EFFECT OF MEASUREMENT AND INSTRUMENTATION ERRORS ON POTENTIAL READINGS

James R. Dimond
Dimondale Co., Inc.
PO Box 838
Middlefield, OH 44062

Frank J. Ansuini
Electrochemical Devices, Inc.
PO Box 31
Albion, RI 02802

ABSTRACT

Among the tools most widely used by a corrosion engineer or technician are a reference electrode and a voltmeter. With them, corrosion potential measurements can be made to assist in determining corrosion of a structure or the effectiveness of a cathodic protection system. However, there are sources of error in these measurements. This paper will discuss some of the more common sources of error and how to reduce them as much as practical.

Keywords: potential measurements, reference electrodes, error sources, IR drop error

INTRODUCTION

Corrosion potential measurements made using a reference electrode and a voltmeter are one of the most common measurements made in corrosion engineering. They provide valuable information on corrosion of a structure as well as being the primary means for determining the effectiveness of a cathodic protection system. In fact, the various industry standard criteria for determining the adequacy of a cathodic protection system all depend, in one way or another, on potential measurements. In order to make sound judgments on the condition of a cathodic protection system, it is very important that corrosion control practitioners understand possible sources of error inherent in potential measurements and use their knowledge and experience to reduce these errors.

MEASUREMENT CIRCUIT

A potential measurement circuit is a simple DC circuit as shown in Figure 1. Figure 1a is a physical layout of the components while Figure 1b is an equivalent electrical schematic of this circuit. The driving voltage for this circuit is the potential which exists between the reference electrode and the structure. When the circuit is complete, such as when a measurement is being made, a current will flow through the circuit as a result of this potential. The magnitude of the current flow follows Ohm's law, $I = E/R$, in that it is inversely proportional to the sum of all the resistances in the circuit. For example, if the circuit potential is one volt and the sum of the resistances is 10 megohm, a tenth of a micro-amp will flow through the measurement circuit.

Voltage drops occur across each of the resistive elements in the measurement circuit. These voltage drops are separate and distinct from the more commonly discussed voltage drops, or IR drops, which are due to external current flowing through the electrolyte. Both measurement circuit voltage drops and external voltage drops become incorporated into potential measurements causing errors. Different methods must be employed to minimize errors caused by each type.

In most cases, resistance of the lead wires and the structure is sufficiently small that the voltage drop that occurs along them during measurements is inconsequential. Using the current values in the above example, if a lead wire or the structure has a one ohm resistance, it will cause a one tenth micro-volt voltage drop. This is well below the detection limit of commonly used meters. Most reference electrodes have an internal resistance on the order of one kilo-ohm. Even if this resistance were to be as high as ten kilo-ohms, the voltage drop across the reference in the above example would only be about one milli-volt.   Electrolyte resistance is highly variable ranging from quite low for potential measurements in seawater to very high for potential measurements in semi-dry concrete or soils. The proper strategy is to select a meter whose internal resistance (input impedance) is several orders of magnitude higher than any other resistance in the circuit so that voltage drop across the meter will, for practical purposes, represent the entire voltage drop in the circuit.

EXTERNAL IR DROP

As previously stated, current flowing in the measurement circuit will cause a voltage (or IR) drop which becomes incorporated into measurements as an error. Similarly, any external currents flowing through the electrolyte in the area between the reference electrode and the structure will cause its own IR drop which also becomes incorporated into the measurement as an error. Cathodic protection systems and electrical power systems are two possible sources of these currents. The magnitude of errors from external IR drops can be substantial. Current practice is to attempt to minimize them as much as possible.

A common method of removing external IR drop in potential measurements is to interrupt the cathodic protection current by momentarily disconnecting the rectifier. This action produces an instantaneous voltage drop which is considered to be the external IR drop. The potential measured immediately after this instantaneous drop is considered to be the "IR drop free" potential of the structure. Clearly, this method only works with an impressed current cathodic protection system where all the rectifiers on that system can be interrupted simultaneously, and there are no other sources of current flowing through the electrolyte.

An issue which should be considered when using current interruption for instant-off measurements is: What is meant by instantaneous? The answer is not simple since it depends upon the structure, the electrolyte and the method of interrupting the current. Putting the answer in electrical terms, it depends upon the capacitance and the inductance of the circuit. IR drop free measurements can be made microseconds after current interruption on small uncoated specimens in a low resistance electrolyte. Large coated structures, such as pipelines, or high resistance electrolytes, such as concrete, usually require several hundred milliseconds or more for IR-drop free measurements. Interrupting current on the AC side rather than on the DC side of the rectifier will increase the time delay because the circuit inductance is higher. A oscilloscope should be used if measurement precision is necessary; it should be either battery powered or connected through an isolation transformer to eliminate ground loops.

For situations where current interruption cannot be reliably used to minimize external IR drop error in potential measurements, cathodic protection coupons are frequently used. These are small pieces of metal similar to the structure which are electrically bonded to the structure through a switch. The coupon is placed close to a reference electrode and the coupon's polarization behavior is presumed to be similar to that of the structure near the coupon. Measurements are made as above except that the coupon rather than the rectifier is momentarily disconnected. Coupons presently are available which minimize the amount of IR drop error in measurements even when current is not interrupted.

SPECIAL PROBLEMS WITH CONCRETE

Making potential measurements in or through concrete presents several sources of error. These measurements are discussed more thoroughly in a NACE State of the Art Report on this topic[1]; a couple of these error sources will be reviewed here.

Current is carried through an electrolyte by means of ions which physically move through the electrolyte. In a potential field, anions move in one direction and cations in the opposite direction. If the ion mobilities are unequal, a balancing potential builds up due to separation of the charges. This potential, termed a junction potential, becomes incorporated into the measurement as an error. In concrete, it is quite common to have areas of different electrolyte compositions. For example, sodium chloride (NaCl) is often spread on the surface for deicing; sodium and chloride ions have very different ionic mobilities. Another example is carbonation of concrete, the reaction of the material with atmospheric carbon dioxide, which proceeds inward from an exposed surface and causes a change in both the chemical composition and pH of concrete. Each of these can contribute to a junction potential error in concrete measurements.

The mobility of all ions in concrete is retarded due to the material's cellular microstructure. Consequently, concrete has high electrolyte resistivity so the presence of any internal current flowing through it will be marked by relatively high IR drops. Sources of these internal currents are often corrosion currents from corrosion of rebars. The associated IR drops become incorporated into corrosion potential measurements and can result in a several hundred millivolt error.

Errors of the same magnitude have been documented for measurements made through concrete, such as to a structure buried beneath a concrete slab. In a detailed study on this topic[2], potential measurements were made on buried tanks at nine different service stations in the northeast. When the

measurement was made with the reference electrode contacting the concrete slab, the potential was from 20 to 260 mV more negative than when the reference electrode was directly contacting the soil through an access hole. The rectifier was off during these measurements to eliminate CP currents as a possible error source. In the same study, potential measurements were made on a pipe located beneath an airport runway. Measurements made through the concrete near the edge of the runway were about 200 mV more negative than the same measurement made through the grass adjacent to the slab. Wetting both the concrete and the grass did not significantly change the measured values. Clearly, measurements of buried structures should never be made through concrete.

METERS

Hand Held Meters

Today, most corrosion personnel use digital meters. The accuracy of even the least expensive meters is one quarter to one half percent.   Such meters would be more than adequate and likely the only type necessary if voltage drop within the measurement circuit were not involved. When a meter is connected to read potential of a structure, the circuit is completed; and current will flow as stated above. The meter measures only the voltage across its own input terminals; voltage drops occurring in the lead wire, reference electrode, electrolyte or structure are not measured. If these other voltage drops are significant, the meter will show less then the true potential. Input resistance of a meter, therefore, is at least as important as its accuracy, perhaps even more so.

Most general purpose digital meters used today for corrosion measurements have 10 mega-ohm input resistance. While this may seem high, it may not be adequate in some circumstances. Consider a structure with a 900mV potential and a circuit resistance external to the meter of 10 kilo-ohms. Ten kilo-ohms is 0.1% of 10 mega-ohms. Thus 0.1% of the voltage will be dropped in the circuit external to the meter and 99.9% will be measured by the meter. Now let's consider the case where the structure is in concrete, rock or dry soil. The external resistance in this situation could be 1 mega-ohm or higher.   The total circuit resistance would now be 11 mega-ohm with 90% being in the meter and 10% external to the meter. The voltage drop in this case would be similarly divided with 810mV across the meter and 90mV external. That would be a major error.

A preferred way of making potential measurements in high resistance circuits is with a potentiometric-voltmeter. This type of meter was the standard field meter for corrosion personal up until the mid 1970s. An internal battery in this meter applies a voltage with opposite polarity to that being measured. The applied voltage is adjusted to exactly balance the potential being measured. The applied battery voltage is then read. With no current flowing through the circuit, there is no IR drop. This type of meter will cost significantly more than a general purpose digital meter so it is easy to understand why they are not as widely used.

The change to digital meters, while appearing to be a technical advance is, in reality, a step back for the corrosion industry.   Potentiometric-voltmeters had virtually eliminated errors caused by IR drop in the meter circuit. Digital multimeters have reintroduced this error when measuring potential in high resistivity electrolytes. Measurement circuit IR drop errors always result in a lower apparent potential reading. This can result in unnecessary and costly up-grades and/or replacements of CP systems. It is possible to convert a voltmeter to a potentiometric-voltmeter with the addition of a simple inexpensive converter. Two such approaches are shown. Figure 2 shows a circuit using one meter which requires

that the potential read on the meter be reversed to give the actual potential. Figure 3 shows a circuit requiring two meters; on this circuit, the potential can be read directly. These are basic conceptual circuits; it may be necessary to adjust the values of some components to suit particular circumstances.

Another way of making measurements in high resistance circuits is to use either a meter that has variable input resistance or two meters with different input resistances[3]. If the reading changes when the input resistance is changed, there is IR drop error present in the readings. The resistance of the external circuit can be calculated using equation (1). When the resistance of the external circuit is known, a correction factor can be calculated using equation (2).

<u>**Equation 1:**</u> **External Circuit Resistance**

$$v_1 \times ((r_1 + R)/ r_1) = v_2 \times ((r_2 + R)/ r_2) \tag{1}$$

$v_1 =$ potential reading 1
$r_1 =$ meter resistance 1
$v_2 =$ potential reading 2
$r_2 =$ meter resistance 2
$R =$ external circuit resistance

<u>**Equation 2:**</u> **Correction Factor**

$$(r + R)/ r = C \tag{2}$$

$r =$ meter resistance
$R =$ external circuit resistance
$C =$ correction factor

Data Loggers and Remote Monitoring Units

The use of data loggers and remote monitoring units (RMUs) has increased greatly in the last few years. Special precautions should be taken when using these units with reference electrodes. As pointed out earlier, when a reference electrode is connected to a structure, a current flows through this circuit. The amount of current is inversely proportional to the circuit impedance. This current causes the reference to polarize, i.e. shift potential, and the amount of shift is proportional to the amount of current flowing. If the shift is small, or of short duration, the reference will usually recover. When the shift is large and/or of long duration, the reference may not recover. Silver/silver chloride references tend to be much more susceptible to polarization than copper/copper sulfate references because their elements are usually smaller. The resultant higher current density on the Ag/AgCl element can damage or destroy it.

Most modern potential measuring devices have an input impedance of at least 10 mega-ohms in order to minimize IR drop error due to current flowing through the circuit; 100 mega-ohm inputs are quite common. These high input impedances are used during the measurement cycle to minimize errors from voltage drops in the measuring circuit while the measurement is actually being made. When the unit is in stand-by or off mode, the impedance may be significantly lower (sometimes only a couple thousand ohms) depending upon the individual components used and the overall circuitry. A drop in impedance

during stand-by or off mode will not affect many transducers but a reference electrode will polarize if this occurs. If a data logger or RMU is to be used with reference electrodes, the input impedance must be a minimum of 10 mega-ohms at all times including during active measurements, standing by between measurements, shut down with power connected or shut down with power disconnected.

Testing for changes in input impedance of a data logger or RMU as it goes through its cycles is relatively simple. A 1 ½ volt battery is connected to the input terminals through a 10 mega-ohm resistor (see Figure 3). The voltage across this resistor is monitored with a portable voltmeter as the unit is put through its cycles. This voltage should be about 0.15 volts for units claiming a 100 mega-ohm input impedance during measurements. If the measured voltage increases to greater than ¾ volt during standby or off cycles, then the unit is capable of damaging a reference electrode connected to it and should not be used. Many RMUs have multiple independent input channels. Each channel must be separately tested through all operating modes to be assured that all of the channels are suitable for reference electrodes.

REFERENCE ELECTRODES

Another major source of errors in potential readings can occur with the improper use or misunderstanding of the reference electrode and how it works. These errors, including those caused by temperature, light, contact resistance and poor maintenance, have been documented elsewhere but will be summarized here[4]. Readings made with a portable reference electrode are more likely to have these errors than are readings made with a permanently installed reference which is normally installed out of harm's way.

Temperature

Reference electrodes are temperature sensitive. $Cu/CuSO_4$ reference electrodes have a temperature coefficient of about 1/2 mV / degree F which can have a significant effect on the measurements.   For example, assume that a portable reference electrode was used to measure a potential of -860mV on a pipe on a day when the temperature is 90F. If the same measurement was to be repeated on a day when the temperature was 40F, the 50F temperature difference would cause a 25 mV shift in the potential of the reference electrode. In this case the pipe would appear to be at -835 mV. The correction is a simple arithmetic adjustment of all readings to a standard temperature; however, today there is no consensus on what standard temperature to use. Very often, an apparent seasonal variation in structure potential is nothing more than the effect of temperature on the portable reference used for the readings.

Light

$Cu/CuSO_4$ reference electrodes are photosensitive. Since many commercial reference electrodes used in the field have clear windows in them, this can cause a real problem in making measurements. In full daylight, shifts of more than 50 mV have been observed. To avoid this problem one should cover the clear window on the portable electrode with tape.

Contact Resistance

Contact resistance between the reference and the soil can be extremely high. If the reference contact end is placed on dry soil, rock or gravel there can be an open circuit. A common practice in many hot and dry areas is to pour water on the ground where there is relatively fine soil and place the reference electrode in this moistened area to make the reading. However, this may not always solve the problem. If the dry soil extends more than a couple of inches below the surface where the measurement is being made, a layer of high resistance soil between the reference and the structure can cause errors in the measurements. There is no practical way to lower the resistance of deeper soil. The only way to be sure to eliminate this error is by using either a potentiometric voltmeter or a variable input resistance meter and then calculating the actual reading.

Maintenance

Portable, liquid filled, reference electrodes must be cleaned and refilled regularly. The copper sulfate solution contains dissolved oxygen. Oxygen gradually reacts with the copper to form copper oxide which shifts the potential of the reference. The more copper oxide the greater the shift. Potential shifts of up to 10 mV in a week's time are possible. This problem can be prevented by cleaning and refilling the reference electrode regularly (preferably weekly but at least monthly). The newer gelled filled portable reference electrodes do not have this problem since the element and gel have minimal contact with the atmosphere.

Another problem occurs on reference electrodes that have a ceramic tip. The insulating tip is porous so that the copper sulfate solution will leak through and allow conductance. If the tip dries out, the holes can become partially plugged with copper sulfate salt which increases the electrical resistance through the reference. The process is progressive, with the resistance increasing a bit more with each dry-down until, eventually, the tip becomes fully insulating (totally resistive). Boiling the ceramic tip in distilled water for an hour or two will restore it. A similar problem to this occurs when the ceramic tip becomes plugged with either dirt or oil. When this happens, the ceramic tip should be replaced.

CONCLUSION

Common sources of error in potential measurements include measurement circuit IR drop, external IR drop, and problems with the reference electrode. Corrosion control practitioners should understand the possible sources of these errors and use this understanding to reduce them as much as practical.

Standard digital multimeters with a 10 meg-ohm input impedance are not suitable for making error-free measurements in high resistivity electrolytes such as dry soil or concrete. In these applications, one should use either a very high input impedance meter designed for corrosion measurements or a potentiometric voltmeter.

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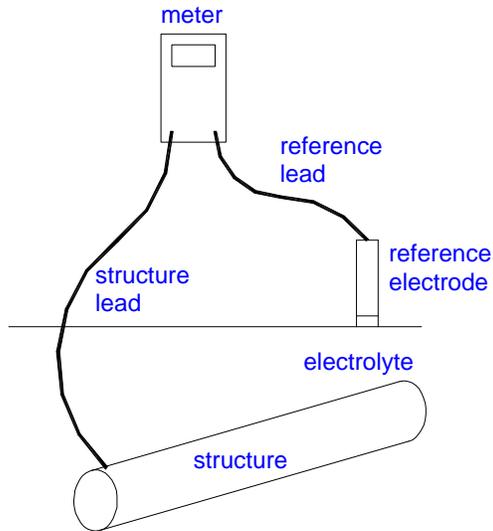4. F. J. Ansuini, J. R. Dimond, Materials Performance 33, 11(1994): p.14-17.

meter

reference lead

reference electrode

structure lead

electrolyte

structure

Figure 1a - Physical model of a potential measuring circuit.

meter

structure lead

reference lead

i

structure
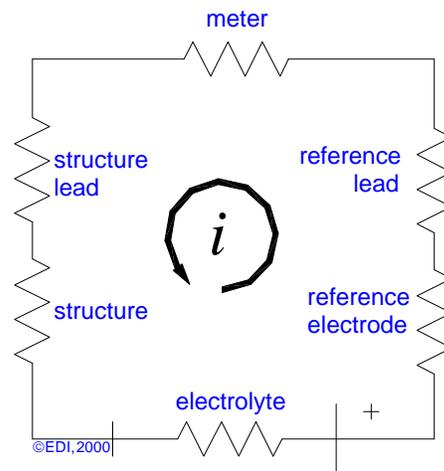
reference electrode
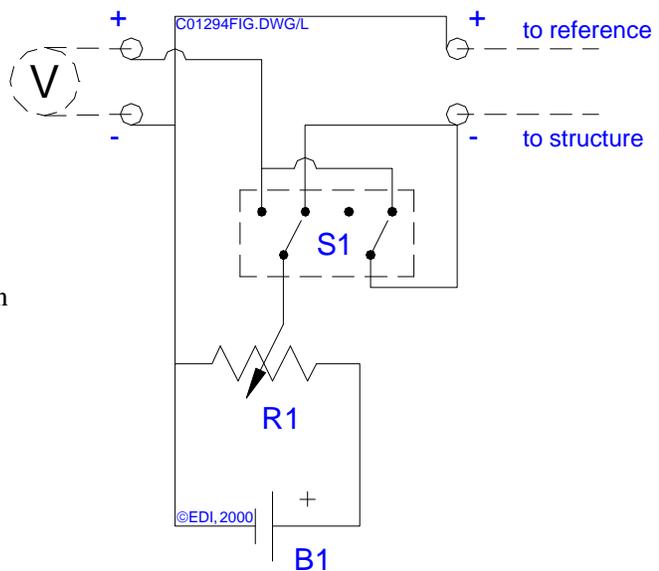
electrolyte

+

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Figure 1b - Electrical model of a potential measuring circuit. The potential difference between the reference electrode and the structure is the driving force for the current flowing in the circuit.

B1 - 3 volt battery
R1 - 100k, 5 turn potentiometer
S1 - DPDT switch
V - voltmeter

Figure 2 - Schematic of single meter potentiometric voltmeter converter. Adjust potentiometer until meter reads zero. Change switch to opposite position to read potential. Potential shown on meter will have the opposite sign of the actual potential.

+   **+**   to reference

V

-   **-**   to structure

C01294FIG.DWG/L

S1

R1

+

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B1

01294/9

B1 - 3 volt battery
R1 - 100k, 5 turn potentiometer
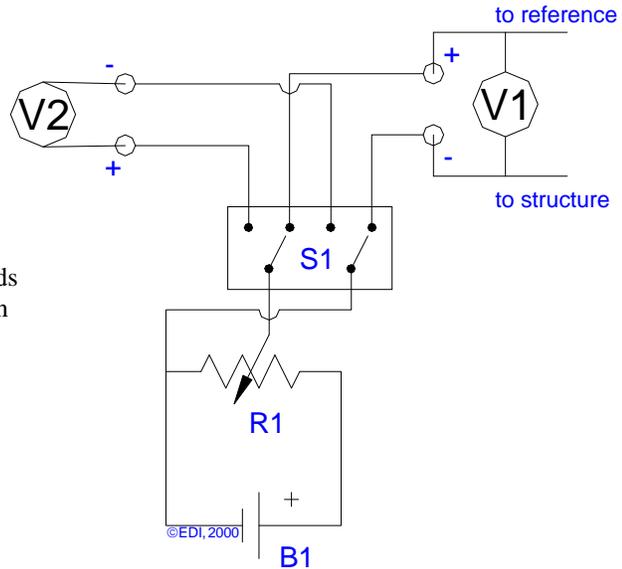S1 - DPDT switch
V1 - voltmeter
V2 - voltmeter

Figure 3 - Schematic of two meter potentiometric voltmeter converter. Adjust potentiometer until meter V1 reads zero. Change switch to opposite position to read potential. Potential shown on meter V2 will have the same sign of the actual potential.
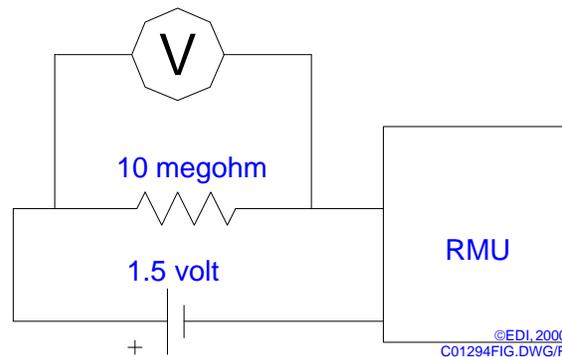
Figure 4 - Test setup for determining changes in input impedance of a data logger or RMU as it goes through its cycles. A 1 1/2 volt battery is connected to the input terminals through a 10 meg-ohm resistor. The voltage across this resistor is monitored with a portable voltmeter as the unit is put through its cycles. If the measured voltage exceeds 3/4 volts at any time, the unit may not be suitable for use with reference electrodes.