt ammeters with lower resistance shunts.

Excess Current Noise

The Johnson noise of a resistor is related only to the resistance, the temperature, and the bandwidth. When current passes through a resistor, the noise will increase above the calculated Johnson noise. This increase in noise is sometimes referred to as "excess current noise." A wirewound resistor is nearly ideal and the noise increase is negligible. Metal film resistors have somewhat greater noise and carbon composition resistors are significantly noisier still. In all cases, this excess noise is directly proportional to the current through the resistor.

2.6.6 Device Connections

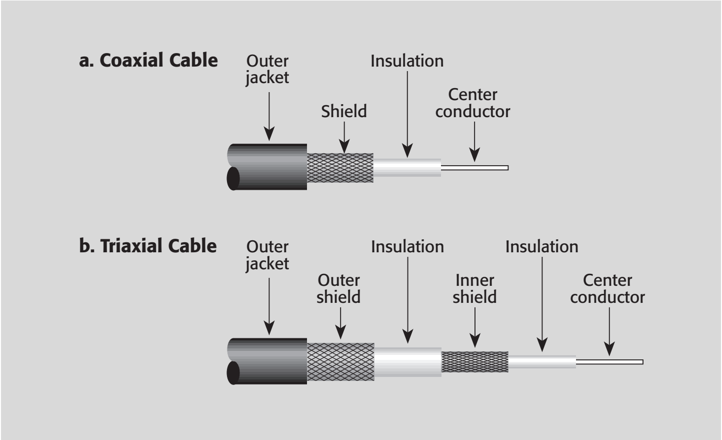
Although instrument accuracy is of great importance when making low level measurements, the integrity of device connections is equally important. The complete signal path from connectors, through the cables, and into the test fixture must degrade the measured signal as little as possible. The following paragraphs discuss cable and test fixture requirements and types of connectors generally used when making low level measurements.

Cable Requirements

Although DMMs often use unshielded test leads, such connection schemes are generally inadequate for low level measurements made with picoammeters, electrometers, and SMUs. These instruments generally use either coaxial or triaxial cables.

A coaxial cable consists of a single conductor surrounded by a shield (**Figure 2-54a**), while a triaxial cable adds a second shield around the first (**Figure 2-54b**). With triax cable, the inner shield can be driven at guard potential in order to reduce cable leakage and minimize circuit rise times.

FIGURE 2-54: Coaxial and Triaxial Cables



The outer shield is usually connected to chassis ground or, in some cases, to the common terminal. In either case, the outer shield must not be allowed to float more than 30Vrms (42.4V peak) above chassis ground for safety considerations. Always use a cable with a tightly woven shield to protect against electrostatic interference.

Both coaxial and triaxial cables are available in low noise versions, which should be used for low level measurements. Low noise cables have internal graphite coatings to minimize current generated by triboelectric effects. (See Section 2.3.4.) In some cases, ordinary coaxial cable such as RG-58 may be adequate, although both leakage and noise currents will be higher than with low noise cables.

When measuring high resistance, the insulation resistance of the cable is important. Good quality triaxial cables use polyethylene insulators and have a typical conductor-to-shield insulation resistance of about 1TΩ/ft. Refer to Section 2.2.2 for more information on insulation characteristics.

Parameters like cable resistance, capacitance, and leakage currents change as cable length increases. Thus, it's important to keep all connecting cables as short as possible. For example, a ten-foot cable with 1TΩ/ft resistance and 100pF/ft capacitance will have an insulation resistance of 100GΩ and a capacitance of 1000pF.

Connector Types

Two general types of connectors are used for electrometer, picoammeter, and SMU measurements. The BNC connector shown in **Figure 2-55** is a type of coaxial connector. It includes a center conductor and shell or shield connection, while the triax connector shown in **Figure 2-56** includes a center conductor, an inner shield, and an outer shield.

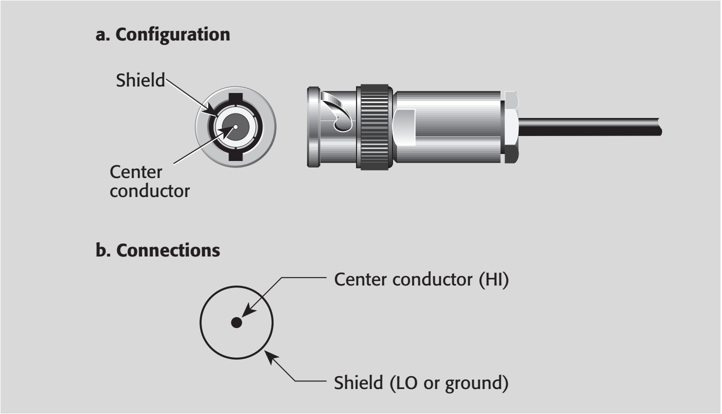


FIGURE 2-55: BNC Connector

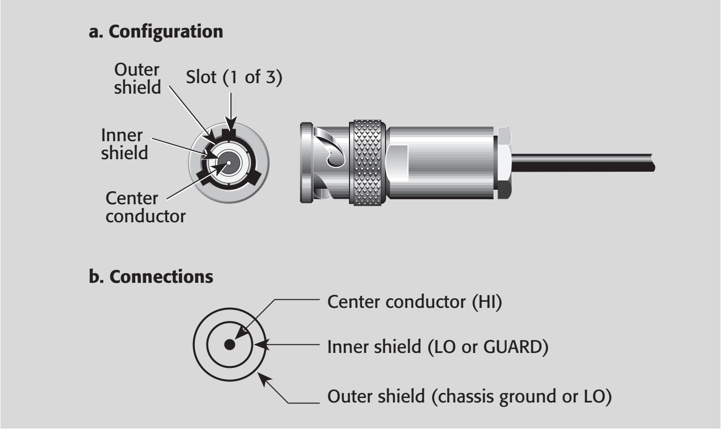


FIGURE 2-56: Three-Slot Triaxial Connector

The center conductor of the BNC connector is connected to input HI, while the outer shell is input LO. Note that the shell may be connected directly to chassis ground at the instrument.

The center conductor of the triax connector is connected to HI. The inner shield is either LO or guard, while the outer shield is usually connected to chassis ground. However, with some SMUs, the outside shield is connected to the LO terminal (common) and is allowed to float off ground. See the discussion that follows for more information on triaxial cable and guarding.

To maintain high insulation resistance, use proper insulating material between the various conductors of all connectors. Towards that goal, most quality BNC and triax connectors use Teflon® insulation between conductors.

Triaxial connectors are available in both two-slot and three-slot configurations. The three-slot design is a more recent development intended to avoid connector damage that could occur when attempting to mate BNC and triax connectors. Most newer equipment uses the three-slot design. Adapters are available to convert between the two types.

Triaxial Cabling and Guarded Connections

As discussed previously, connecting a guard voltage to the shield of a coaxial cable can present a safety hazard if the guard voltage is >30Vrms. Triaxial cabling avoids this problem by surrounding the guard shield with an outer shield connected to earth ground or LO.

For unguarded operation of an electrometer, triaxial cabling is normally connected as follows:

- Center Conductor: High impedance lead (HI)
- Inner Shield: Low impedance lead (LO)
- Outer Shield: Ground (GND)

This arrangement provides the capability of safely carrying two signals, neither of which is at ground potential, while maintaining high impedance integrity by shielding both leads and maintaining a high resistance between each conductor and ground.

When an electrometer is in the guarded mode or if an SMU is used, a triaxial cable is connected in the following manner:

- Center Conductor: HI
- Inner Shield: GUARD
- Outer Shield: Ground or LO

With an electrometer, the guard connection is useful when measuring high resistance or when measuring voltage from a high source resistance. It's not needed when measuring low current, because the guard in a feedback ammeter circuit of an electrometer is always LO. Newer electrometers provide internal switching to change between guarded and unguarded connections.

When using an SMU to measure low current, the guard terminal is used to reduce leakage current of the cable and test fixturing.

Test Fixture Requirements

Test fixtures used for low level measurements have several important requirements:

- *Insulation Resistance:* The insulation resistance of all connectors, internal wiring, terminals, and sockets should be as high as possible. Generally, a good-quality fixture will use Teflon insulation in all connectors and sockets.

- *Shielding and Guarding:* The fixture should provide adequate shielding for sensitive circuits. For high impedance measurements, provisions should be included to carry guard into the fixture as close to the DUT as possible.
- *Light:* A light-tight fixture is a necessity when testing light-sensitive components.
- *Special Fixture Requirements:* Special applications, such as high resistance or very low current measurements, often require fixtures designed with good insulation characteristics, which may only be possible by using special materials, such as sapphire.

2.6.7 Analog Outputs

Some electrometers have two analog outputs, a 2V analog output as well as a preamplifier, or unity gain output. The 2V analog output is useful for connecting to recorders while the preamp output is useful for buffering, guarding, and external feedback. This section discusses these outputs and possible loading errors when using these outputs. Refer to Section 2.6.8 for details on using the analog output with a floating input.

2V Analog Output

The typical analog output is ±2V for a full scale input signal. Depending on the instrument design and function, the output may be inverting or non-inverting. The output resistance may range from 1Ω to 10kΩ. Any device connected to the output, such as a chart recorder or oscilloscope, will have a finite input resistance and will attenuate the analog output. See the section on *Loading Errors* for more information.

Preamp Output

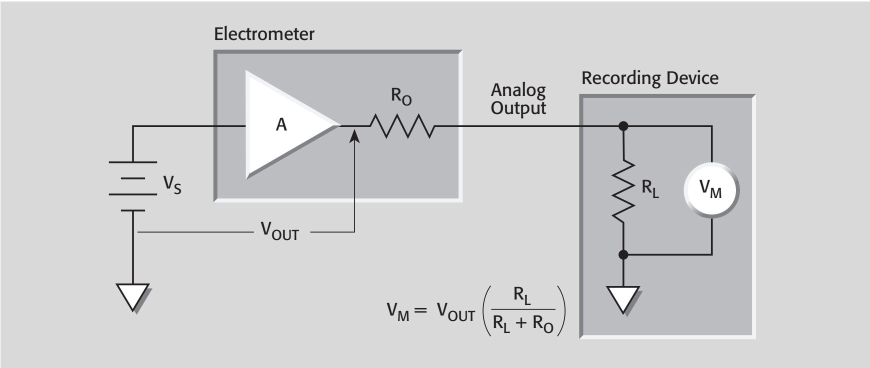
The preamp output follows the signal amplitude applied to the input terminal of the electrometer. The preamp out is the guard voltage for volts and ohms (constant-current method only). It's useful for buffering the input signal. It may be inverting or non-inverting, depending on the function selected.

Loading Errors

Although the output resistance of a typical analog output is low, it isn't zero, so consider the possibility of loading by external instrumentation. In principle, the concepts of analog output loading are identical to those for source loading, discussed in Section 2.2.1.

Figure 2-57 demonstrates how loading can affect the accuracy of the analog output. A voltage to be measured (V_S) is applied to the electrometer input. The signal is amplified by an amplifier (A) with output resistance (R_O), then connected to a recording device. The input resistance of the recording device (R_L) and the analog output resistance (R_O) form a voltage divider that attenuates the output signal. For a typical analog output resistance of 1kΩ, the recording device must have an input resistance of at least

FIGURE 2-57: Analog Output Loading



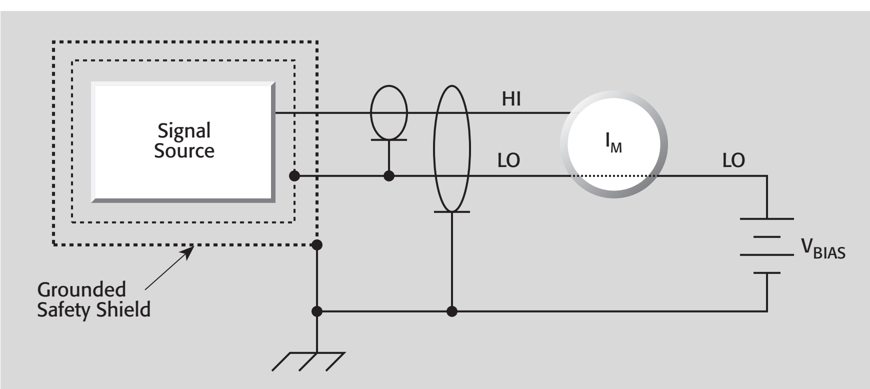
1MΩ if error due to loading is to be kept under 0.1%. This error can be calculated using the equation shown in **Figure 2-57**.

2.6.8 Floating Input Signals

The majority of electrometer or picoammeter applications involve an input signal referred to earth ground. However, in some applications, it's necessary that the electrometer or picoammeter be biased off ground. Examples of such applications include the flame ionization detector of a gas chromatograph and the Faraday cup in a mass spectrometer.

In a typical low level test setup, shielding is required to reduce noise, as shown in **Figure 2-58**. In most cases, this "noise" shield is connected to the LO input terminal of the meter. If the LO terminal must be biased more than 30V with respect to earth ground, the noise shield will be at a hazardous voltage and will pose a shock hazard. To avoid shock hazards with

FIGURE 2-58: Safety Shielding with Floating Circuits



floating circuits, a second grounded safety shield must be added to enclose the noise shield completely.

Most picoammeters and electrometers use a triaxial input connector with the outside shield connected to earth ground for safety. By using a triaxial connector at the safety shield and a triaxial cable between the test setup and the instrument, a completely shielded and safe system will result. Note: Maximum float voltage ratings must be observed to prevent breakdown between the inner conductors and the outer grounded shield.

For SMUs with the outside shield connected to LO and for picoammeters with a coax input, the input should not be allowed to float more than 30Vrms (42V peak) from ground.

2.6.9 Electrometer Verification

All measuring instruments require periodic recalibration, typically once per year. It may be desirable to check the functions of the instrument more frequently. This section describes simple tests to verify electrometer functions.

Amperes

First, turn the power on and allow the meter to warm up for the time specified in the service manual. Then place a shield cap over the input connector and link the low impedance input terminal to ground. The zero check should be enabled. Next, set the meter to the most sensitive current range, zero the meter, and then disable the zero-check switch. After several seconds, the meter reading should settle to within a few digits. The indicated current is the input offset. If it exceeds the instrument specification by 25% or so, leave the power on overnight and repeat the test. If the current is still excessive, the instrument should be repaired.

The ammeter input should never be short-circuited because it will then have no negative feedback. While no damage will occur, the result will be meaningless.

Volts

A single flashlight cell or a 9V battery will give a rough check on the voltage function. (Be sure to try both polarities.)

Ohms

The ohms function can be checked with almost any known resistor, but it's best to use as high a resistance as possible.

Coulombs

The coulombs function can be checked using a low leakage capacitor and a voltage source. A known capacitor in the range of 100pF to 1000pF can be charged to a known voltage via a flashlight cell. The capacitor is then connected to the electrometer input after setting the meter to coulombs and disabling the zero check switch. Conversely, this procedure can be used to determine the value of the capacitor.

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