MEASUREMENTS ON METAL AND OXIDE THERMOCOUPLES

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PREFACE

The ability of two dissimilar metals to produce an electric current when there is a temperature differential existing between the two junctions has long been known. Various experiments have been performed to measure the electromotive force produced with different metals at different temperature differentials, but the results as reported by different experimenters have varied appreciably. One source of error is quite likely in the instrumentation techniques used by the various experimenters.

The objective of this thesis is to present the reader with optional methods of measurements on thermocouples and to list the advantages, disadvantages and errors to be expected with each method. A method of measuring high-impedance thermocouples is proposed in which vacuum tubes are used. Circuit design procedures are also outlined. The author hopes that the instrumentation procedures outlined in this thesis will assist experimenters in making accurate and reproducible measurements on thermocouples.

ACKNOWLEDGMENT

The author wishes to express his most sincere appreciation to Professor Paul A. McCollum for his guidance and personal interest in the preparation of this thesis. He also wishes to extend thanks to Dr. Attie L. Betts for stimulating the author's interest in thermocouples. The author also wishes to express his appreciation to Professor A. Naeter for making possible the writing of this thesis.

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CHAPTER I

INTRODUCTION

The problem of obtaining electrical power to satisfy the needs of many of the complex machines (such as missiles or rockets) now being produced with their varied requirements has caused research and engineering staffs to turn from conventional power sources to those types which might be termed unconventional. Some of the properties these unconventional power supplies should have are (1) ruggedness, the ability to stand extreme shock without damage; (2) simplicity and a minimum of moving parts; (3) reliability, *i.e.*, the ability to produce power instantly when needed, regardless of the length of time from fabrication to use; (4) noiselessness, *i.e.*, very little audible noise, and no radio frequency noise. It would also be very desirable if waste or by-product energy could be utilized in producing electrical power. A device which could convert heat or light directly to electrical energy with a very high efficiency would be an ideal solution to the problem.

Thermoelectric generators, or thermopiles, apparently fulfill all of the above requirements with the present exception of high efficiency. Relatively little serious work has been done on thermocouples as power sources since 1890, although thermocouples as temperature measuring devices have reached a high degree of development. Since thermoelectric generators have the ability to utilize heat from such sources as waste factory heat, heat from the sun, and jet aircraft or rocket exhausts, they could convert energy which is now lost to usable electric power at low cost. In many applications, it is desirable to have sources of power available which may lie dormant for long periods of time, and then with little or no preparation must be instantly available for use. The inherent nature of a thermocouple meets this requirement very well, especially in applications such as missiles which require an inexpensive, rugged, and dependable source of power and are light weight. The missiles have waste heat available to provide the source of energy for the generator.

Although more promising efficiencies have been obtained from other phenomena, such as the photovoltaic effects,[1] it is believed that a direct-conversion device utilized in converting directly from heat to electric power will have a greater number of applications. There are several phenomena which convert heat energy to electrical energy. These have been observed by various scientists through the ages. One of these is the pyroelectric effect. The pyroelectric effect showed promise and was investigated in some detail, but the extremely high internal resistivity in relation to the internal electromotive force ruled out its use as a power source.

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[1] D. M. Chapin and D. E. Thomas, "Solar Battery Powers Transmitter," Radio-Electronics, p. 76

It is the object of this thesis to review and develop various instrumentation techniques to be used in making performance measurements on both low and high impedance thermocouples. Most practical applications of electrical power sources require a low internal impedance, but since the advent of low current loads such as transistors it is conceivable that higher impedance thermocouples, made from oxides or allied materials, may have greater application in the future. Oxide thermocouples do have one advantage over metal types in that, in general, oxides can be selected which will produce a much higher electromotive force than the best known metal types.

In order to evaluate thermocouple materials, with their potentiolities as practical power sources in mind, it is necessary to be able to measure electromotive force, power, and efficiency. This thesis will discuss various techniques of measurement and will offer comments on the accuracy to be expected when applied to different types of sample materials. Methods of thermocouple and furnace construction will also be discussed. It is hoped that use of the instrumentation techniques outlined in this thesis will lead to a more direct route to the solution of the problem of developing a practical thermoelectric generator.

CHAPTER II

BACKGROUND THEORY

The Seebeck Effect

In the year 1826, Seebeck[1] discovered that when two dissimilar metals were joined and a temperature differential established between the two junctions, a current would flow in the circuit. As a result of his experiments, Seebeck was able to arrange thirty-five metals in an order such that if the hot junction of a thermocouple was made of two of the metals, current would flow from the one of higher order to that of lower order. The list accumulated by Seebeck in descending order is Bi, Ni, Co, Pd, Pt, U, Cu, Mn, Ti, Hg, Pb, Sn, Cr, Mo, Rh, Ir, Au, Ag, Zn, W, Cd, Fe, As, Sb, Te and several commercial metals which were available at that time. The order of metals as observed by Seebeck does not coincide in all cases with observations made by other scientists. This is to be expected when it is realized that the samples were undoubtedly not of the same degree of purity, and in many cases with unequal temperature differentials or unequal cold-junction temperatures.

The Peltier Effect

Peltier,[2] in the year 1834, discovered a complementary phenomenon to Seebeck's, that when a current is forced

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[1] T. J. Seebeck, Phogg. Ann., Bd. VI, (1826).

[2] A. Peltier, Ann.d. Chim.et de Phys. 2 series, 56, (1834).

through a circuit composed of two dissimilar metals, one of the junctions tends to become colder, while the other becomes warmer. The amount of heat released or absorbed will depend on the metals used, the current flowing across the boundary (i.e., the charge), and upon the absolute temperature of each of the junctions. The Peltier effect is a reversible effect; i.e., if the two junctions are at a dissimilar temperature, current will tend to flow in the circuit and heat will be absorbed at the junction with the higher temperature while heat will be released at the junction with the lower temperature. The amount of current flowing will be proportional to the difference of temperature between the two junctions and to the absolute temperature of each junction. The Peltier heat must be carefully differentiated from the Joule heat in the circuit which is an irreversable process and contributes heat to both junctions. The Peltier effect, if used in a forward sense, may be used as a source of power, or inversely may be used for refrigeration or heating applications.

The Thomson Effect

Sir William Thomson (later Lord Kelvin), reported in 1857 to the Royal Society of Edinburg on a finding in thermoelectricity which has been called the Thomson effect. Thomson, in attempting to verify Peltier's discovery, noted that more heat was absorbed at the hot junction than was expelled at the cold junction. In accounting for the losses in the circuit, Thomson theorized that there must be another reversible effect taking place. As the Peltier effect occurred at the boundaries of the two conductors, Thomson proposed that the reversible thermoelectric effect must take place in the individual conductors, and must be due to the finite temperature differential along the length of each homogeneous conductor.[3] The specific heats of electricity in the different metals were designated σ_1 , σ_2 , σ_3 , etc., and as the electromotive force is dependent upon the temperature differentials through the conductor, the following equation for the electromotive force in a conductor with its extremes at different temperatures was evolved.

$$F = \int_{T_1}^{T_2} \frac{\sigma}{t}\, dt. \qquad (1)$$

Referring to Figure 1, both the Peltier and Thomson effects may be shown to contribute to the total electromotive force in the circuit.

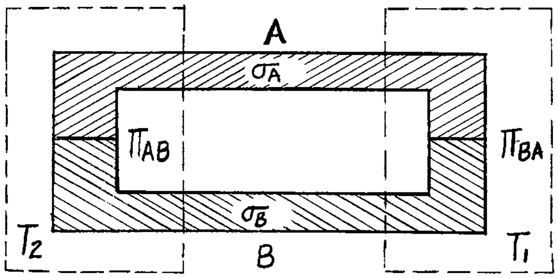

Figure 1. The Thomson and Peltier Effects in Relation to the Closed Circuit Electromotive Force.

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[3] Sir William Thomson, "On the Dynamical Theory of Heat," *Transactions of the Royal Society of Edinberg* 21, (1857), p. 133.

As applied in Figure 1, Π is the Peltier electromotive force and σ, the Thomson coefficient, is the specific heat of electricity.

$$F_T = \Pi_{AB}\Big]^{T_2} + \int_{T_2}^{T_1} \frac{\sigma_B}{t}\,dt. + \Pi_{BA}\Big]^{T_1} + \int_{T_1}^{T_2} \frac{\sigma_A}{t}\,dt \qquad (2)$$

$$F_T = \Pi_{AB}\Big]^{T_2} + \Pi_{BA}\Big]^{T_1} + \int_{T_1}^{T_2} \frac{(\sigma_A - \sigma_B)}{t}\,dt. \qquad (3)$$

Therefore, the total electromotive force is the algebraic sum of all circuit forces, which may not all be of the same sign. To illustrate an example of the effect of inserting a third conductor and three temperature differentials in the circuit, reference is made to Figure 2.

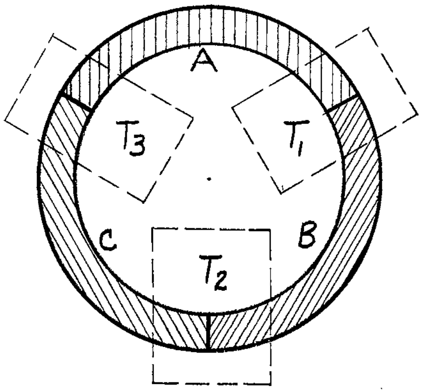

Figure 2. The Effect of 3 Conductors and 3 Temperature Differentials.

The total electromotive force in the circuit of Figure 2 is given in equation (4).

$$F_T = \Pi_{BA}\Big]^{T_1} + \int_{T_1}^{T_3} \frac{\sigma_A}{t}\,dt + \Pi_{AC}\Big]^{T_3} + \int_{T_3}^{T_2} \frac{\sigma_C}{t}\,dt + \Pi_{CB}\Big]^{T_2} + \int_{T_2}^{T_1} \frac{\sigma_B}{t}\,dt \qquad (4)$$

Contact Potential

Contact potential, often referred to as the Volta effect,[4] is due to the difference in work functions of two conductors joined at only one point. The work function of a metal is defined as the cohesive force the conductor exerts on an electron to prevent its crossing the boundary of the conductor. Referring to Figure 3, the contact potential will be equal to the voltage from point C to point F which is called V_{CF}.

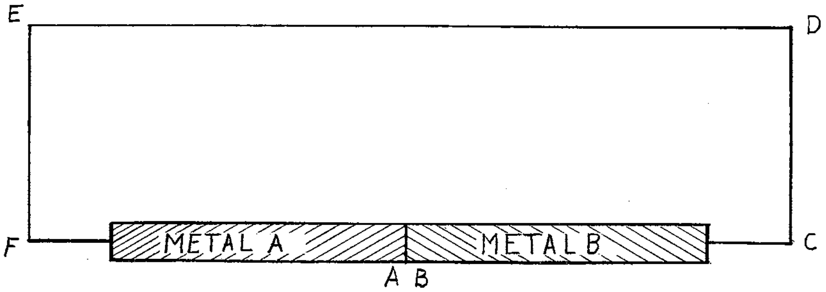

Figure 3. A Circuit to Show that Contact Potential Exists Between two Dissimilar Metals in Contact at One Point.

If current is flowing, there will be a Peltier difference of potential between points A and B which is designated as V_{AB}. Proceeding around the circuit along the path CBAFEDC, the total electromotive force in the circuit may be determined as

$$V_{CF} - \frac{\phi_B}{e} + \frac{\phi_A}{e} \pm \Pi_{AB} = 0, \quad (5)$$

or

$$V_{CF} = \frac{\phi_B - \phi_A}{e} \mp \Pi_{AB}. \quad (6)$$

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[4] Norman E. Gilbert, Electricity and Magnetism, p. 507.

If the Peltier electromotive force is relatively small (the usual case), the contact potential is

$$V_{CF} = \frac{\phi_A - \phi_B}{e} . \tag{7}$$

where e is the charge on the electron, and ϕ_A and ϕ_B are the work functions of the conductors used. It may be seen by a similar analysis that if a closed loop is made of the two conductors as shown in Figure 4, the resultant electromotive force of the circuit is zero if both junctions are at the same temperature.

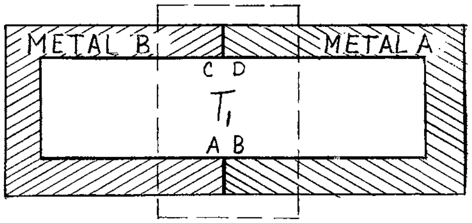

Figure 4. The Effect on Contact Potential When the Circuit has a Closed Loop.

Starting at point A, the electromotive force around the closed loop is

$$V_{AB} - \frac{\phi_A}{e} + \frac{\phi_B}{e} - \Pi_{AB} - \frac{\phi_D}{e} + \frac{\phi_C}{e} + \Pi_{DC} + V_{DC} = 0. \tag{8}$$

If $\Pi_{AB} = \Pi_{DC}$, which would be true if the temperature is uniform, and $\phi_A = \phi_C$, also $\phi_B = \phi_D$, which is true due to the same conductor boundary at A and C, and at B and D, the total electromotive force of the loop is given by equation (10).

$$V_{AB} + V_{DC} = 0 \tag{9}$$

Therefore,

$$V_{AB} = -V_{DC} = V_{CD}. \qquad (10)$$

The work function of a conductor has been shown to vary with temperature,[5] although this variation is of a very small magnitude. To determine the variation of work function, the following equation may be used

$$W = W_a - W_i \qquad (11)$$

where W is the work function in ergs, W_a is the work an electron must do against electrical and other forces while it escapes from the surface, and W_i appears as an integration in equations dealing with the Fermi distribution. W_i may be approximated very closely by the formula,

$$W_i = k\,\omega_i = \left(\frac{h^2}{2m}\right)\left[\frac{3nv^2}{4\pi G}\right]^{3/2} - \left[\frac{2m\pi k^2}{12h^2}\right]\left[\frac{3nv'}{4\pi G}\right]^{3/2} T^2 \qquad (12)$$

where k is Boltzman's constant, h is Planck's constant, m is the mass of the electron, n is the number of electrons per centimeter squared, V' is the number of free electrons per atom, usually assumed to be equal to the number of electrons in the outermost shell, and G is the statistical weight equal to 2 for electrons. To convert the work function, W, from ergs to electron volts, equation (13) may be used.

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[5] J. A. Becker, "The Thermionic Work Function and the Slope Intercept of Richardson Plots," Physical Review, Vol. 45, p. 696.

$$\phi = \frac{W}{e} = \frac{k\omega}{e} = \frac{k(\omega_a - \omega_i)}{e} \qquad (13)$$

It may be seen from equations (12) and (13) that the work function varies a relatively small amount with temperature. It has been shown to be in the order of 10^{-6} volts per degree at 1000°K.[6]

Due to the relatively small variation of contact potential with the change in temperature, it is usually not considered in the study of thermocouples. However, when vacuum tubes are employed in instrumentation with very high resistances in the grid circuit, care must be exercised to avoid errors in instrument readings.

General

On examination of the Peltier and Thomson effects and contact potential, it may be shown by using an example that the Seebeck effect is actually the algebraic sum of all the potentials in the circuit. Referring to Figure 5, and writing the voltage equation around the entire loop, it will be found that the voltage discovered by Seebeck is

$$emf = V_{AB}\Big]^{T_1} + \Pi_{AB}\Big]^{T_1} + \int_{T_1}^{T_2} \frac{\sigma_B}{t}\,dt + \int_{T_2}^{T_3} \frac{\sigma_B}{t}\,dt + V_{BA}\Big]^{T_2} + \Pi_{BA}\Big]^{T_2} + \int_{T_3}^{T_1} \frac{\sigma_A}{t}\,dt. \qquad (14)$$

Considering that temperature has little effect on contact potential,[7] equation (14) may be rewritten as follows:

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[6] *Ibid.*

[7] *Ibid.*

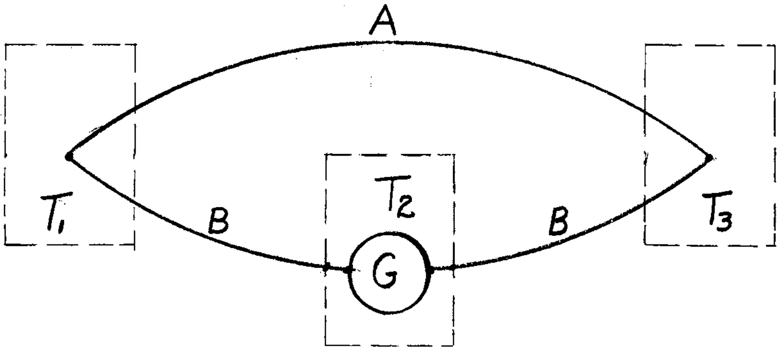

Figure 5. A Circuit to Show that the Seebeck Effect is Actually the Combination of the Thomson and Peltier Effects.

$$emf = \Pi_{AB}\Big]^{T_1} + \int_{T_1}^{T_3} \frac{\sigma_B}{t}\,dt + \Pi_{BA}\Big]^{T_3} + \int_{T_3}^{T_1} \frac{\sigma_A}{t}\,dt\,, \tag{15}$$

$$emf = \Pi_{AB}\Big]^{T_1} + \Pi_{BA}\Big]^{T_3} + \int_{T_1}^{T_3} \frac{(\sigma_B - \sigma_A)\,dt}{t}\,. \tag{16}$$

The effect as noted by Seebeck would then be the electromotive force of equation (16).

Laws Relating to Thermocouples

1. A current may not be drawn from a single homogeneous conductor even though there are temperature differentials along it's length. In order to prove this law, refer to Figure 6. On writing the voltage equation around the homogeneous conductor A, there are no boundaries between dissimilar metals, therefore the only electromotive force in the circuit will be due to the Thomson effect. Starting at point B and continuing around the circuit the electromotive force is given by equation (17).

$$emf = \int_{T_1}^{T_2} \frac{\sigma_{A_2}}{t}\,dt + \int_{T_2}^{T_1} \frac{\sigma_{A_1}}{t}\,dt = \int_{T_1}^{T_2} \frac{(\sigma_{A_2} - \sigma_{A_1})}{t}\,dt\,. \tag{17}$$

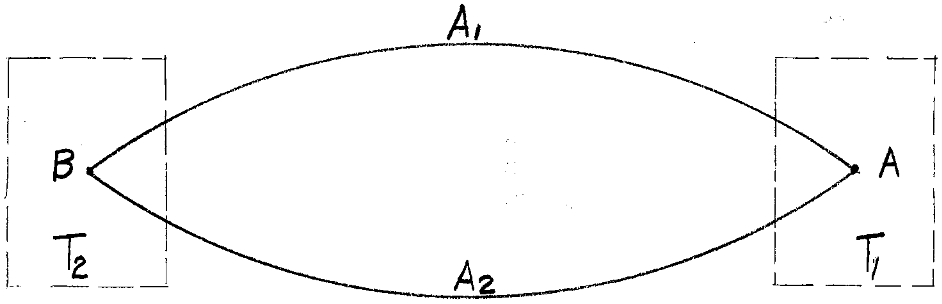

Figure 6. A Circuit Demonstrating that the Total Electromotive Force is Zero in a Single Homogeneous Conductor with Temperature Differentials.

When a homogeneous conductor is used, the Thomson coefficients, σ_{A_1} , and σ_{A_2} , are equal and the electromotive force as expressed in equation (18) will be equal to zero.

$$emf = \int_{T_1}^{T_2} \frac{(\sigma_{A_2} - \sigma_{A_1})}{t} dt = \int \frac{0}{t} dt = 0 \, . \tag{18}$$

2. A third conductor may be inserted in one of the thermocouple elements without affecting the electromotive force of the thermocouple, provided both junctions of the third conductor are at the same temperature. Figure 7 will be used in proving that this is true.

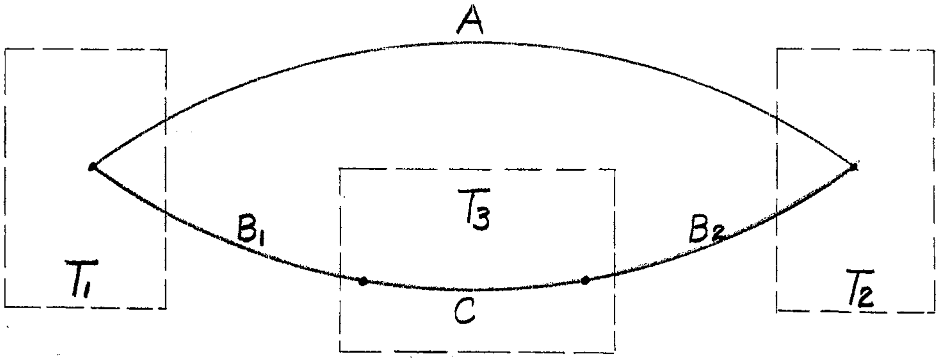

Figure 7. A Third Conductor at Constant Temperature May be Inserted and not Effect the Electromotive Force of the Thermocouple.

$$emf = \Pi_{BA}\Big]^{T_2} + \int_{T_2}^{T_1}\frac{\sigma_A}{t}\,dt + \Pi_{AB}\Big]^{T_1} + \int_{T_1}^{T_3}\frac{\sigma_{B_1}}{t}\,dt + \Pi_{B_1C}\Big]^{T_3} + \int_{T_3}^{T_3}\frac{\sigma_C}{t}\,dt + \Pi_{CB_2}\Big]^{T_3} + \int_{T_3}^{T_2}\frac{\sigma_{B_2}}{t}\,dt, \qquad (19)$$

$$emf = \Pi_{BA}\Big]^{T_2} + \int_{T_2}^{T_1}\frac{\sigma_A}{t}\,dt + \Pi_{AB}\Big]^{T_1} + \int_{T_1}^{T_2}\frac{\sigma_B}{t}\,dt, \qquad (20)$$

$$emf = \Pi_{BA}\Big]^{T_2} + \Pi_{AB}\Big]^{T_1} + \int_{T_1}^{T_2}\frac{(\sigma_B - \sigma_A)}{t}\,dt. \qquad (21)$$

Equation (21) shows that conductor C does not contribute an electromotive force to the closed loop. If, however, the two junctions of conductors B and C had been at different temperatures, equation (19) shows that the electromotive force would have been changed.

3. If a multiple-junction thermocouple (a thermopile) is connected such that the junctions are in series, the total electromotive force will be the algebraic sum of the individual thermocouple electromotive forces.

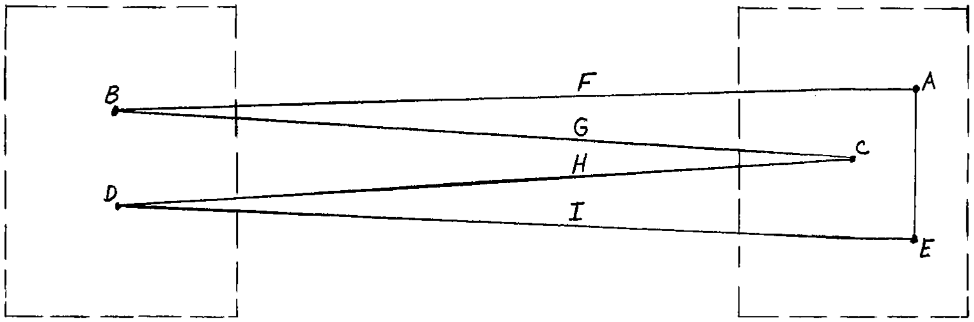

Figure 8. A Series Thermopile.

The total electromotive force of the circuit in Figure 8, starting at A and continuing around the circuit back to A, is given in equations (22) and (23).

$$emf = \int_{T_1}^{T_2} \frac{\sigma_F}{t}\,dt + \Pi_{FG} \Big]^{T_2} + \int_{T_2}^{T_1} \frac{\sigma_G}{t}\,dt + \Pi_{GH} \Big]^{T_1} + \int_{T_1}^{T_2} \frac{\sigma_H}{t}\,dt + \Pi_{HI} \Big]^{T_2} + \int_{T_2}^{T_1} \frac{\sigma_I}{t}\,dt + \Pi_{IF} \Big]^{T_1}, \tag{22}$$

$$emf = \int_{T_1}^{T_2} \frac{(\sigma_F - \sigma_G + \sigma_H - \sigma_I)}{t}\,dt + (\Pi_{FG} + \Pi_{HI}) \Big]^{T_2} + (\Pi_{GH} + \Pi_{IF}) \Big]^{T_1} . \tag{23}$$

The Thermoelectric Diagram

It has been found experimentally that an empirical equation[8] can be written to express the electromotive force of any thermocouple within a limited range of temperatures. The equation takes the form

$$\mathcal{E} = at + \tfrac{1}{2}bt^2 + \tfrac{1}{3}ct^3 . \tag{24}$$

By differentiating equation (24) with respect to the temperature, $\frac{d\mathcal{E}}{dt}$ is obtained, which is defined as the thermoelectric power of a thermocouple and has the unit of volts per degree.

$$\frac{d\mathcal{E}}{dt} = a + bt + ct^2 . \tag{25}$$

Evaluating a, b, and c in equation (25) makes it possible to draw a plot of the thermoelectric power of a thermocouple. When the thermopower of a metal is plotted and compared with that of a standard metal, a useful thermoelectric diagram is obtained. There are two standard metals that are commonly used as references: lead, which has a Thomson coefficient

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[8] Gaylord P. Harnwell, *Principles of Electricity and Electromagnetism*, p. 186.

of zero, and platinum with its ability to withstand high temperatures and corrosive effects. Figure 9 is a thermoelectric diagram showing the thermoelectric power[9] of two metals commonly used in temperature measuring thermocouples.

In order to plot the thermoelectric diagram in Figure 9. Table II was prepared which shows the values of $\frac{d\mathcal{E}}{dt}$ at several values of temperature within the range of a and b.

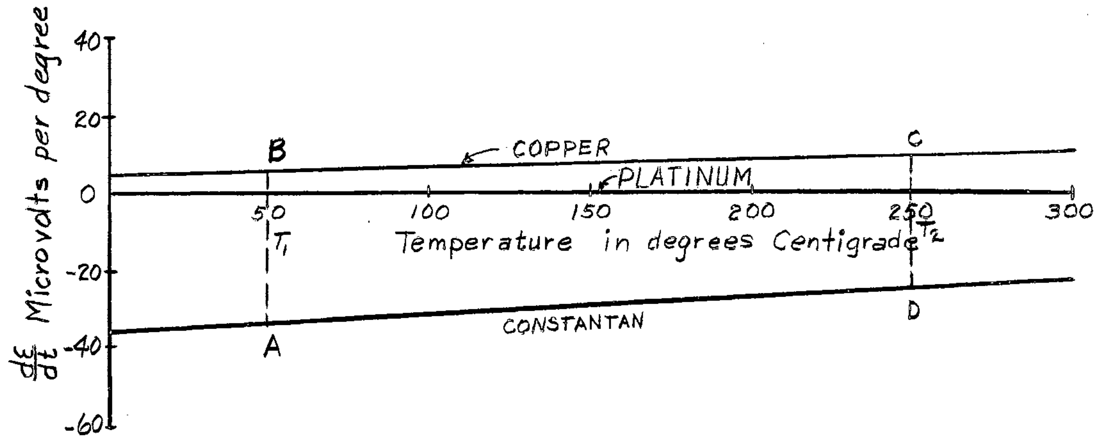

Figure 9. A Thermoelectric Diagram for Copper and Constantan.

Using Figure 9, it is possible to predict the electromotive force to be expected when a thermocouple of copper and constantan is used within the temperature range covered in Figure 9. The electromotive force of the thermocouple will be

$$e_{T_1}^{T_2} = \int_{T_1}^{T_2} \frac{d\mathcal{E}_{cu}}{dt}\,dt + \int_{T_1}^{T_2} \frac{d\mathcal{E}_{cu\text{-}Ni}}{dt}\,dt \quad . \qquad (27)$$

From Figure 9, the integral of curve BC is actually the

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[9] Thermoelectric power by common usage refers to the differential of electromotive force to the differential of temperature.

TABLE I

The Constants of Copper, and Constantan[10]

Metal	Reference Metal	Temperature Range degrees centigrade	a microvolts	b
Cu-Ni	Pt	0 to 300	36.87	4.712
Cu	Pt	0 to 900	3.13	2.460

$$\frac{d_M E_R}{dt} = a + bt\ (10^{-2}) + Ct^2\ (10^{-5})$$[11]

TABLE II

The Thermoelectric Power at Various Temperatures for Copper and Constantan[12]

Temperature degrees C	Metal	Reference Metal	$\frac{dE}{dt}$
0	Copper	Platinum	3.130
50	Copper	Platinum	4.36
100	Copper	Platinum	5.59
150	Copper	Platinum	6.82
200	Copper	Platinum	8.05
250	Copper	Platinum	9.28
300	Copper	Platinum	10.51
0	Constantan	Platinum	-36.87
50	Constantan	Platinum	-34.51
100	Constantan	Platinum	-32.17
150	Constantan	Platinum	-29.8
200	Constantan	Platinum	-27.44
250	Constantan	Platinum	-22.75

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[10] _International Critical Tables_, VI, p. 219.

[11] _Ibid_.

[12] _Ibid_.

area under the curve; therefore the area under curves BC and AD can be computed mechanically to obtain the electromotive force of the thermocouple.

$$e_{T_1}^{T_2} = t_1 BC t_2 + t_1 AD t_2 . \qquad (28)$$

CHAPTER III

METAL THERMOCOUPLE MEASUREMENTS

Construction of Thermopiles for Measurements

The main consideration to be observed in constructing a thermocouple or a multiple-junction thermopile, upon which laboratory measurements are to be taken, is to use techniques which will give reproducible results. The output of a thermopile may be influenced by several factors, notably the previous history of the metal and the amount of impurity at the junction as well as throughout the metal. It is important that oxidation and other chemical reactions at the junction be kept to a minimum.

There are three commonly used methods of joining conductors to form a thermocouple: (1) use of a carbon arc[1] to weld the ends, (2) use of an oxygen-hydrogen torch,[2] (3) use of a conducting bath covered with a substance such as oil which isolates the junction from oxygen while the welding operation is taking place. Figure 10 shows typical elements used in method 3.

Thermocouples, when constructed for power and efficiency measurements, could conveniently consist of multiple-unit "piles," called thermopiles. When measuring efficiency, it

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[1] Paul H. Dike, Thermoelectric Thermometry, P. 20.

[2] Ibid.

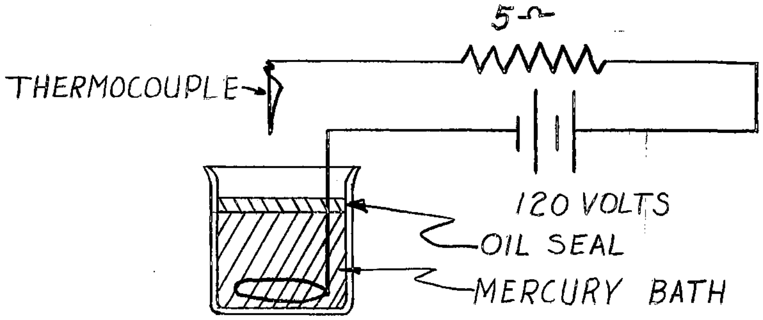

Figure 10. A Method of Welding Small Conductor Thermocouples.

is necessary to have the heat loss from the furnace low enough in relation to the heat absorbed in producing power that an accurate comparison can be made. Therefore, thermopiles will give a more accurate indication of the efficiency than will a single junction thermocouple.

Construction of a Furnace for the Thermopile

In constructing a furnace for the thermopile, the following items should be considered. The heat loss of the furnace should be as low as possible. This dictates the use of the best thermal insulation available. Geometrical design of the furnace is very important also, as it is very desirable that the elements all be at the same temperature regardless of the power drawn through the individual thermocouples. The distance from the hot to the cold junction should be as short as possible in order to keep the resistance of the thermopile as low as possible. The design proposed in Figure 11 seems to fulfill the requirements satisfactorily. The insulation used might be a commercial product, such as Kast-O-Lite,[3] which may quite readily be cast around the thermopile as indicated in Figure 11.

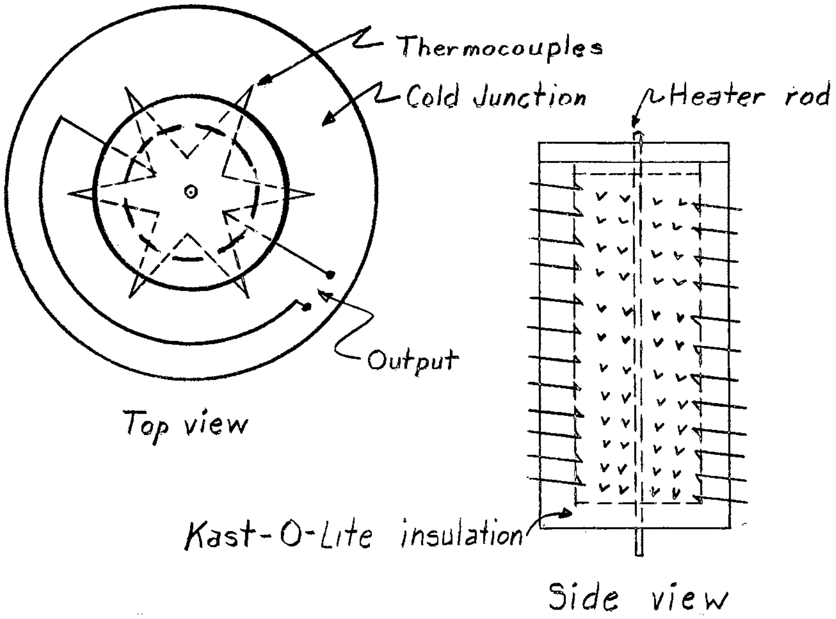

Figure 11. Construction of a Thermopile for Measurement Purposes.

The temperature measuring devices should be installed within the walls of the furnace, if a cast type furnace is to be used.

Temperature Measuring Devices

Of the temperature measuring devices available, temperature measuring thermocouples are probably the most convenient to use. A series arrangement of thermocouples used in conjunction with a calibrated temperature measuring potentiometer[4] will read the average temperature of all the

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[3] Manufactured by the A. P. Green Firebrick Company, Mexico, Missouri.

[4] A typical calibrated temperature measuring thermocouple potentiometer is the G. E. TJ-1-B8.

thermocouples used. When it is desired to determine the temperature at different locations throughout the furnace, individual thermocouples can be imbedded in the furnace and leads brought out to a multi-junction switch[5] before connecting to the potentiometer. Switches, when used with thermocouple temperature measuring devices, should be constructed such that error will not be introduced due to added junctions at the switch contacts.[6] Thermocouples used for temperature measurements should have the cold junction temperature held constant; otherwise errors will be introduced. Placing the cold junctions in ice water is recommended, for if the cold junction is maintained at room temperature, changes in the ambient room temperature will introduce errors. The potentiometers used in conjunction with the thermocuples should also be thermally compensated so that error will not be introduced due to temperature differentials within the potentiometer.

Measuring the Electromotive Force of a Thermopile

In measuring the electromotive force of a thermopile, current can not be allowed to flow if a true reading of the internal emf is to be obtained. A balancing type instrument is required, with a source of potential that is equal to the electromotive force of the thermopile. An instrument such

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[5] General Electric transfer switch 2855639 GR1 is an example of a compensated multicontact switch.

[6] Ibid.

as the potentiometer is ideal for balancing purposes when used in conjunction with a sensitive low-resistance galvanometer as a balance indicator. The potentiometer is an instrument containing a source of potential, across which a calibrated tapped resistor is inserted. Figure 12 shows a circuit diagram of the Leeds and Northrup type K-1 potentiometer.

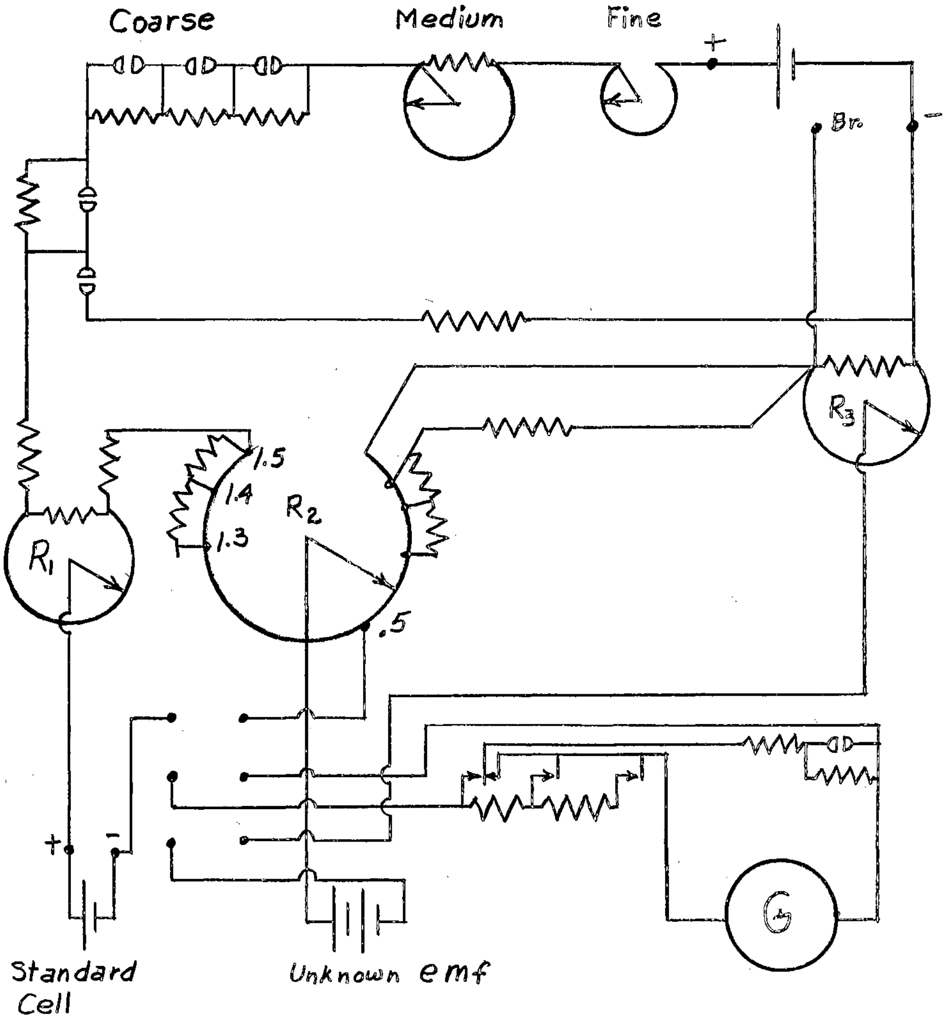

Figure 12. The Leeds and Northrup Type K-1 Potentiometer.[7]

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[7] Forest K. Harris, *Electrical Measurements*, p. 151.

The Leeds and Northrup type K-1 potentiometer is calibrated in the following way. (1) The transfer switch is thrown so that the standard cell is in the circuit. (2) The dial setting of R_1 is set to correspond to the electromotive force of the standard battery. (3) The coarse, medium, and fine calibration controls are adjusted until a zero reading on the sensing galvanometer is read. The accuracy of calibration will then depend on the standard battery, the potentiometer dial, and the resistance and sensitivity of the galvanometer.

The accuracy with which the electromotive force of a thermocouple can be read will depend on the resistance of the galvanometer and the accuracy of the potentiometer. If the resistance of the unknown circuit is 1000 ohms or less, a galvanometer with a sensitivity of the order of 5×10^{-8} ampere per millimeter and a resistance of 15 ohms can be used in conjunction with a potentiometer which will read down to 0.5×10^{-6} volts, in which case the electromotive force may be balanced to within $\pm 0.5 \times 10^{-6}$ volts. When the resistance of the thermopile becomes greater than about 10,000 ohms, it is possible to balance to within about 5×10^{-6} volts when using the same galvanometer. With the addition of a more sensitive balancing galvanometer, one whose sensitivity is 10^{-10} amperes per millimeter for example, it would be possible to balance a circuit having up to 10 megohms within $\pm 1 \times 10^{-6}$ volts. Therefore, when the resistance of the thermopile is higher, a more sensitive balancing galvanometer is required.

Another possible source of measurement error is due to thermoelectric emfs set up internally within the potentiometer instrument. Several potentiometers have been developed in which the internal thermoelectric forces are minimized. Some methods used to reduce the thermoelectric forces are to enclose the potentiometer in a cast case to reduce temperature differentials, to use metals having very low contact and thermoelectric potentials, and to make low resistance connections such that little heat will be dissipated due to the Joule heating effect. The Leeds and Northrup "Wenner" potentiometer is an example of a specially constructed thermocouple potentiometer.

Efficiency and Power Measurements of Metal Thermocouples

Since the terms efficiency and power in the thermocouple literature have been used rather loosely, they should be more completely defined. Efficiency can mean the efficiency of the thermocouple itself considering only the thermal efficiency of the thermocouple, or the overall efficiency of the system of which the thermocouple plays a part. Efficiency, when considering only the thermocouple, will be designated thermocouple efficiency, and when the system as a whole is considered it will be called thermopile efficiency.

The term thermopower has been used profusely in literature to identify the derivative of the emf produced by a thermocouple with respect to the temperature. However, in the following discussion the emf of the thermocouple will be referred to simply as emf, and the term power will mean electrical power in watts.

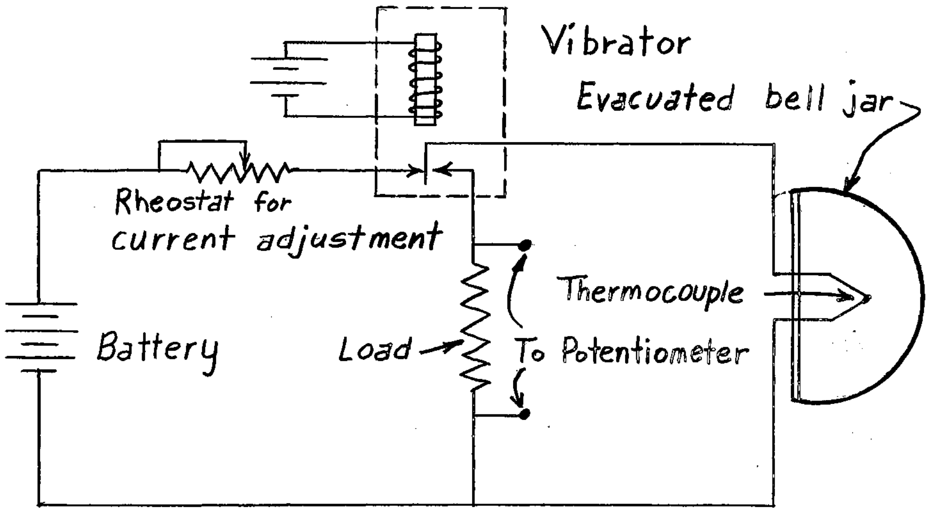

Figure 13. Efficiency and Power Measuring Circuit used at the Franklin Institute.[8]

One method of measuring the efficiency and power of a thermocouple is illustrated in Figure 13. The method in Figure 13 makes use of Joule heating at the junction as a source of heat. Incorporated in the input circuit, a voltmeter and ammeter, or a wattmeter may be used to measure input power. For output power and efficiency measurements, the voltage could be measured by using a potentiometer and the current could be computed provided the load resistance is known. From Figure 13 it may be seen that the thermocouple

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[8] The Franklin Institute, Chemical Engineering and Physics Division, "Progress Report No. 1," May 10, 1947 to August 31, 1947, Contract No. W-36-039-sc-33654, Evans Signal Laboratory, Signal Corps, U. S. Army.

power could then be calculated as

$$\text{Power out} = E_{LOAD} \times I_{LOAD} = \frac{E^2_{LOAD}}{R_{LOAD}} \quad . \tag{1}$$

The efficiency of the thermocouple would then be,

$$\%\ \text{Efficiency} = \frac{\text{Power out}}{\text{Power in}} \times 100 \quad . \tag{2}$$

When calculating the power in, the Joule heat (I^2R) produced in the leads to the thermocouple need not be taken into consideration if the instruments are connected close to the thermocouple. The measurements will be more accurate when shorter leads are used. The overall efficiency of a generator will depend upon the load resistance; therefore, several loads should be used so that a curve of load versus efficiency can be plotted to determine maximum efficiency at each temperature. The temperature of the junction can be varied by increasing or decreasing the current flow through it.

The internal resistance of the generator will change with each temperature; therefore, the maximum efficiency will not be found at the same resistance value for different temperatures. When it is desired to ascertain the value of thermocouple resistance, it may be determined by measuring the open-circuit potential which will be identical to the internal electromotive force developed, and then measuring the voltage and current under load. Equation (3) will be used in determining the thermocouple resistance.

$$R_{THERMOCOUPLE} = \frac{emf - E_{LOAD}}{I_{LOAD}} \quad . \qquad (3)$$

For maximum electrical power output, the load resistance should equal the thermocouple resistance.

Figure 14 shows a second type of power and efficiency measuring circuit. The construction of the furnace is the type shown in Figure 11.

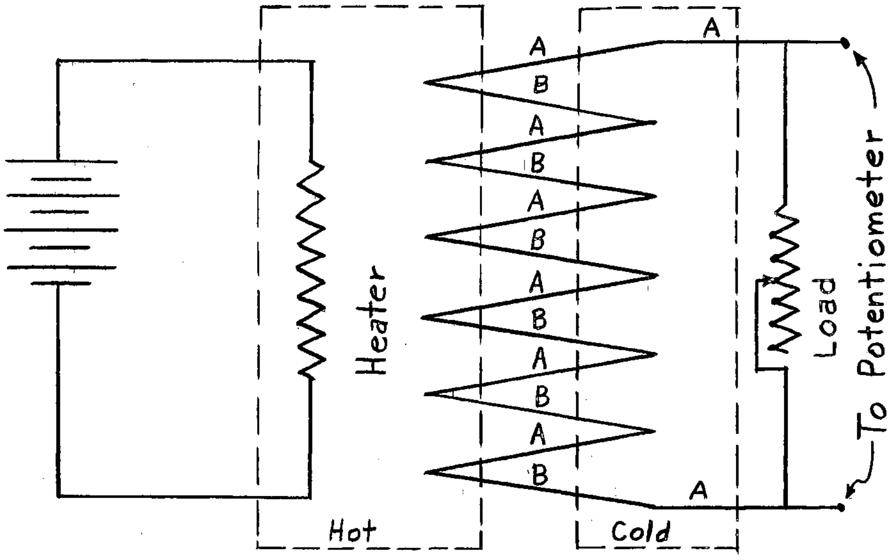

Figure 14. Thermopile Circuit for Power and Efficiency Measurements

When the overall efficiency of the system is desired, the measurements should include the power input to the heater and the power output to the various loads. The true thermopile efficiency and power may be obtained by measuring the power input necessary to obtain an equilibrium temperature in the heating box with the thermopile at open circuit, and then the power necessary to maintain the same temperature with the thermopile under load. The power necessary to supply the equivalent heat energy for the thermopile would then be the difference between the power input when the thermopile is loaded and the power input when the thermopile is under open-circuit conditions. Equations (1), (2), and (3) are equally applicable to this measuring procedure.

CHAPTER IV

OXIDE THERMOCOUPLE MEASUREMENTS

Furnace Configurations to Reduce Resistance

Measurements on oxide thermocouples, due to several inherent qualities of oxides, are very difficult. The properties causing the most serious difficulties in measuring the electromotive force of oxides are the resistivity of the oxides, the physical stability of the materials, and the physical binding of the materials. High resistance of the oxides makes the measurement of the thermoelectric force difficult and inaccurate when using a potentiometer and balancing galvanometer.[1] When measurements are attempted using conventional electrometers or vacuum-tube electrometers, leakage paths may make measurements inaccurate. To show the resistance of lead oxide at various temperatures, Table III has been prepared showing the resistance of a sample of lead oxide one centimeter long with a cross-sectional area of 0.126 square centimeters. This size was chosen as it corresponds to the size used by Bidwell[2] who has measured the thermal electromotive force of several oxides. An oxide, when heated to a high temperature may change in chemical composition such that the oxide, after one test,

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[1] See page 23.

[2] Charles C. Bidwell, "Thermal Electromotive Forces in Oxides," Physical Review, V. III, p. 204.

TABLE III

Resistance vs Temperature of Lead Oxide Samples of the Size Used by Bidwell.[3]

Oxide	Temperature degrees centigrade	A	n	Resistance ohms
PbO	384	2.59	7	821.03×10^6
PbO	572	2.67	5	8.46×10^6
PbO	787	1.22	3	$.03867 \times 10^6$

may not have the same chemical composition during subsequent tests. The physical make-up of oxides, which normally are in the form of a powder, requires that they be bound in some manner for testing purposes. The form of binding used by Bidwell and other authors has been to fuse the sample in an oxygen-hydrogen flame, or to bake the sample, which contains some binding material, in an oven. During the fusing or baking process the oxide may change in chemical composition due to the effect of the heat applied. If other methods are used, such as packing the sample in a tube, the resistance of different samples may not be the same, and in all probability the electromotive force developed will be different for each sample unless they are packed with a uniform pressure. It has been shown that the electromotive force of materials will

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[3] Computed from constants given in the International Critical Tables, p. 153.

change appreciably under the influence of tension or compression within a sample.[4]

There seems to be a definite correlation between the resistivity of a material and the thermoelectric force obtained from that material. Bidwell[5] points out that as a general rule the thermoelectric force is high where the resistance is high, both in metals and oxides.

Bidwell has measured the thermal electromotive force of several oxides using a technique of making the sample quite small. No attempt was made to keep the cold junction at any specific temperature, but to let it absorb heat from the hot junction. However, a temperature differential did exist between the junctions and thus a thermal emf was produced. The samples, where possible, were fused in an oxygen-hydrogen flame. In cases where the sample could not be fused, it was baked and cut to size. Conventional measurements were made, using a potentiometer and a sensitive galvanometer. There is a possibility of very large errors in reading the thermal electromotive force of the oxide samples at low temperatures using conventional measuring methods. As an example, if the thermal electromotive force of Bi_2O_3 at a mean temperature of 225°C was measured, using a galvanometer with a sensitivity of 10^{-10} amperes per millimeter as a balance indicator, the balance would be accurate within

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[4] International Critical Tables, Vol. VI, p. 225.

[5] Bidwell, loc. cit.

only 0.742 volts. Table IV has been prepared in order to show the resistance at various temperatures for two samples having the same dimensions as those used by Bidwell.

The furnace shown in Figure 15 was used by Bidwell to heat the small samples. The furnace was constructed with nickel heating wire wound around the outer concentric support, and the sample was supported by the hot junction measuring thermocouple. The hot junction was in the center of the furnace, and the cooler junction was at the bottom of the furnace and shielded by a concentric ring of quartz. In this type of furnace, the hot junction and cold junction temperature must be measured simultaneously with the thermal electromotive force. If the temperature of each junction and the electromotive force are not measured at

TABLE IV

Resistance vs Temperature of Oxide Samples of the Size Used by Bidwell.[6]

Oxide	Temperature degrees centigrade	A	n	Resistance ohms
CuO	12.2	2.12	6	67.2×10^6
CuO	265	3.55	3	$.1317\times10^6$
CuO	463	1.67	2	$.00529\times10^6$
CuO	750	2.08	0	$.0000691\times10^6$
Bi_2O_3	225	2.34	8	$7420.\times10^6$
Bi_2O_3	424	1.44	5	4.56×10^6
Bi_2O_3	645	6.01	3	$.190 \times 10^6$

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[6] Computed from constants given in the International Critical Tables, p. 153.

the same time, error will be introduced due to changes in temperature during instrument reading time. Referring to Figure 15, the hot junction temperature may be measured at points A and A', and the cold junction temperature at B and B'. The thermal electromotive force of the sample is measured at points A and B, or at points A' and B'. The temperature differential across the sample could be measured by connecting points A and B together and measuring from A' to B' if the sample resistance is very high. When measuring the electromotive force of a sample,

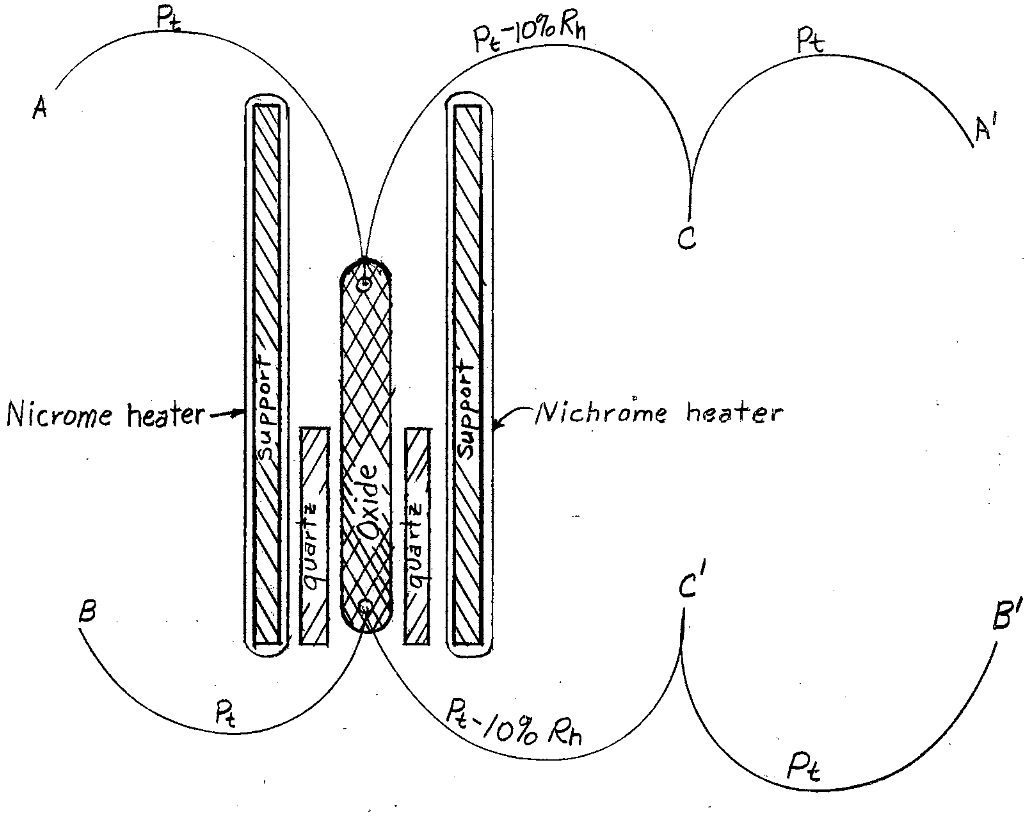

Figure 15. Bidwell's Furnace[7]

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[7] Bidwell, loc. cit.

the leakage resistance at point C to point C' must be very high if correct readings are to be obtained.

It is believed by this author, that there is some question as to the accuracy of measurements recorded by Bidwell on the higher resistances samples, especially at low temperatures. For example, with a sample of lead oxide having a mean temperature of 384°C and the same physical size as the samples used by Bidwell, and a balancing galvanometer with a sensitivity of 10^{-10} ampere per millimeter, the balancing accuracy would be 82,100 microvolts, and if lower temperature measurements were attempted, the balance would become more inaccurate. Figure 16 shows the relation between electromotive force, as determined by Bidwell, and the resistance of a sample having the same dimensions as Bidwell's versus temperature for lead oxide.

When making measurements on oxides using the potentiometer method, the physical configuration of the furnace shown in Figure 17 should prove superior to the one used by Bidwell. The sample used in this furnace may be packed rather than fused, and the cold junction can be held at a constant specific temperature. The advantage of the furnace shown in Figure 17 over the type used by Bidwell is the reduction of sample resistance due to the lower ratio of length to area. A comparison of the resistance of a sample having the same dimensions as Bidwell's lead

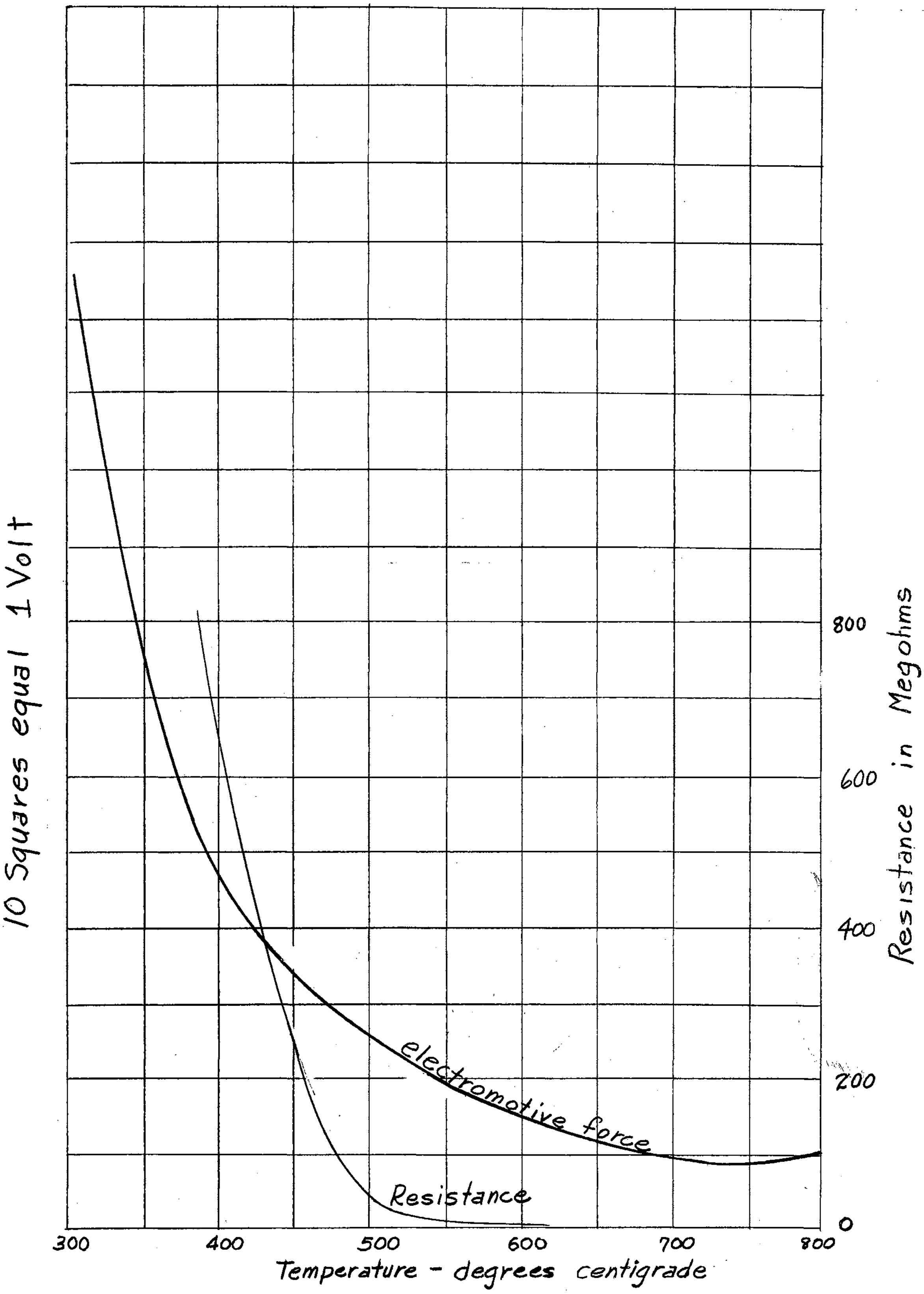

Figure 16. The Electromotive Force of Lead Oxide as Determined by Bidwell, and the Resistance of a Sample of Lead Oxide Having the Same Dimensions as Bidwell's, at Different Temperatures.

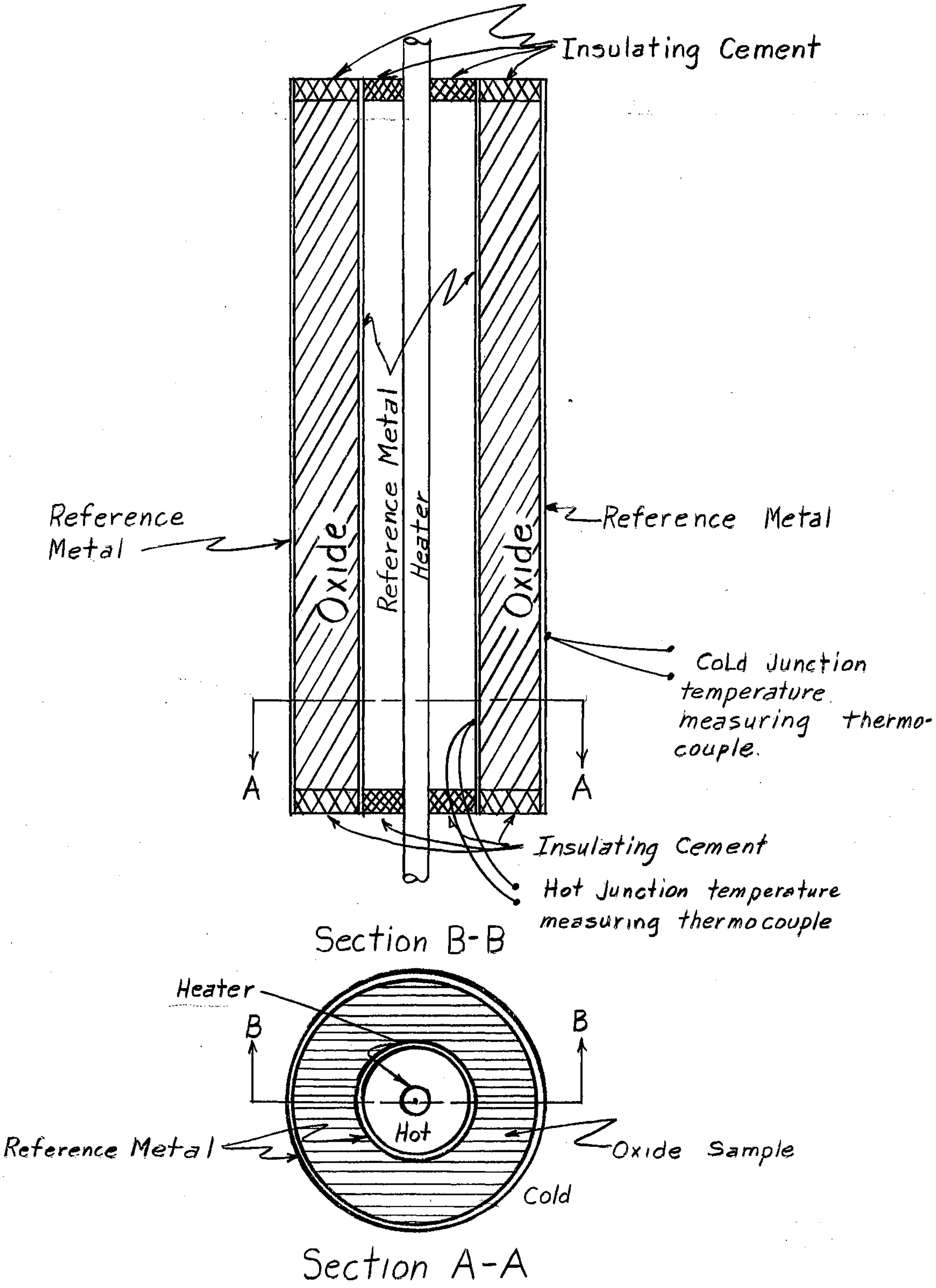

Figure 17. A Furnace Configuration to Reduce Resistance of the Test Sample.

oxide sample, and the resistance of a sample to be used in the proposed furnace of Figure 17, is given in Table V. The proposed furnace may be heated in one of two ways. The inner reference material may have a high current source connected to both ends at points A and A' and Joule heating (I^2R) used as a source of heat, or a heater element may be inserted within the hollow cylinder formed by the inner reference material.

TABLE V

Comparison of the Resistance vs Temperature of Two Samples Using Different Furnace Configurations[8]

Oxide	Temperature degrees centigrade	Resistance in Ohms	
		Sample in Figure 17	Sample in Figure 15
PbO	384	$.914 \times 10^6$	821×10^6
PbO	572	$.00942 \times 10^6$	8.46×10^6
PbO	787	$.00004306 \times 10^6$	$.03867 \times 10^6$

The two cylinders of resistance material are cemented in place with an insulating cement and the oxide packed in between the cylinders. The top is then cemented with insulating cement to hold the oxide in place. The insulating cement used must not be an electrical conductor, and it should not develop a thermoelectric potential either with the oxide or the reference material. The reference material should be as thin as possible to reduce temperature

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[8] Computed from constants given in the International Critical Tables, p. 153.

differentials through the material, and should not react chemically with the oxide or the insulation cement.

Methods of Measuring the Thermal Electromotive Force of Oxide Thermocouples

The resistance of oxide thermocouples makes their use as thermopiles impractical for most applications. The total resistance of an oxide thermopile would be the sum of the resistances of each thermocouple, and the resistance would, in some cases, approach an astronomical figure. While the potentiometer method may be used to measure the thermal electromotive force of oxide thermocouples which have low resistances, when the resistance of a thermocouple is ten megohms, and a balancing galvanometer is used which has a sensitivity of 10^{-10} amperes per millimeter, the inability to read balance may result in voltage-reading discrepancies as great as ± 100 microvolts. For thermocouples with higher resistances, a string electrometer or vacuum-tube electrometer should be used. A very high sensitivity for a string electrometer is 2,500 millimeters per volt.[9] The potential of a typical oxide thermocouple, using a string electrometer as the measuring instrument, could then be read to the order of ±40 microvolts. Vacuum-tube electrometers have been built, incorporating special vacuum tubes, with a sensitivity

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[9] B. J. Thompson, "Measuring $\frac{1}{100,000,000,000,000,000}$ of an Ampere," Electronics, Vol. 1, p. 291.

of 250,000 millimeters per volt.[10] Macdonald and Campbell[11] constructed a bridge circuit using conventional receiver tubes, having a balance sensitivity of 2×10^{-6} volts with the grid of the input tube floating, and used in conjunction with a galvanometer having a sensitivity of 10^{-10} amperes per millimeter as a balance indicator.

Power and Efficiency Measurements on Oxide Thermocouples

The oxide thermocouple, due to its higher internal resistance, seems impractical as a power source at this time. The usefulness of an oxide thermocouple might be as a point potential source from which no power is drawn. Power and efficiency measurements are impractical, as the amount of power available from oxide thermocouple is so small that it would be very difficult to separate the losses of the furnace from the additional heating power required to produce the power in the thermocouple.

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[10] *Ibid*.

[11] P. A. Macdonald and E. M. Campbell, "Floating Grid Direct Current Amplifier," *Physics*, Vol. 6, p. 211.

CHAPTER V

DESIGN FOR VACUUM-TUBE MEASURING CIRCUITS

General Considerations

There are several considerations to be observed in the design of vacuum-tube measuring circuits for oxide thermocouple measurements. The input impedance of the circuit should be much greater than the impedance of the thermocouple under measurement, so that the thermocouple will not be under load for true electromotive force measurements. The tube selected for the circuit is the most important element. The tube used should draw extremely low grid current. The input impedance is[1]

$$Z_g = \frac{\partial E_g}{\partial I_g} \quad . \tag{1}$$

The tube should have very low inherent noise, as the maximum sensitivity of the circuit will be limited by the noise of the tube in addition to the external pickup noise. After proper preheating, the tube must be extremely stable so it will not drift and give erroneous readings. Another consideration in selecting the tube to be used is that the tube should be available in a new condition. Old tubes tend to become gassy, which causes the tube to be noisy and also

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[1] W. B. Nottingham, "Measurement of Small D. C. Potentials and Currents in High Resistance Circuits by Using Vacuum Tubes," Journal of the Franklin Institute, Vol. 209, p. 294.

increases the grid current flow due to positrons liberated from collisions between electrons and the gas particles within the tube. Considerations other than the tube selected should include the other components in the circuit, both separately and in the total circuit. High-capacity batteries should be used to avoid, as far as possible, fluctuations in supply voltages and consequent loss of sensitivity. High-capacity lead-acid storage batteries are generally recommended. The highest quality insulation should be used in the grid circuit, preferably either quartz or amber. Contact potentials should be kept to a minimum in the circuit, and the thermoelectromotive forces of connections should be reduced to as low a value as possible. Good mechanical and electrical connections will tend to reduce the thermal electromotive forces by reducing the resistance at the junctions, thereby reducing the Joule heating (I^2R) at the junctions. Junctions of unlike materials should be avoided wherever possible, especially where temperature differentials exist. The components should be very stable under the influence of heat; i.e., they should have a very low temperature coefficient. The measuring instrument should be shock mounted to prevent noise due to "microphonics" within the tube. Magnetic and electrostatic shielding should be used over the entire circuit including the supply batteries when precision measurements are to be made. Metcalf and Dickinson,[2] used

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[2] G. F. Metcalf and T. M. Dickinson, "A New Low Noise Vacuum Tube," Physics, Vol. 3, p. 11.

a shield consisting of three layers of 0.020" transformer iron separated by layers of 0.020" copper to reduce magnetic noise pickup in an amplifier capable of measuring as low as 0.1 microvolt.

The type of circuit selected should be determined by the measurement problem. Single-sided circuits have the highest sensitivity of any of the circuits and are less expensive and easier to construct, but are not as stable as balanced circuits. The balanced two-tube circuit has greater stability, but is more expensive and has less sensitivity than the single-sided circuit. The greater stability is achieved because both tubes use the same battery source, and any change in battery voltage affects both tubes simultaneously. The ideal situation for greatest stability is to have both tubes of the balanced circuit in the same envelope and using the same filament.

In specifying operating conditions for the vacuum tubes used, it is well to understand the causes for grid current in vacuum tubes. Thompson[3] has made an exhaustive study of the sources of grid current in a vacuum tube. These include

1. Electrons from the filament.
2. Positive ions formed by collisions between the electrons constituting the plate current and the gas molecules in the space.
3. Electrons emitted by the grid due to its temperature.
4. Leakage.
5. Positive ions emitted by the filament.

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[3] Thompson, <u>loc. cit.</u>

6. Electrons emitted from the grid under the influence of light from the filament.
7. Electrons emitted from the grid under the influence of the soft X-rays given off by the plate due to its bombardment by the plate current.

By approaching the problem systematically, Thompson designed a tube having a grid current of 10^{-15} amperes and an input impedance of 10^{-16} ohms.[4] Some of the techniques used by Thompson are to operate the grid at a negative voltage to reduce electron current flow, to evacuate the tube thoroughly to reduce collisions between electrons and gas within the tube, to operate the filament of the tube at a reduced potential to decrease the number of positrons emitted, and to operate the plate at a lowered potential to reduce the velocity of the electrons so that electron-gas collisions will not cause an avalanche effect producing large numbers of positrons. The tube designed by Thompson also contained a shield grid to repel positrons back to the filament. The operating voltages and currents, along with the transconductance, plate resistance and amplification factor for the GL5740/FP54 are listed in Table VI.

Macdonald and Turnball,[5] have found that the transconductance of the GL5740/FP54 can be increased over the value given by Thompson if a corresponding lowering of input

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[4] GL 5740/FP54

[5] P. A. Macdonald and W. E. Turnball, "Operating Characteristics of the FP54 Thermionic Direct-Current Amplifying Tube." <u>Physics</u>, Vol. 6. (1935), p. 304.

TABLE VI

Operating Characteristics of the GL5740/FP54 as Determined by Thompson[6]

Plate voltage	6.0 volts
Space-charge grid voltage	4.0 volts
Control grid voltage	4.0 volts
Filament voltage	2.5 volts
Filament current	110 milliamperes
Plate current	40 microamperes
Mutual conductance	25 microamperes per volt
Amplification factor	1.0

impedance is not objectionable. Table VII gives a list of the operating conditions which will increase the transconductance of the GL5740/FP54.

TABLE VII

Operating Characteristics of the FP54 as Determined by Macdonald and Turnball[7]

	Operating Characteristics	Rated Characteristics
Filament potential	2.5 volts	2.5 volts
Plate potential	8.0 volts	6.0 volts
Space charge grid potential	6.0 volts	4.0 volts
Mutual conductance	70 microamperes/volt	25 microamperes/volt
Grid impedance	10^{14} ohms	10^{16} ohms

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[6] Thompson, loc. cit.

[7] Macdonald and Turnball, loc. cit.

Tube Selection

The three most important requirements a tube must meet are low grid current, low noise, and high stability. Although gain through the tube is desirable, thus allowing a less sensitive balancing instrument to be used, it is not absolutely necessary. The tube is used primarily as an isolation stage and an impedance transformation device from high impedance to a lower impedance for measurement pruposes. There are several commercial laboratory tubes available which are quite satisfactory, although they are very expensive. The General Electric GL 5740/FP54, the GL 5674, and the Western Electric D-96475 all meet the requirements quite well. There are a few receiver-type tubes which may be used if extreme accuracy and stability are not necessary. The type 22 and 959 have both proven satisfactory in limited applications. It should be stressed, however, that these tubes will work only if in a new condition, since a tube which was made a long time ago tends to become gassy and will draw excessive grid current.

Operating Voltages

Recommended values for the operating voltages for special-purpose tubes are available.[8] When tubes other than the special-purpose types are used, it is necessary to test each tube individually to determine the grid characteristics of the tube in order to determine the input impedance.

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[8] Table III and IV and Manufacturers Tube Manuals.

The point of maximum input impedance will be the point of inflection on the grid characteristic curve. This is the point where the positron and electron current flow are equal. If the grid current flow is equal to zero,

$$Z_g = \frac{\partial E_g}{\partial I_g} = \frac{\partial E_g}{0} = \infty \quad , \qquad (3)$$

then the total input impedance will be equal to the leakage resistance from grid to ground. In order to reduce positron current flow to the grid, the total voltage drop between any two elements in the tube should be less than the ionization potential of any residual gas within the tube. In order to reduce positron current flow from the filament, it should be operated at as low a current as will sustain a steady plate-current flow.

Circuit Selection

Selection of the type of circuit to use is dictated by the precision of the measurements to be made, the sensitivity desired, and the stability required, as well as the cost of the components. The single-sided circuit shown in Figure 18 is one of the most sensitive of the circuits. It is also less expensive but is less stable. The instability is the result of using a vacuum tube in one arm of the balanced bridge, while a resistor is used in the other arm. The tube has nonlinear characteristics, while the fixed resistance has linear characteristics. Therefore, any change in supply voltage will cause the circuit to go out

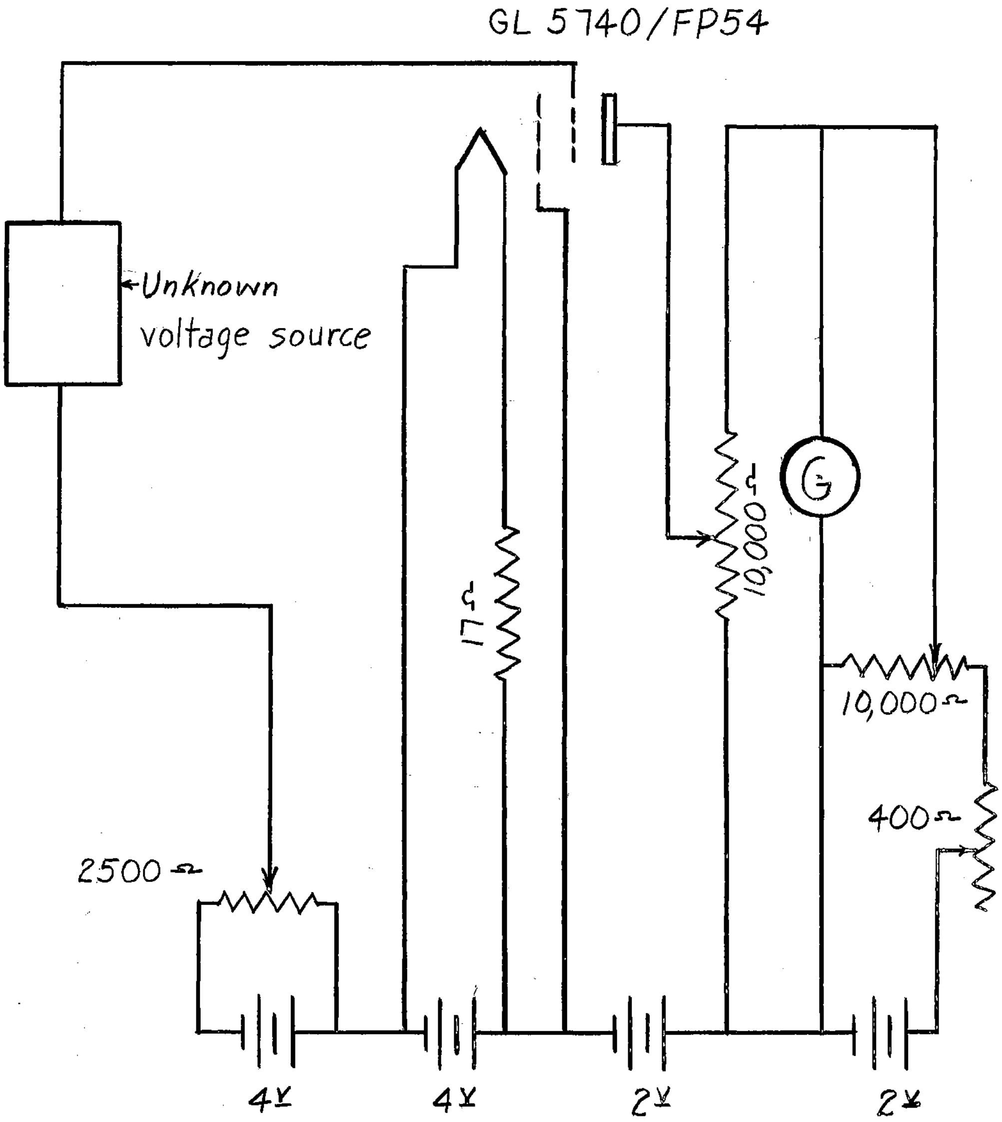

Figure 18. A Single-sided Vacuum-tube Electrometer Circuit.

of balance which will produce erroneous readings. Thompson[9] claims a sensitivity of 250,000 millimeters per volt for this type of circuit when a GL 5740/FP54 is used as the input tube and a galvanometer with a sensitivity of 10^{-10} amperes per millimeter is used as a balance indicator. The balanced two-tube circuit shown in Figure 19 has greater stability than the single-tube circuit. The increased stability is due to the use of two tubes, one in each arm of the bridge. In this case, any change in supply voltage is impressed upon similar nonlinear resistances, and the bridge remains in balance. The sensitivity of this circuit is less, being only 75,000 millimeters per volt in comparison to 250,000 millimeters per volt for the single-tube circuit. The ideal circuit, where stability is concerned, is a balanced two-tube circuit in which both tubes are in the same envelope and utilizes a common heater. The GL 5674, a tube of this type, is manufactured by the General Electric Company.

Circuit Components

The source of supply voltage for the tube should be very stable. It is recommended that large-capacity lead-acid storage batteries in a new and fully charged condition be used for all circuit voltages. All resistances in the circuit should be extremely stable and have low inherent noise. The use of low-temperature coefficient wire-wound

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[9] Thompson, loc. cit.

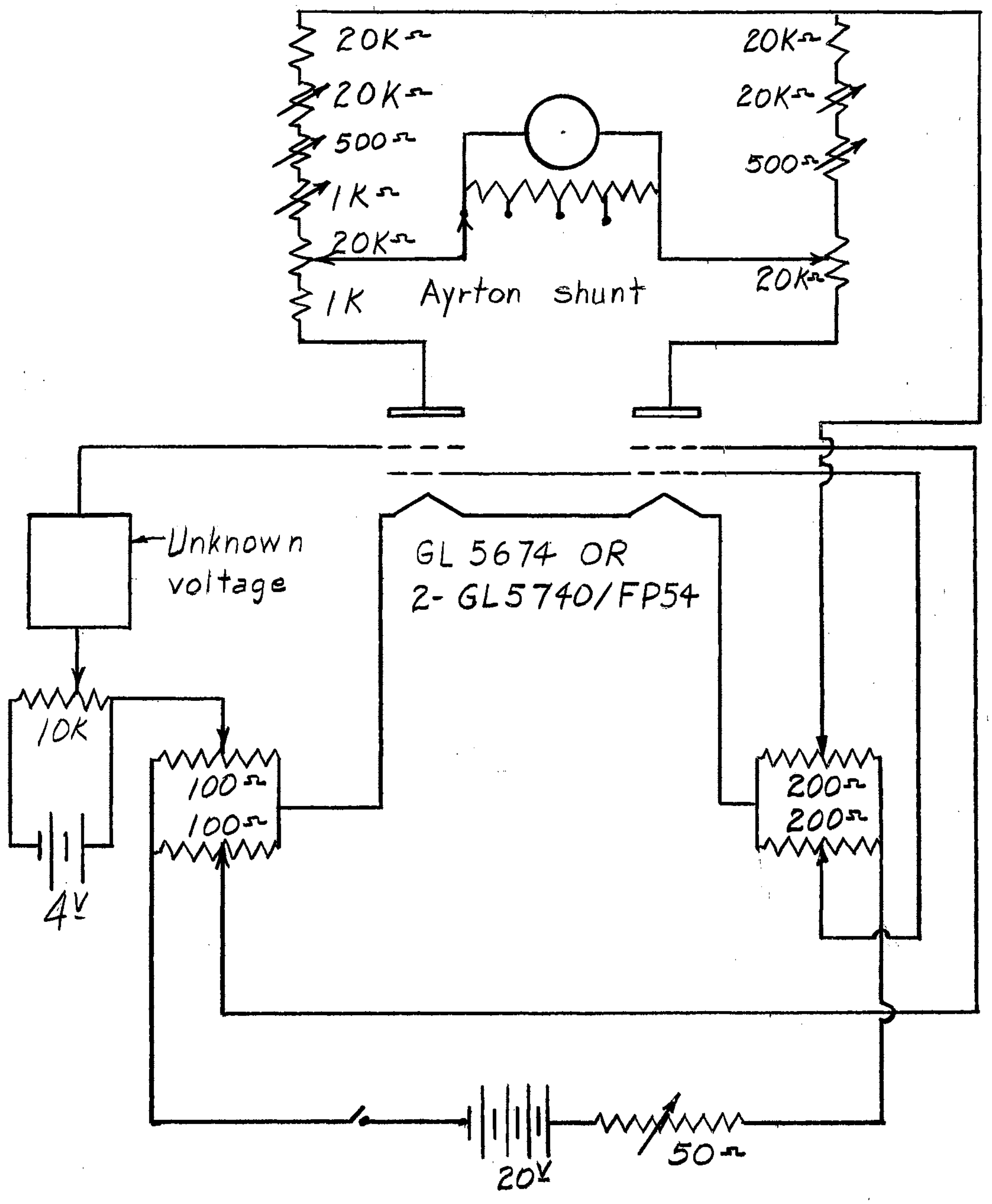


Figure 19. A Balanced Vacuum-tube Electrometer Circuit.

resistors prove to be the most satisfactory. The input impedance of the circuit will, in part, be dependent on the quality of insulation used; therefore, only the best insulation available should be used. If there is any leakage in the insulation, it will appear in the output of the circuit as noise and thus reduce the sensitivity of the circuit. The best quality quartz, polystyrene, or amber insulation is better than other types. Switches, when used in the grid circuit, must be designed so there are no contact potentials present. They should be constructed so that good contact is maintained at all times when the switch is closed. Rheostats, when used in a circuit, should have broad brushes and make good contact at all times. A metal band may be used on the surface of a glass envelope to dissipate static charges. The band is installed as shown in Figure 20. It will reduce the warm up time for the circuit by grounding static charges below the band that might migrate to the grid and cause unstable operation.

The Complete Circuit

The complete circuit should be completely shielded against both magnetic and electrostatic pickup. Any spurious noise introduced into the circuit will tend to reduce the sensitivity of the circuit and possibly introduce errors in the readings. The circuit should be well constructed mechanically, and all connections should have a low electrical resistance. The completed instrument should be

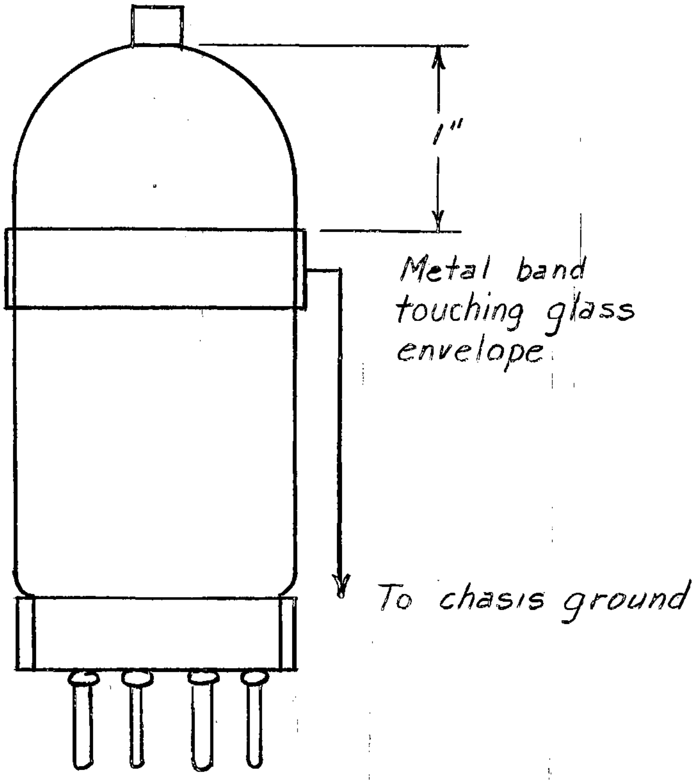


Figure 20. Banding a Vacuum Tube to Reduce Errors Due to Static Charge on the Envelope

shock mounted to minimize microphonic noise due to mechanical vibration of the tube.

Use of the circuit

After a new circuit has been completed, there are certain prerequisites that must be met for stable operation and maximum sensitivity. The circuit should operate for several hours with normal operating voltages and current before each test. This allows all parts to attain their normal operating temperatures and charges on the tube envelope to drain away. If the warm-up period is not long

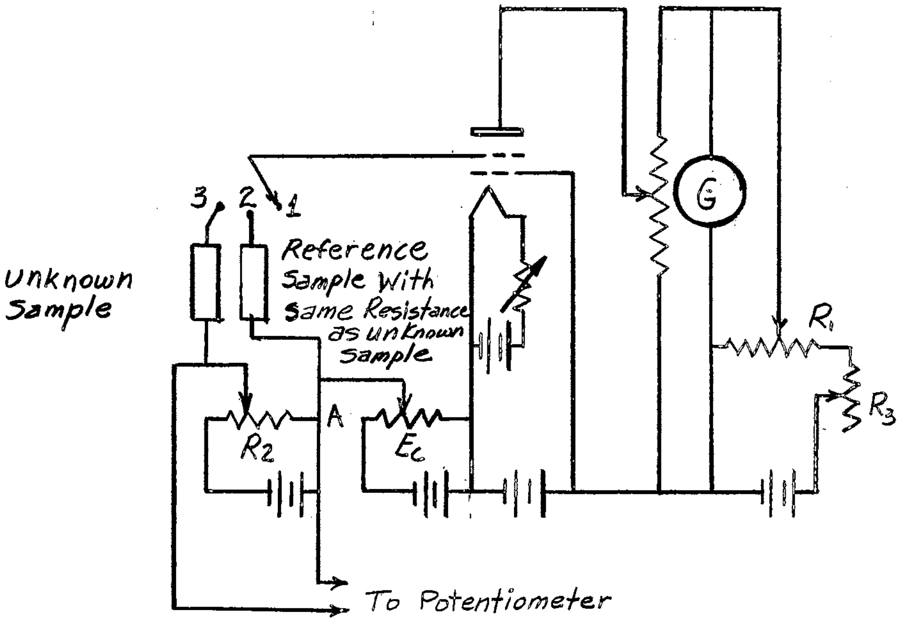


Figure 21. The Circuit for a Single Tube Electrometer Used to Measure the Electromotive Force of an Oxide Thermocouple.

enough, the zero balance in the circuit will tend to drift and give erroneous readings. With reference to Figure 21, a typical measurement procedure will be discussed.

When it is desired to operate the tube at a floating grid potential, the input switch is placed in position 1 and the circuit is brought to balance by adjusting the voltage divider R_1 until the galvanometer reads zero. The input switch is then changed to position 2, and E_c varied until the galvanometer again reads zero. The switch is then placed in position 3, and the voltage divider R_2 is adjusted until the galvanometer again reads zero. The voltage from the center arm of the voltage divider R_2 to point A is then equal to the electromotive force of the unknown source under test. This potential may then be read using a potentiometer.

CHAPTER VI

EXPERIMENTAL RESULTS

General

Three types of commercial receiving tubes were tested under dynamic operating conditions. These were the types 38, 5692, 5693. The unbalanced electrometer tube circuit, as shown in Figure 18, and the balanced vacuum-tube electrometer circuit, as shown in Figure 19, were both used.

The Type 38 Tube

The type 38 tube tested was old, and although it would operate with a floating grid it was extremely unstable. The tube was eleven years old, and it was impossible to determine whether the instability was characteristic of the type 38 tube or was due to residual gas within the tube resulting from long storage. Due to the condition of the tube the tests as performed are inconclusive.

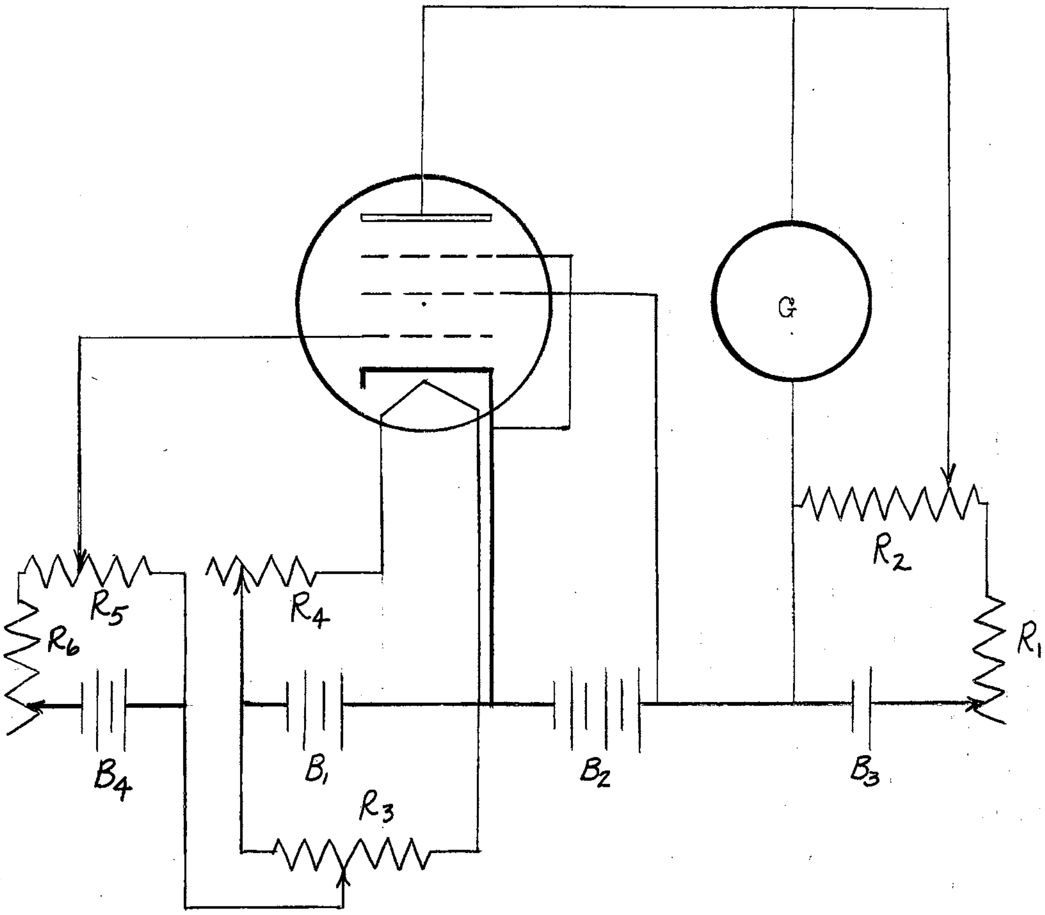
The Type 5692 Tube

The next tube tested was the type 5692. Grid current was 2.66×10^{-10} amperes for this tube when a plate voltage of 90 volts was used and the filament potential was 4 volts. When an attempt was made to use a smaller plate voltage, the tube would not operate at a floating grid potential. The plate current was very unstable, which made it impossible to accurately zero balance the circuit so that measurements could be made. When a balanced circuit was tried using both triode elements in a common envelope, the circuit was still so unstable that accurate measurements were not possible. The tests on the 5692 were made using three different 5692 tubes, with results which were similar. It was concluded that grid current flow for a 5692 tube is so high that it is not satisfactory as an electrometer tube.

The Type 5693 Tube

The 5693 was the next tube tested. The 5693, when initially tested without ageing, was not satisfactory due to poor stability and high grid current. After the tube was aged for fifty hours at reduced electrode potentials, it was found that the tube would operate with a floating grid and quite good stability. The stability of the plate and screen-grid supply voltages for this tube are very critical when the voltages are low, since any drift in plate and screen-grid voltages appears as a shift in the zero point of the balancing galvanometer. Therefore it is recommended that a large-capacity lead-acid storage battery be used for the plate and screen-grid supply. Dry batteries do not seem to have the necessary voltage stability. The filament and grid-bias supplies were found to be very critical also. Therefore, lead-acid storage cells were used to supply these potentials.

It was found that for longer periods of ageing on the 5693 tube, the floating grid potential was lower and the overall stability was better. The circuit of Figure 22 was found to be the most satisfactory. Using a galvanometer having a sensitivity of 1.11×10^{-8} amperes per millimeter,



R_1 - 2M Ω
R_2 - 50K Ω
R_3 - 2500 Ω
R_4 - 60 Ω
R_5 - 60 Ω
R_6 - 2M Ω

Tube - 5693

G - 1.1×10^{-8} amperes/mm
B_1- $6^{\underline{V}}$ lead-acid battery
B_2-$22.5^{\underline{V}}$ dry cell
B_3-$1.5^{\underline{V}}$ dry cell
B_4-$1.5^{\underline{V}}$ dry cell

I_f - 210 ma
I_b - 57.5 μa
E_c - $0.8^{\underline{V}}$ floating potential

Figure 22. Circuit Used in Testing the Type 5693 Vacuum Tube.

it was found that a balance sensitivity of ± 50 microvolts could easily be attained.

The circuit, as constructed, had a very linear drift of approximately 8.8 x 10^{-8} amperes per hour. However this appeared to be due to the dropping of potential of the plate and screen-grid battery due to gradual discharge. A change in plate supply voltage of 500 microvolts has a very marked effect on plate current.

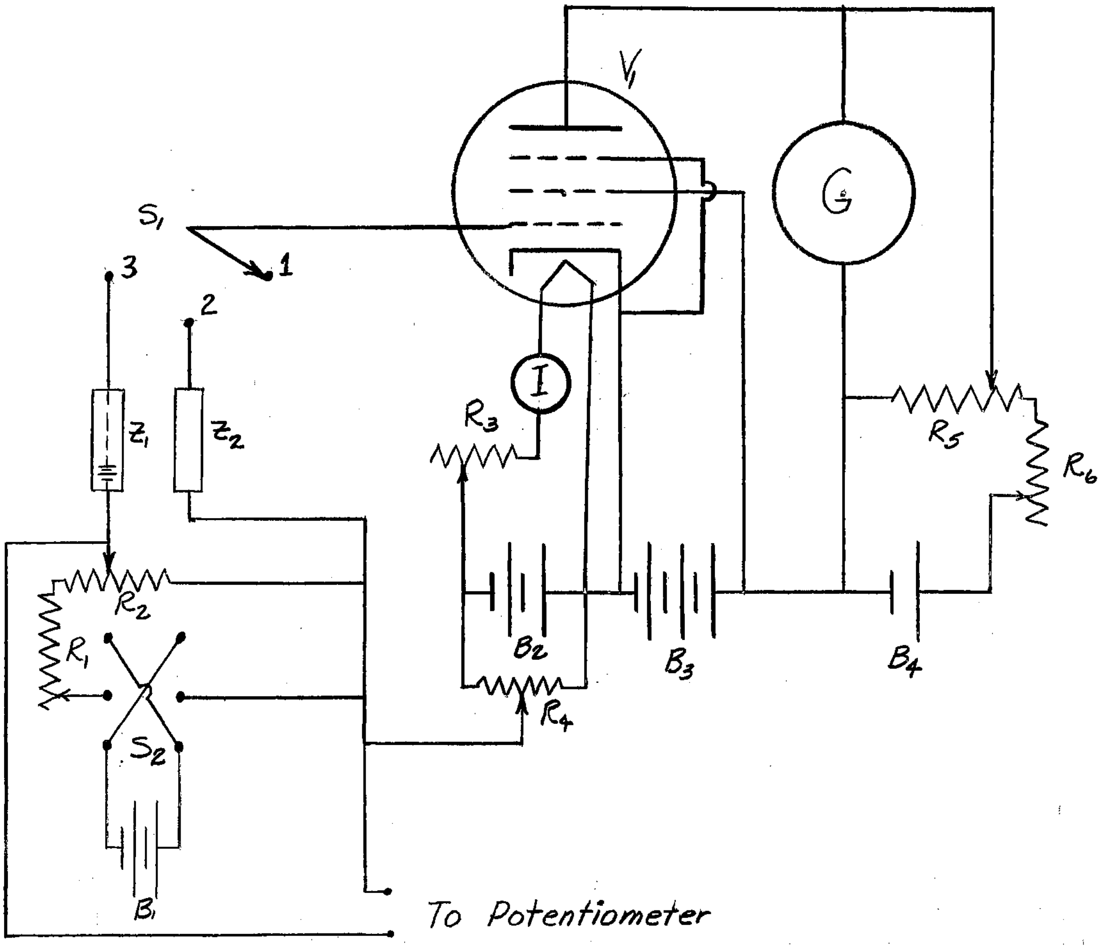
Due to insufficient time, the circuit has not been thoroughly tested, and it is possible that greater sensitivities may be attained.

Using a Practical Circuit

The circuit of Figure 23, is capable of making measurements to within 50 microvolts, with very high source impedances. The minimum voltage that can be measured by this circuit is limited only by the ability to obtain an accurate balance and the measuring ability of the external measuring potentiometer. In order to obtain the highest sensitivity, and good stability the tube should be tested in a circuit similar to the one shown in Figure 22. Since the 5693 is a mass produced vacuum tube, its characteristics will vary. It is very important that the tube be properly aged.

The procedure employed in operating the circuit of Figure 23 is as follows:

(1) The switch in the control grid circuit is first placed in position 1, and the galvanometer zeroed by varying



V_1 - 5693 vacuum tube
R_1 - 1M Ω
R_2 - 2.5K Ω
R_3 - 60 Ω
R_4 - 2500 Ω
R_5 - 50K Ω
R_6 - 2M Ω
G - 1.1×10^{-8} a/mm galvanometer

Z_1 - sample of Z internal impedance and an electromotive force
Z_2 - Sample $Z = Z_1$, but with no electromotive force.
B_1 - Larger than any emf to be measured
B_2 - $6^{\underline{V}}$ storage battery
B_3 - $22^{\underline{V}}$ storage battery
B_4 - $2^{\underline{V}}$ storage battery

Figure 23. A Practical Measuring Circuit Using the Type 5693 Vacuum Tube.

rheostats R_5 and R_6.

(2) The control grid switch is placed in position 2, and the rheostat R_4 adjusted until the galvanometer again reads zero. Step 2 balances the voltage drop across an impedance which is equal to the impedance of the generator to be measured, and returns the grid to its floating potential.

(3) The control grid switch is then placed in position 3, and the source potential balanced using the rheostat R_2, and adjusting until the galvanometer again reads zero. It may be necessary to reverse the polarity of battery B_1 with the reversing switch S_1 if the generator potential is not opposite to the battery potential.

(4) The generator voltage may then be determined by measuring the voltage from point A, to the center arm of rheostat R_2 with a potentiometer.

CHAPTER VII

SUMMARY AND CONCLUSIONS

Summary

The object of this thesis was to review instrumentation techniques which have been used in making measurements on thermocouples and to propose new techniques. It has been shown that thermocouples having unlike tensions in their respective materials will demonstrate different values of electromotive force. Therefore, methods of preparing sample thermocouples have been discussed, as well as the necessary precautions which must be observed in fabricating the thermocouples to obtain identical samples. Each type of thermocouple presents a different instrumentation problem. Examples have been given to illustrate that the measurement techniques for low-impedance thermocouples is quite different from the techniques employed in measuring high-impedance thermocouples. Different furnace configurations have been discussed, demonstrating that the physical construction of the furnace can appreciably affect the impedance of the thermocouple under consideration. Each type of furnace configuration has certain advantages and disadvantages which were discussed.

The design of vacuum-tube circuits for measurements on high-impedance thermocouples was discussed. Methods of increasing the input impedance of vacuum-tube circuits were pointed out, and sensitivities of various circuit configurations were given, as observed by different authors. The vacuum-tube circuits may be used either with special-purpose laboratory type tubes, for maximum sensitivity, or with receiver type tubes if a reduced sensitivity is not objectionable.

Experiments with the 5693 tube have shown that measurement of extremely low potential sources having very high internal impedances can be measured satisfactorily by incorporating tubes and components of modest cost. This is made possible by proper tube selection and ageing, and by observing good practices of electrical and thermal shielding. In addition, the use of highly stable power supply sources aid materially in achieving high stability of circuit operation.

Recommendations for Further Study

The instrumentation techniques for oxide thermocouples, while adequate, can be made even more sentitive by the addition of highly stable amplifiers.

Investigation of the effect of different atmospheres on the conductivity of oxide materials should be pursued. A group, headed by Dr. H. D. Bailey, has conducted tests on the conductivity of zinc oxide in various atmospheres and reports that hydrogen increases the conductivity, while nitrogen reduces the conductivity.[1] They have not studied

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[1] Personal communication from Dr. H. D. Bailey, Phillips Research Laboratory, Bartlesville, Oklahoma.

the effect of the atmospheres on the thermal electromotive force of zinc oxide. A thorough theoretical study of the effects of the different atmospheres is lacking; therefore, it is impossible to determine whether the conduction is taking place on the surface of the oxide or through it. If the conduction is taking place on the surface of the oxide, the effect on a thermocouple would mean an extra load. If the effect is to decrease the resistivity of the oxide material, it may be possible to use atmospheres other than air to reduce the resistance of oxide thermocouples, and have a higher potential thermocouple with an internal impedance appreciably lower than is now possible.

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