EXPERIMENT 11
THE POTENTIOMETER

I. THEORY

The purpose of this experiment is to measure the electromotive force (emf) and internal resistance of a dry cell.

The terminal voltage of a cell is the potential difference between its terminals. The emf of a cell may be defined as the terminal voltage of the cell when not under load, that is, delivering no current.

When the terminal voltage of a cell is measured as a function of current, it is found that the terminal voltage V decreases in an approximately linear manner as the current increases, as described by the equation

$$V = \varepsilon - Ir \qquad\qquad (1)$$

in which r is the internal resistance. The internal resistance may thus be defined as the negative of the slope of a graph of terminal voltage versus current.

As a dry cell ages or becomes "discharged" due to use, its emf declines somewhat and its internal resistance increases greatly. Thus, the condition of a dry cell may be determined by measuring its internal resistance.

We expect from equation (1) that the graph of terminal voltage versus current will be linear. In this experiment, however we will probably observe some curvature in the graph, due to the fact that as current increases the temperature of the cell increases, making the ions more mobile within the cell, thus decreasing the internal resistance.

We will find that the terminal voltage changes only a rather small amount with the moderate currents that we will use. In order to plot a meaningful graph of terminal voltage versus current, we must measure terminal voltage with some precision. This is done with the potentiometer.

Like the Wheatstone Bridge, the potentiometer exists in both slide-wire and box forms. The box form is more accurate and readily portable, but we will use the slide-wire form in this experiment, so that the function of each component can easily be seen and understood.

In the general schematic diagram in section IV, AB is a length of uniform wire eleven meters long. The battery 1, called the working battery, maintains a constant current I from A to B. The resistor R_1 controls the amount of current in the wire, and the switch S_1 prevents the working battery from running down when the potentiometer is not actually being used.

Points C and D are movable points on the wire: C can be moved rapidly for coarse adjustment of the potentiometer, and D can be moved slowly for fine adjustment. The potentiometer is said to be balanced when points C and D have been found so that there is no current through the galvanometer G.

When $I_G = 0$, there is no voltage drop across the resistance r_G of the galvanometer, or across the internal resistance r_2 of the test cell. Applying Kirchhoff's Second Rule to the lower loop of the diagram we have

$$-IR_{CD} + \varepsilon_2 = 0 \quad \text{or} \quad \varepsilon_2 = IR_{CD} \tag{2}$$

in which R_{CD} is the resistance of the section of wire between points C and D. Let the length of this section be L_2.

We now replace the test cell ε_2 by a standard cell ε_S, whose emf is known very precisely, and balance the potentiometer again. In general, points C and D will change to points C' and D', which we will say are a distance L_S apart. Applying Kirchhoff's Second Law to the lower loop in this case we obtain

$$-IR_{C'D'} + \varepsilon_S = 0 \quad \text{or} \quad \varepsilon_S = IR_{C'D'} \tag{3}$$

The current I is the same in equations (2) and (3). This may be proven by applying Kirchhoff's Second Rule to the upper loop, and remembering that $I_G = 0$, in each case.

Dividing equation (2) by equation (3), we obtain

$$\varepsilon_2/\varepsilon_S = R_{CD}/R_{C'D'} \tag{4}$$

Since we are dealing with two parts of a single uniform wire, we can replace the ratio of resistances by the ratio of lengths. Then equation (4) becomes

$$\varepsilon_2/\varepsilon_S = L_2/L_S \quad \text{or} \quad \varepsilon_2 = \varepsilon_S L_2/L_S \tag{5}$$

Thus, an unknown emf may be calculated from a known standard emf by measuring two lengths of the wire.

The detailed schematic diagram in section IV shows the eleven-meter wire extending from socket 10 to socket 0, and finally to a binding post at -1. Each section is one meter long. The coarse adjustment at C is accomplished by moving a traveling plug from one socket to another, as needed. The fine adjustment at D is accomplished by moving a slider between socket 0 (0 cm) and the binding post at -1 (100 cm). The lengths L_2 and L_S are obtained by adding the integral number of meters at C to the fraction of a meter at D. The three-button galvanometer contains the three components G, S_G, and r_G. Pressing different buttons of the galvanometer varies the internal resistance, and thus the sensitivity, of the galvanometer.

Also shown in the detailed diagram are an ammeter AM and a resistor R_3. These are shown connected to the potentiometer with dashed lines because they are used only in that part of the experiment in which the test cell is under load, that is, delivering current. In this case, there will be a current I_2 through the ammeter and in the load resistance, but NOT through the galvanometer, when the potentiometer is balanced. Let C" and D" be the adjustment points at which balance occurs. Applying Kirchhoff's Second Rule to the lower loop, we obtain

$$-IR_{C"D"} - I_2r_2 + \varepsilon_2 = 0 \quad \text{or} \quad \varepsilon_2 - I_2r_2 = IR_{C"D"} \qquad (6)$$

From equation (1), we see that the left side of the second form of this equation is just the terminal voltage V_2 of the test cell under load. Thus, we have

$$V_2 = IR_{C"D"} \qquad (7)$$

Dividing equation (7) by equation (3), we obtain

$$V_2/\varepsilon_S = R_{C"D"}/R_{C'D'} \qquad (8)$$

Again, we have the ratio of two resistances, which may be replaced by the ratio of two lengths. Then we obtain

$$V_2/\varepsilon_S = L_{2'}/L_S \quad \text{or} \quad V_2 = \varepsilon_S L_{2'}/L_S \qquad (9)$$

in which $L_{2'}$ is the length of wire measured with the test cell under load and the potentiometer balanced.

For maximum precision, all of the measured lengths should be as long as possible, without changing the current I. We achieve this by choosing the points C and D so as to include almost the entire eleven meters of wire when measuring the highest voltage. The resistor R_1 is adjusted to accomplish this.

The working battery must, of course have an emf higher than any of the voltages to be measured. As shown in the detailed diagram, the working battery is actually two 1.5 V cells in series.

II. LABORATORY PROCEDURE

1. Refer to the detailed diagram in section IV. Clean the terminals of the knife switch with a piece of emery cloth. Connect one terminal of the knife-switch to the binding post at point -1. Connect the other terminal of the switch to the negative terminal of one of the small 1.5 V cells. Connect the positive terminal of that cell to the negative terminal of the other small cell. Se the 3-dial resistance box to zero and connect it to the positive terminal of the second cell. Connect the other terminal of the box to the fixed binding post at socket 10. This completes the upper loop of the diagram.

2. Connect either terminal of the three-button galvanometer to the long steel bar. Connect the other terminal of the galvanometer to the negative terminal of the large square 1.5 V-cell, which is the test cell. Connect the positive terminal of the test cell to the central binding post. Finally, connect the traveling plug to the same central binding post, and place the traveling plug in socket 9. ***Do not include the ammeter or the load resistor R_3 at this time.*** This completes the lower loop of the circuit.

3. Place the slider at about the 50 cm position. Close S_1. Hold one end of the slider down, and momentarily depress the left button of the galvanometer, observing the direction of the deflection of the needle. Now increase the resistance of the 3-dial box and repeat the procedure. Continue this process until the galvanometer deflection is reduced to a minimum. DO NOT CHANGE THIS RESISTANCE DURING THE REMAINDER OF THE EXPERIMENT.

4. Adjust the position of the slider until no deflection of the galvanometer is observed when the left button of the galvanometer is depressed. Repeat for the middle and right buttons. The potentiometer is now balanced. Record the length L_2, which is the sum of the integral number of meters determined by the position of the traveling plug and the fraction of a meter determined by the position of the slider. Estimate the slider position to the nearest mm (0.001 m).

5. Use the Resistor Color Code in the introductory section of this manual to identify the 100-Ω resistor on the board of resistors. Connect one terminal of the 100-Ω resistor on the resistor board to the negative terminal of the 1.5 V test cell, while leaving the cell connected to the potentiometer. Connect the other terminal of the resistor to the 0.1 A terminal of the ammeter. Connect the positive terminal of the ammeter to the positive terminal of the test cell. Compare your circuit to the detailed diagram in section IV. Balance the potentiometer by moving the slider to the left, NOT by changing the 3-dial resistance box. Record the current I_2, the length $L_{2'}$, and the load resistance R_3.

6. Change to the 1.0 A range of the ammeter. Replace the 100-Ω load resistor by the 22-Ω resistor from the same resistor board. If the current is less than 0.1 A, switch back to that range. Balance the potentiometer by again moving the slider to the left. If balance is not attained by the time the slider reaches 0 cm, move the traveling plug to the next lower position. Again record the current, the length, and the load resistance.

7. Repeat step 6 using the 10-, 5-, and 2- Ω ceramic resistors individually. Use the 1.0 A range of the ammeter.

8. Remove the ammeter and the load resistor from the circuit. Replace the test cell with the standard cell, maintaining correct polarity. Balance the potentiometer and record the length L_S. The standard cell voltage is supplied by the instructor. Return the standard cell to its special box. Remove the traveling plug from the potentiometer.
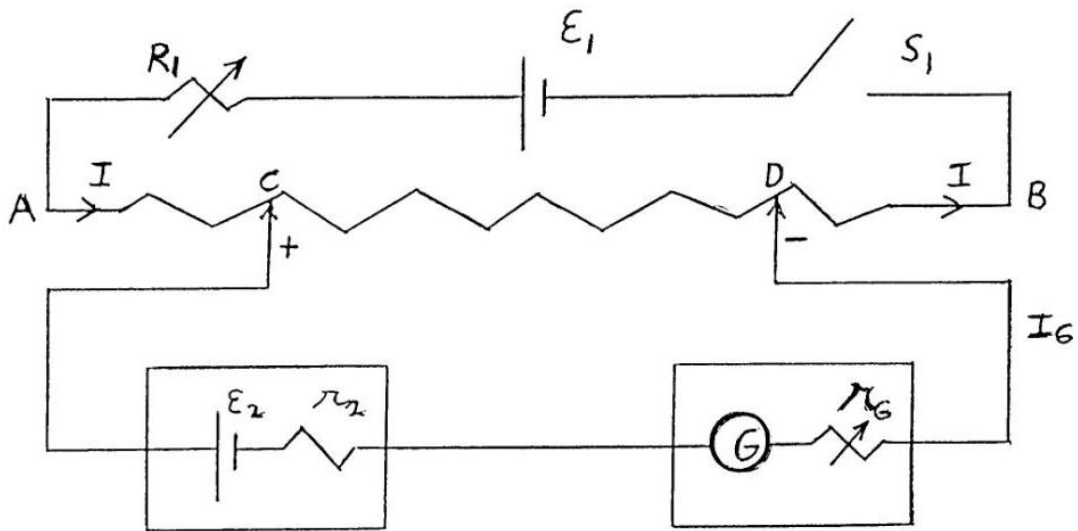
III. CALCULATIONS

Remember to use correct significant figures in your calculations below.

1. Calculate the emf of the test cell.

2. Calculate the terminal voltage of the test cell for each of the load resistors. Make a table containing the quantities Load Resistance, Length ($L_{2'}$), Terminal Voltage and Ammeter Current.

3. Plot a graph of the terminal voltage versus supplied current. Include the measured emf at zero current. The range of measured voltage should cover most of the vertical axis, so zero volts should NOT be on the graph. Use a straightedge to draw in the straight line which best fits the plotted points.

4. Calculate the slope of the graph by using the Method of Least Squares. Include the point at zero current as one of the data points, making six data points in all. Include a calculator or computer printout, or list the four sums of page I-8 of this manual.

5. What is the internal resistance of the test cell, in ohms?

6. Suppose that the terminals of the test cell were connected together by a wire of zero resistance.
    (a) Find the terminal voltage of the cell by applying Ohm's Law to the wire.
    (b) Find the short-circuit current I_{SC} by applying Kirchhoff's Loop Rule. This procedure is not actually recommended for a cell, but the calculation provides an upper limit to the current which the cell can deliver to any external circuit.

IV. DIAGRAMS

General Schematic Diagram

Detailed Schematic Diagram