THE THERMOPILE GENERATOR AS A SOURCE OF ELECTRICAL ENERGY

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PREFACE

With the increased use of low powered electrical components such as transistors and other semi-conductor devices the use of a thermopile generator as source of electrical energy could be realized in the near future instead of being classed as an impractical type of power supply. Utilizing waste heat as a source of thermal energy, the thermopile converts this heat into an electromotive force by the well-known thermoelectric effect discovered by Thomas J. Seebeck.

This thesis is concerned with the design, selection of materials, construction, performance, an analysis of the results, and a study of the practical application of the thermopile generator. This thesis also represents a part of the research program for the Wright Air Development Center, United States Air Force, in connection with their investigation of unconventional power supplies.

Indebtedness is acknowledged to Professor Paul A. McCollum, P.E., project leader of the research project mentioned above, for his valuable guidance as advisor and for making possible the opportunity of writing this thesis.

This author also wishes to extend his thanks to the following for their assistance in the procurement of performance data used in this study: Mr. Wayne Gayler, Mr. Earl Deshazo, Mr. Warren Ray, Mr. Ralph Fisher, and Mr. Kenneth Proctor.

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CHAPTER I

INTRODUCTION

For over a hundred years the conversion of heat to electrical energy by the thermoelectric effect has been considered a desirable means of obtaining pure d-c power. The advantage of this method is the absence of mechanical motion, little maintenance, and quietness of operation. However, because of the low efficiencies encountered and the relatively low output obtained, little success has been realized in a practical sense. Now, with the new discoveries in the field of low powered transistors and semi-conductors, a device of this nature has considerable possibilities, despite its low efficiency.

Many experimenters and inventors have done much work on the subject of thermocouples and thermopiles in the past. However, by and large, this work was done on a small scale with a great deal of emphasis on the application of instrumentation. The text of this thesis is concerned with a practical thermopile generator as a source of electrical energy. It is the expectation of the author that in the near future generators similiar to the one described in the following pages will be important to the industry of this country, particularly in the fields of high altitude aviation, portable communication equipment, and standby emergency power supplies.

CHAPTER II

HISTORICAL REVIEW

As near as can be determined, the earliest observations of the thermoelectric effect were made by the German physicist, Thomas J. Seebeck[1] (1770-1831) in the early part of the 19th century. Seebeck discovered that when a circuit is formed of two dissimilar metals joined together at one end, and this junction is heated to a temperature higher than that of the free ends, a small electromotive force is created.

Besides the Seebeck Effect there are two other thermoelectric effects: the Peltier Effect, discovered by the French physicist, Jean C. A. Peltier (1785-1845), and the Thomson Effect discovered by William Thomson, who in later years became Lord Kelvin.[2]

The Peltier Effect, discovered in 1834, is concerned with the junctions of the thermocouple wires.[3] Peltier noted that an electrical current flowing in the thermocouple has a tendency to cool the hot junction and heat the cold junction, according to the direction of the

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[1] Grenville B. Ellis, "Thermoelectric Generator Designs: Sources of Electric Energy," American Institute of Electrical Engineers, No. S-42, (New York, 1951), p. 47.

[2] Erich Hausman and Edgar P. Slack, Physics, (2d. ed., New York, 1939), p. 492.

[3] G. L. Farrar and A. M. Platt, "Some Fundamentals of Temperature Measurements with Thermocouples," The Petroleum Engineer, Vol. 21, No. 13, pg. C-5, December, 1949, p. 1.

current. This Peltier effect acts as if it were a counter electromotive force. Various attempts have been made to utilize the Peltier effect for artificial refrigeration, but until recently they have not appeared to be commercially successful. In January, 1955, Radio Corporation of America[4] announced an all-electronic refrigerator capable of producing sufficiently low temperatures to freeze an appreciable amount of water and to provide cool storage for perishable foods. The "thermocouple refrigerator" can produce these low temperatures as rapidly as many standard electric refrigerating systems. The heat supplied to maintain a constant temperature differential is called the Peltier heat, always less than the heat supplied to the hot junction, and is responsible for nearly all the electrical energy produced in the thermocouple.

An analysis of the foregoing effects prompted Lord Kelvin, in 1851, to theorize that an emf must exist between different parts of the same metal if they are at different temperatures.[5] This emf disturbs the temperature distribution (Thomson Effect) and can only be corrected by an unrelated supply of heat in contact with the hot junction. The Thomson heat is that heat that must be supplied when a current flows from a point at one temperature to a point of higher temperature. The Thomson heat is very small and usually can be neglected in a practical sense.

During the late 19th century and early 20th century, inventors attempted to produce thermopile generators that would be accepted by

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[4] David Sarnoff, New Developments In Electronics, Dept. of Information, Radio Corporation of America, (New York, 1955), pp. 19-23.

[5] Hausman, p. 493.

the public as a practical source of electrical energy. In most instances these designs resulted in thermal-electric units that were large and cumbersome, unreliable, expensive to construct, and used considerable amounts of fuel. For example in 1865, S. Marcus[6] designed a "Thermo-Electric Battery" that would deliver an emf of 60 volts. However, this "battery" required 240 pounds of coal per day and had a large weight per unit power ratio. In 1876, Latimer Clark[7] announced a "Thermo-Electric Battery" that would deliver up to 25 watts, but because of the high operating temperatures it was very easy to overheat, thus destroying the antimony-zinc alloy thermocouples. These elements were also extremely brittle. In 1888, G. Betz[8] disclosed a "battery" that would deliver 68 watts, but again the weight of the generator was 600 pounds, occupying 12 cubic feet of space, and consuming 30 cubic feet of gas per hour. In 1895, Harry B. Cox[9] improved on the thermoelectric generator by adding an outside water jacket to further increase the temperature differential. The output was somewhat increased but the weight was 800 pounds, and also required a water source as well as a heat source. During the first world war, James J. Cook[10] decided that steam and water

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[6] S. Marcus, "A New and Very Powerful Thermo-Electric Battery," American Journal of Science, Ser. 2, Vol. 40, September, 1865, pp. 257-258.

[7] Latimer Clark, "Clamond's Thermo-Electric Battery," Electrical Review, Vol. 4, June, 1876, pp. 154-157.

[8] G. Betz, "E. Raub's New Thermo-Electric Battery, Electrical Review, Vol. 22, March, 1888, p. 332.

[9] Harry B. Cox, "The Cox Thermo-Electric Generator for the Conversion of Heat Directly into Electrical Energy," Electrical Engineer, Vol. 19, May, 1895, pp. 383-385.

[10] James J. Cook, Thermo-Electric Generator, U. S. Patent, No. 1,083,191., December 30, 1913.

would further increase the temperature differential. About 50 watts of power was delivered, but the device required a source of steam and a source of coolant which prohibited its adaptability for field use. Also the antimony-selenium elements were fragile and easily damaged. In addition, the leaks which developed in the steam pressure furnace caused a considerable maintenance problem.

These are just a few of the early inventors and their ideas for practical thermopile generators. A close examination of this past work indicates that the solutions of the problems encountered were not always satisfactory. Their choice of materials was limited and the material structure was not well understood. Also the laboratory equipment which the inventors used was not as advanced or as plentiful as it is today. Toward the early part of the 20th century when the rotating types of generators became more universal, further attempts to perfect thermoelectric generators received less emphasis. No thermopile generator has ever been developed that approaches the efficiency of motor generator sets and gasoline-engine-driven generators.

World War II renewed the interest in thermopile generators as they did offer certain characteristics for portable power supplies such as complete portablity, a pure source of d-c power, low maintenance, and quietness of operation. The United States Army actually developed a thermoelectric generator for portable equipment in 1946[11] capable of delivering 20 watts of power. It was designed by the Signal Corp Engineering Laboratories to supply a 14-tube F-M radio transmitter and receiver. It was also used to charge the newly developed portable 2-volt

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[11] J. M. Lee, "Thermoelectric Generator for Portable Equipment," Electronics, Vol. 19, No. 5, May, 1946, pp. 196-202.

lead-acid storage battery, and was even used as a stove for heating and cooking. The hot temperature was provided by burning high octane gasoline which was not always readily available. Valves, gauges, and pumps were also necessary for control of the fuel burner which required some maintenance. The Signal Corp laboratories were concerned with the problems of (1) thermocouples for maximum power efficiency; (2) optimum heat transfer system; (3) a proper heat source; (4) economy; (5) weight; (6) size; (7) noise; and (8) efficiency.[12] It was found that all these factors were dependent on each other which made the solutions more complex and difficult. The Army further developed and experimented with the thermopile generator until a few years ago.

In 1953, the United States Air Force initiated a large research program into the possibility of using an "unconventional" type of power supply for high altitude aircraft. The high altitudes at which modern aircraft fly have a tremendous adverse affect on the bearings and brush life of rotating types of generators. Since the thermopile generator contains no moving parts, this problem would be eliminated. This research is being conducted for the Wright Air Development Center project, "Unconventional Electrical Power Sources," at Oklahoma A. and M. College. The investigation sponsored by the Air Force in regard to a thermopile generator includes (1) efficiency of power conversion; (2) required overall weight and size per power output, and operating time; (3) range of voltages and currents which can efficiently be provided; (4) life and reliability which can be expected; (5) methods of voltage control; (6) and audio and radio noise effects of environment conditions. This

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[12] Ellis, p. 47.

research[13] is in progress at the present time and will be continued in the future.

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[13] Attie L. Betts and Paul A. McCollum, "Unconventional Electrical Power Sources," Wright Air Development Center Technical Report 54-405, (Oklahoma A. and M. College, September, 1954), pp. vii-viii.

CHAPTER III

THEORETICAL CONSIDERATIONS

The principle of operation has already been mentioned in Chapter II concerning the Seebeck, Peltier, and Thomson effects. It was stated that the Peltier heat is responsible for nearly all the electrical energy created in the thermocouple. This should be discussed further in order to have a better understanding of the thermal and electrical relationship.

The Peltier heat of any thermocouple is very nearly a linear function of the temperature provided the temperature limits selected produce no abrupt change of state, change of crystalline structure, or oxidation. Since the Peltier heat into any thermocouple varies almost linearly with the temperature, the electrical energy created is also nearly a linear function of the temperature. This relation can be observed in the thermocouple calibration curves shown in Figure 1. Thermocouples of copper-constantan and iron-constantan were used to illustrate this point because these combinations were actually used in the two types of generators constructed and tested in this thesis. Later reference will be made to these curves.

As shown in Figure 2, both the Peltier Effect and Thomson Effect contribute to the total electromotive force in the circuit. The thermoelectric effects are best understood in qualitative terms of the conduction-electron "gas" which occupies the volume of the two metals. Let the junctions be semipermeable membranes for this gas. The symbol π is

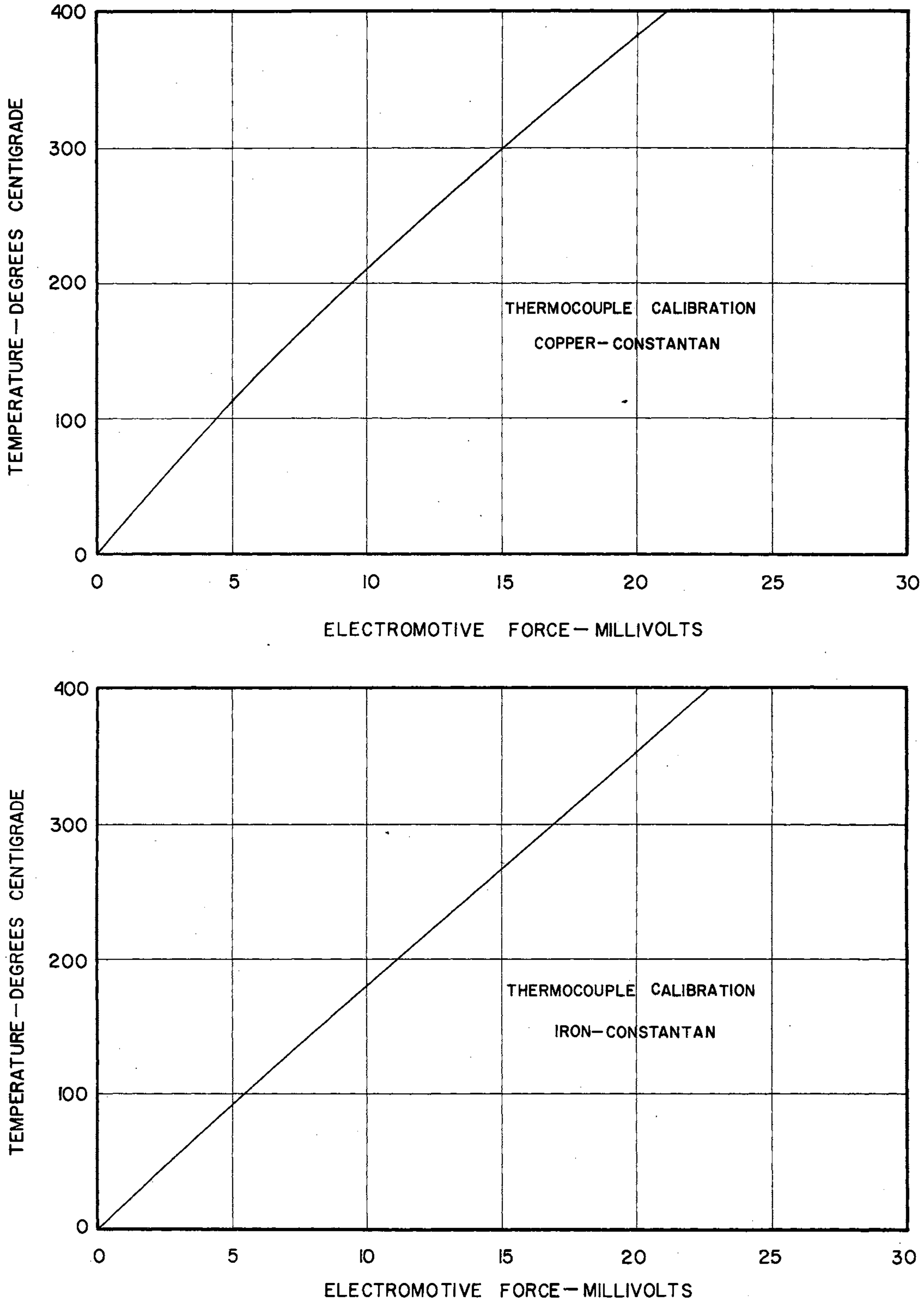

Figure 1. Thermocouple calibration curves. (From values given in Tables of Thermocouple Characteristics, General Electric Publication GET-1415, Schenectady, N. Y.)

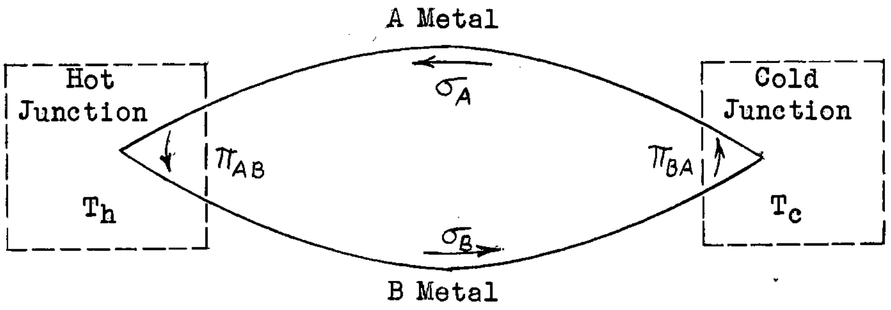

Figure 2. Total electromotive force in a closed thermocouple circuit.

the Peltier electromotive force, and is the same at both junctions. The electron gas densities on the two sides of a boundary will not change in the same way with the temperature; therefore, π must be considered a function of temperature T. The symbol σ is used to designate the specific heat of electricity, also called the Thomson coefficient, and is the work necessary to take a unit charge through a unit temperature interval, $dW = \sigma dT$. It is a function of the temperature as well as of the metal. The work necessary to circulate a unit charge is the emf in the circuit, and can be expressed by:[14]

$$T_hT_c\mathcal{E}_{AB} = T_h\pi_{AB}+\int_{T_h}^{T_c}\sigma_B dT - T_c\pi_{BA}\int_{T_h}^{T_c}\sigma_A dT. \qquad (1)$$

This is the fundamental equation of the thermocouple, and likewise it is the principal of the conservation of energy. The derivation of equation (1) is best understood by graphical means as shown in Figures 2 and 3.

A practical thermocouple is seldom as elementry as that just described. For instance, the circuit must be broken to introduce a measuring

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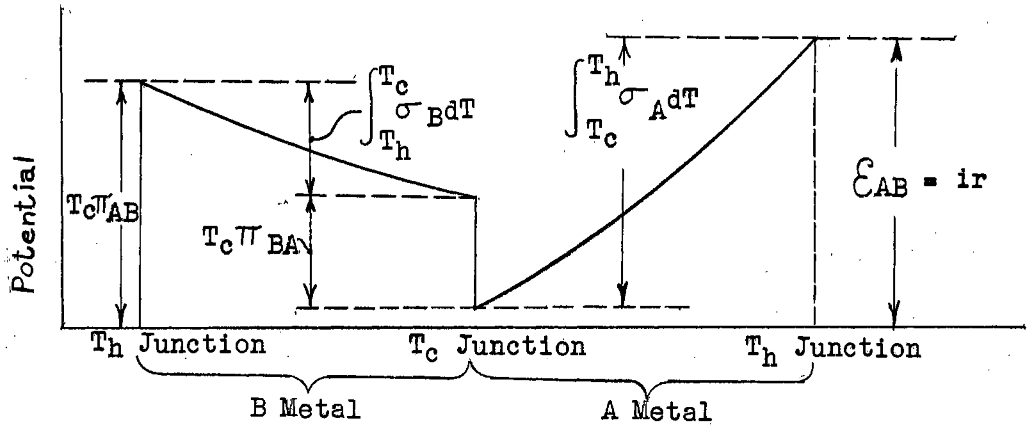
[14] Gaylord P. Harnwell, Principles of Electricity and Electromagnetism, (1st. ed., New York, 1938), p. 184.



where $T_h\pi_{AB}$ is the Peltier emf at T_h,
$T_c\pi_{BA}$ is the Peltier emf at T_c,
$\int_{T_h}^{T_c} \sigma_B dT$ is the Thomson emf in B metal,
$\int_{T_c}^{T_h} \sigma_A dT$ is the Thomson emf in A metal,
$\mathcal{E}_{AB}$ is the total emf existing in the circuit.

Figure 3. Graphical repensentation of the total electromotive force in a closed thermocouple circuit.[15]

device, or in the case of a generator, an electrical load. But for the purpose of this thesis a detailed analysis of the complexity involved with this phenomenon would be of little value in a discussion of a practical generator.

It is possible to use any two dissimilar metals in making a thermocouple. However, for obvious reasons, the metals should be chosen such that (1) the Thomson emf's in each wire and the Peltier emf's are mutually additive; (2) both emf's should vary directly with

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[15] Harnwell, p. 184.

temperature; (3) the potential generated by the thermocouple should be as great as possible; (4) the thermocouple should be resistant to oxidation at operating temperatures; (5) the thermocouple should also have a low ratio of thermal to electrical conductivity; and (6) they should have continued reproducibility within narrow limits.[16] Although it is impossible to obtain all these characteristics in any one thermocouple, some combinations of metals conform reasonably well. The metals are assumed to be in the polycrystalline state, and their specific electric resistance, specific heat of conductivity, and thermoelectric power are know functions of the temperature. Also, the metals should be suitably annealed and their physical properties should not change during the operation of the thermocouple.

In order for a thermopile generator to be practical, "base metals" should be used for the elements. Base metals not only meet the above mentioned requirements reasonably well, but they are also readily available and inexpensive. The most commonly used couples for measuring purposes, which would also be desirable as voltage generators, are given in Table I.

TABLE I

COMMON THERMOCOUPLES AND MAXIMUM TEMPERATURES

POSITIVE ELEMENT	NEGATIVE ELEMENT	MAXIMUM TEMPERATURE
Chromel	Alumel	1093° C
Iron	Constantan	900° C
Copper	Constantan	260° C

In Figure 4, the electromotive force generated as a function of

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[16] Farrar, pp. 1-2.

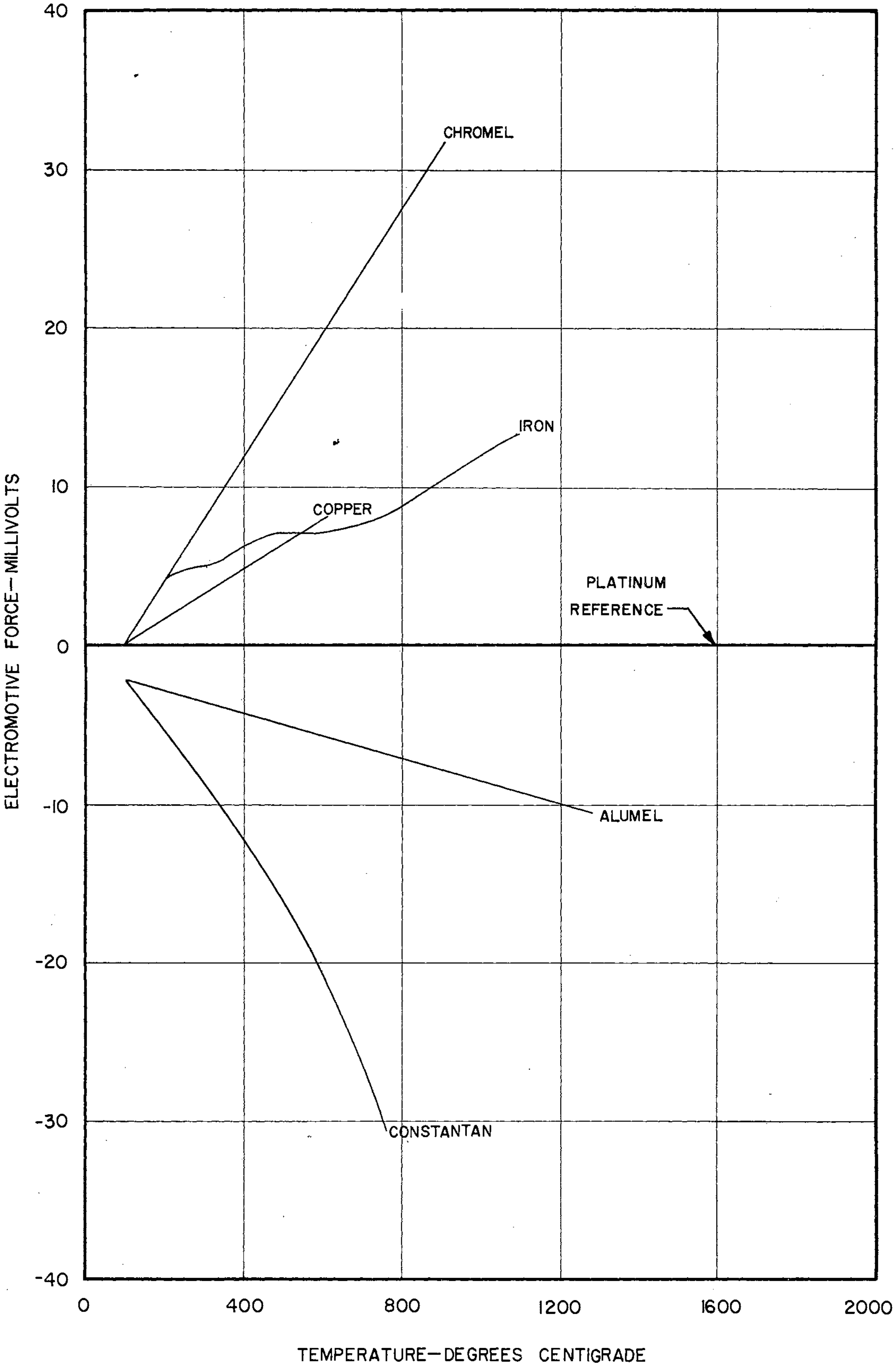

Figure 4. Emf's of metals.

temperature is shown for each metal used in making up these three thermocouples. The curves are drawn so that platinum is used as a standard reference metal for comparison. The emf that will be developed by any combination of two metals may be determined by reading the vertical difference between the curves of the two metals at the proper temperature.[17]

Of the three types of thermocouples mentioned in the table, copper-constantan and iron-constantan operate at the lower temperatures. For a practical type of thermopile generator the operating temperatures should be in a suitable or easily obtainable range. These two types of thermocouples not only operate in a desirable range of temperatures, but also have a high thermoelectric power and moderately low internal electrical resistance.

It should be mentioned at this point that the thermocouple junctions must be free of any additional electrical resistance introduced when the connection is formed. A varity of methods for producing satisfactory junctions are available. Soldering, welding, or fusing techniques can be used, but care must be taken to prevent imperfect joints and oxide layers. It was found from actual tests that silver solder produced juctions having up to 1.66% lower resistance than those which were fused or spot welded. However, this limits the hot junction temperature to the melting point of silver solder which is 730 degrees centigrade. The effect of thermal diffusion was reduced by keeping the amount of solder used to a minimum. Also this soldering material did not interfere with the physical characteristics of the thermocouple materials.

Construction of hot junctions prove to be the most troublesome.

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[17] Ibid.

During prolonged operation at relatively higher temperatures, thermal corrosion and deterioration may occur which increase the electrical resistance and therby decrease the efficiency.

Obviously, one thermocouple would not generate sufficient power to be of any value as a practical generator. This necessitates the use of a multiple arrangement. A number of junctions arranged in series or parallel constitutes a thermopile, such as is shown in Figure 5. In this case the total electromotive force developed in any thermopile is the number of junctions multiplied by the emf per junction. As mentioned previously, the emf developed is approximately proportional to the radiant energy of the heat source. Parallel connection of the thermopiles are sometimes used to obtain larger currents. There is no limit to the number of thermocouples which may be used in a thermopile generator, but practically, the size, weight, and expense become intolerable at the extreme.

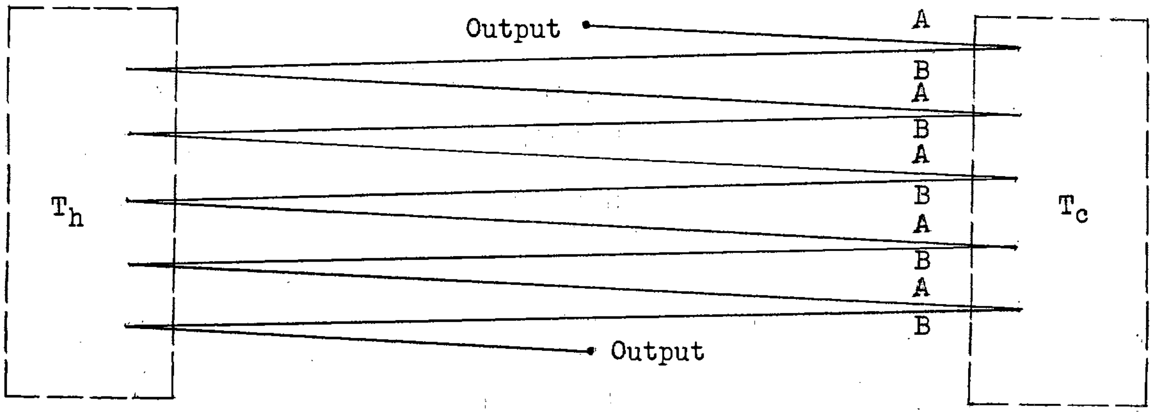

Figure 5. A series thermopile.

The total electromotive force developed by a thermocouple is:[18]

$$E = e(\Delta T) \tag{2}$$

where
E is expressed in volts per junction,
e is the thermoelectric power in volts per degree centigrade,
ΔT is the temperature differential in degrees centigrade between the hot and cold junctions of the thermocouples.

If the current is expressed as I in amperes, and the electrical resistance of one thermocouple wire is $\frac{\rho_A \ell_A}{a_A}$ in ohms, then the power output may be expressed as:

$$P_o = eI(\Delta T) - I^2\left(\frac{\rho_A \ell_A}{a_A} + \frac{\rho_B \ell_B}{a_B}\right) \tag{3}$$

where
P_o is expressed in watts per junction,
$eI(\Delta T)$ is the theoretical power output in watts,
$I^2\left(\frac{\rho_A \ell_A}{a_A} + \frac{\rho_B \ell_B}{a_B}\right)$ is the power loss due to the electrical resistance of the wires in watts.

The quantity of heat required to generate the theoretical power output, $eI(\Delta T)$, can be expressed as:[19]

$$\frac{eI(\Delta T)T_h}{\Delta T} = eIT_h \tag{4}$$

where
T_h is the temperature of the hot junction in degrees Kelvin.

The heat conduction losses, neglecting the Thomson Effect and assuming the walls of the insulating material to be perfect insulators, can be expressed as:[20]

$$\Delta T\left(\frac{k_A\ a_A}{\ell_A} + \frac{k_B\ a_B}{\ell_B}\right) \tag{5}$$

where
k_A, k_B are the coefficients of heat conduction of the two metals in watts per centimeter,

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[18] Betts, p. I-11., (Equation 2 is only applicable in the linear range of operation).

[19] Ibid., p. I-12.

[20] Ibid.

degrees centigrade,
a_A, a_B are the cross sectional areas of the two metals in square centimeters,
ℓ_A, ℓ_B are the lengths of the two metals in centimeters.

From equations (4) and (5) the theoretical power input in watts, can be written:

$$P_i = eIT_h + \Delta T\left(\frac{k_A\ a_A}{\ell_A} + \frac{k_B\ a_B}{\ell_B}\right) \qquad (6)$$

And from equations (3) and (6) the general efficiency can then be calculated from:[21]

$$\eta = \frac{\text{output}}{\text{input}} = \frac{eI(\Delta T) - I^2\left(\frac{\rho_A\ \ell_A}{a_A} + \frac{\rho_B\ \ell_B}{a_B}\right)}{eIT_h + \Delta T\left(\frac{k_A\ a_A}{\ell_A} + \frac{k_B\ a_B}{\ell_B}\right)} \qquad (7)$$

Equation (7) shows the effect of the various parameters on the efficiency including the fact that the electrical and thermal conductivities of the metals themselves affect the overall efficiency.

It is very important that the efficiency of the thermopile generator be carefully analyzed. The maximum efficiency of a thermopile generator has been represented in the following general equation:[22]

$$\eta\,\text{max.} = \frac{\Delta T}{T_h}\left[1. + \frac{2.}{A} - \frac{2.}{\sqrt{1.+A}}\quad\left(1.+\frac{1.}{A}\right)\right] \qquad (8)$$

where
$$A = \frac{e^2 T_h}{4\left[\frac{(\rho_A\ \rho_B)}{2}\frac{(k_A\ k_B)}{2}\right]}$$

The maximum power output of such a device is obtained when the external load resistance equals the internal resistance of the thermopile. Therefore, since one-half of the electrical energy will be dissipated internally, it is obvious that the useful efficiency of the generator, at maximum output, is one-half of the efficiency based on total energy

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[21] Ibid.

[22] Ibid., p. I-13.

conversion. However, the useful efficiency could be greatly improved if the heat dissipated internally be utilized by recirculating this heat to raise the temperature of the fuel or of the hot junctions. In order to obtain the maximum efficiency, it is necessary to select the thermocouple metals having the lowest ratio of thermal to electrical conductivity. This is called the Wiedemann-Franz-Lorenz ratio and is expressed by:[23]

$$\frac{k}{\sigma} = 2.45 \times 10^{-8} T \qquad (9)$$

where k is the coefficient of heat conduction of the metal in watts per centimeter, degree centigrade,
σ is the coefficient of electrical conductivity in mho per centimeter,
T is the temperature in degrees kelvin.

This expression states that at ordinary temperatures, the ratio of thermal to electrical conductivity is constant for all pure metals, for a given temperature, and this seems to conform approximately in practice. However, certain alloys have higher ratios and a limited number have lower ratios than that predicted by Wiedemann-Franz-Lorenz. The basis of this law is that the conducting electrons are responsible for the flow of both the electric charge and the heat energy. The ratio of thermal to electrical conductivity appears in the expression for the efficiency of the thermopile generator. The numerical value of k/σ, is of great importance in determining what materials are suitable for such a device. Materials having the most favorable ratio of thermal to electrical conductivity are usually found among good conductors, while materials having a favorable thermoelectric power are usually found

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[23] Maria Telkes, "The Efficiency of Thermoelectric Generators," M.I.T. Solar Energy Conversion Research Project Publication No. 20., Journal of Applied Physics, Vol. 18., December, 1947, pp. 1120-1122.

among poor conductors. A compromise is therefore required.

In the preceding theoretical considerations it was assumed that there were no heat losses in the refractory insulation. Actually, it is the refractory heat loss that accounts largely for the difference between calculated and measured results. This lateral heat loss can be minimized by arranging the thermocouples in a closely packed assembly with a minimum of insulating material between the wires. When neglecting refractory losses, it can be pointed out that the efficiency of the thermocouple is not effected by the length of the wires. The length of the thermocouple wire is inversely proportional to the power output, and also the heat output through the thermopile. As the length of the thermocouple is increased, a smaller heat loss occurs in the longer wires, although the resistance is increased. The efficiency, therefore, is constant because the conduction ratio remains the same, but the maximum power is reduced.

The heat flow through the insulating material is calculated in a slightly different manner than for the thermocouple wires as in equation (5). This is due to the cylindrical shape of the thermopile which will be described in detail in Chapter IV. This heat flow is given by the expression:

$$q = \frac{2\pi k \ell (\Delta T)}{\ln(\frac{r_2}{r_1})} \qquad (10)$$

where
q is expressed in calories per second,
k is the thermal conductivity of the material in calories per centimeter, second, degrees centigrade,
ΔT is the temperature differential in degrees centigrade between the inside and outside of the thermopile,
ℓ is the height of the cylinder wall in centimeters,
r_1 is the inner radius of the cylinder in centimeters,
r_2 is the outer radius of the cylinder in centimeters.

Efforts have been made to reduce the electrical resistance of a thermocouple by increasing the cross sectional area and decreasing the length of the wires. However, this results in an increase in the thermal conductivity which means a greater transfer of heat from the hot junctions to the cold junctions. In general, materials with low resistivity also have low thermoelectric power.

It should be pointed out that because of their low efficiencies, thermopile generators are best suited for the utilization of waste heat. For some applications, consideration should be given to the direct burning of cheap commercial fuels.

A thermopile generator properly designed and having an efficiency in excess of eight per cent would revolutionize conversion units in the small power field. Such a device would find a definite place in the commercial and military fields of application.[24]

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[24] Ellis, p. 50.

CHAPTER IV

THERMOPILE GENERATOR DESIGN AND INSTRUMENTATION

Since the theoretical considerations have now been explored, the actual design and construction of the thermopile generator may be examined. Also the method of instrumentation is discussed in this chapter. In the search for optimum performance, two identical generators were built using different thermocouple materials. However, the construction described below will apply equally well to both generators.

The three principle parts of the thermopile generator are the generator housing, a heat source, and a coolant or cooling fins. The generator housing was given the most consideration as its construction is critical. Because of the thermoelectric effect, no prime mover is needed, as required by electromagnetic type of generators. Actually, a thermopile generator can be constructed with no moving parts since the direct current generated requires no commutation. With these thoughts in mind, an extremely simple design was made possible. Since there must be an insulating material between adjacent wires and the hot junctions should all receive equal heat, a cylindrical design with a hole through the axis was used as shown in Figure 6. In addition to supplying the hot junctions with equal heat, this design also provides a channel for the heat to flow. The cold junctions on the outside of the cylinder are easily accessible to a coolant or for the addition of cooling fins.

The general construction consisted of pie-shaped wafers into which the thermocouples were embedded during the casting process. After the

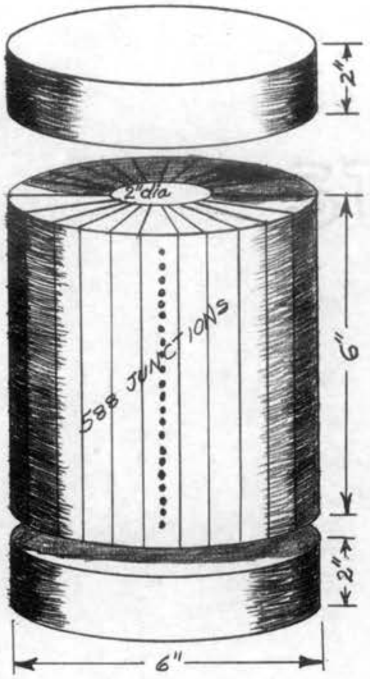


Figure 6. Thermopile generator construction

refractory material was allowed to dry at room temperature, the wires were silver soldered together to form the hot and cold junctions. A photograph of a completed wafer is shown in Plate I. The wafers are then cemented together with the same refractory material to form the cylinder shown in Figure 6. Plate II shows a photograph of the two halves of the cylinder just before they were cemented together. Next, the wafers were all connected in series except for the output leads. Cast ends then completed the generator.

An effort was made to obtain a refractory insulating material of the lowest thermal conductivity. In Table II, a comparison of four commercial refractories shows "Kast-o-lite" to have an unusually low thermal conductivity. The refractory material was allowed to cure at room temperature since a suitable furnace was not available for firing as recommended by the manufacturer. If they were to be fired, it would

Plate I

Typical Thermopile Wafer

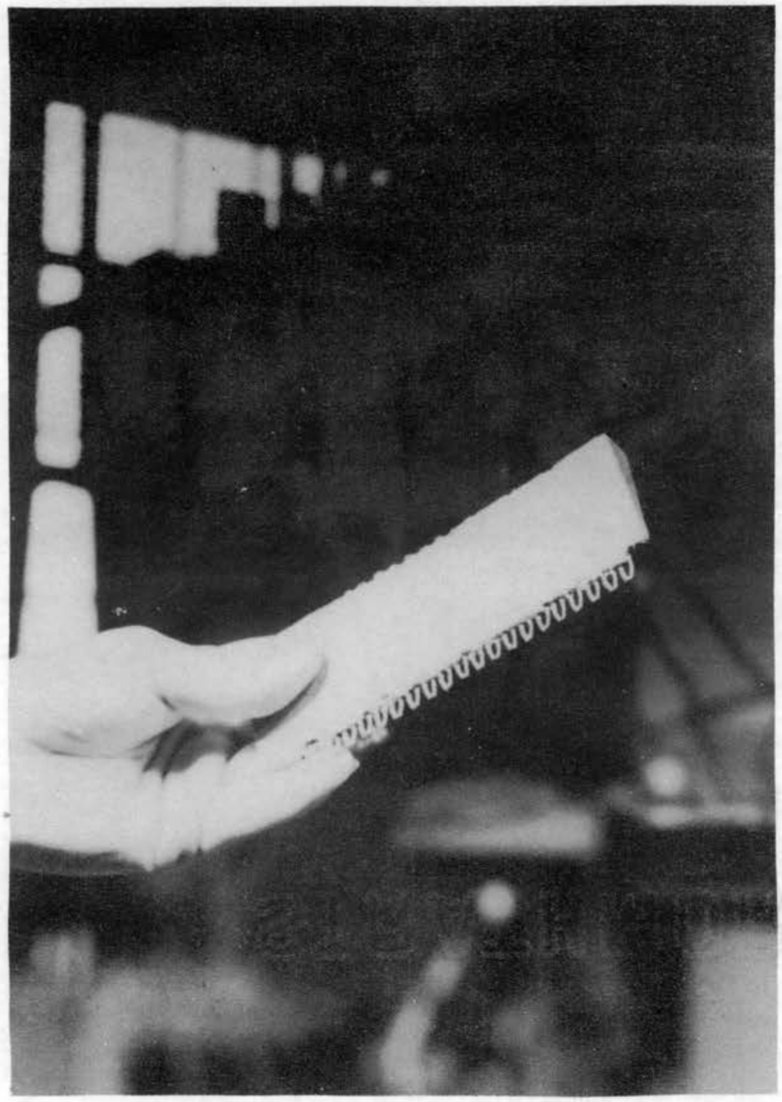
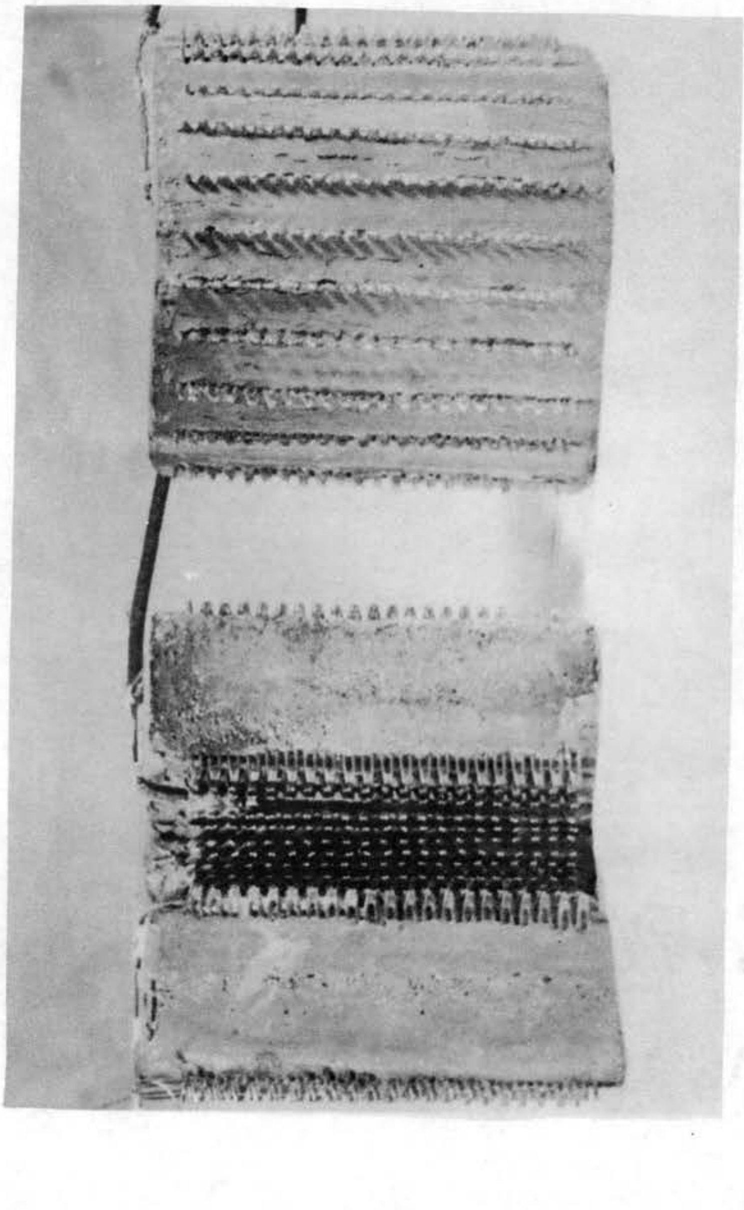


Plate II

Two Halves of the Generator Housing



be necessary to provide a large quantity of an inert gas to prevent oxidation of the thermocouples during the firing. A more detailed discussion of oxidation will be presented in Chapter VIII. Unfired samples of two of the refractory materials were tested in the laboratory and "Kast-o-lite" still proved to be superior as shown in Table III.

TABLE II

COMMERCIAL REFRACTORY MATERIALS.

TRADE NAME & MANUFACTURER	THERMAL CONDUCTIVITY Btu./sq.ft.-Hr.-^{o}F-in.	TEMP. ^{o}F.	CHEMICAL ANALYSIS Per Cent
"KAST-O-LITE" (A.P. Green Co. Mexico, Mo.)	1.79	600	Silica - 40% Alumina - 35% Iron Oxide - 4.5% Lime - 15% Magnesia - 1% Titania - 2.5% Alkalies - 2%
"ALFRAX" No. 58 (Christy Firebrick Co., St. Louis, Mo)	7.30	600	Alumina bubbles with Calcium Aluminate - 100%
"ALSIMAG" 202 (American Lava Corp., Chattanooga, Tenn.)	8.70	600	Cordierite-Ceramic.
Fire Clay (pure) (Mark's Handbook, Fifth Edition.)	6.50	600	Standard.

TABLE III

LABORATORY TESTS OF REFRACTORY MATERIALS.

TYPE	TEST DATA (unfired) Btu/sq.ft.-Hr.-^{o}F-in.	MANUFACTURER'S DATA (fired) Btu./sq.ft.-Hr.-^{o}F-in.
"KAST-O-LITE"	6.45	1.79
"ALFRAX"No.58	10.20	7.30

Although the thermopile was designed for the utilization of waste heat, it was necessary to provide a uniform and controlled heat source for accurate laboratory performance data. In the testing of the generators, a commercial heating rod was used that met the above qualifications. A "Globar" heater rod ($\frac{1}{2}$" x 6" x 13"), consisting of self-bonded crystals of silcon carbide and manufactured by the Carborundum Company of Niagara Falls, New York, was placed in the center of the thermopile and held in position by the cast ends. A controlled source of current through the "Globar" allowed the input heat to be accurately regulated.

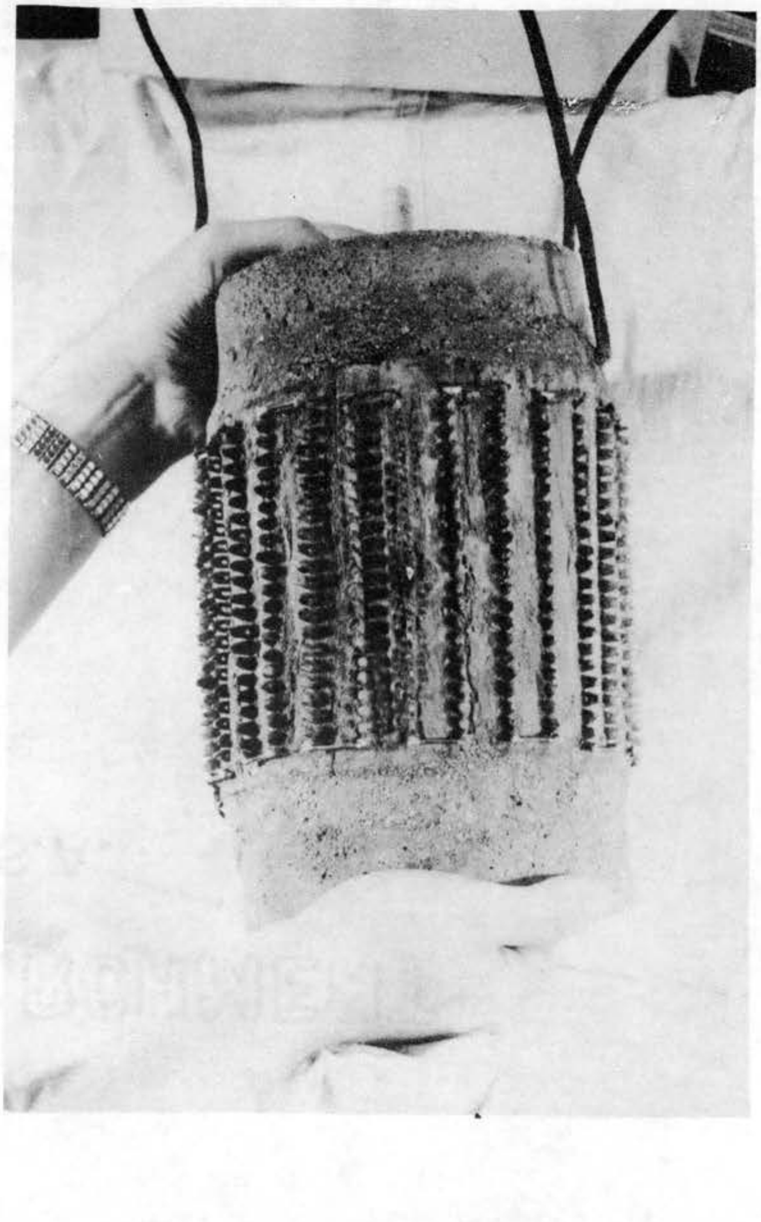
During the early test runs on both generators, an external coolant was used to obtain a larger temperature differential. The generators were placed in a metal container and crushed dry ice was packed around the outside of the thermopile. Cooling fins were later added for a more practical type of generator and the results will be discussed in Chapter VI.

Additional thermocouples were also used in the thermopile generator as temperature measuring devices. Three thermocouples were connected directly to the hot junctions on the inside of the thermopile to obtain an average T_h. Three more were connected to the cold junctions on the outside to obtain an average T_c. A General Electric potentiometer was used to measure the emf's of these thermocouples. The temperatures were then read directly from the graphs in Figure 1. Plate III is a photograph of the completed thermopile generator ready for testing.

Standard commercial laboratory equipment was used in the testing of the thermopile generators. The three principle parts of the test setup are the heater circuit, the thermopile load, and the temperature measuring equipment. Figure 7, shows the schematic diagram of the equipment arrangement and Plate IV is a photograph of the entire test

Plate III

The Thermopile Generator



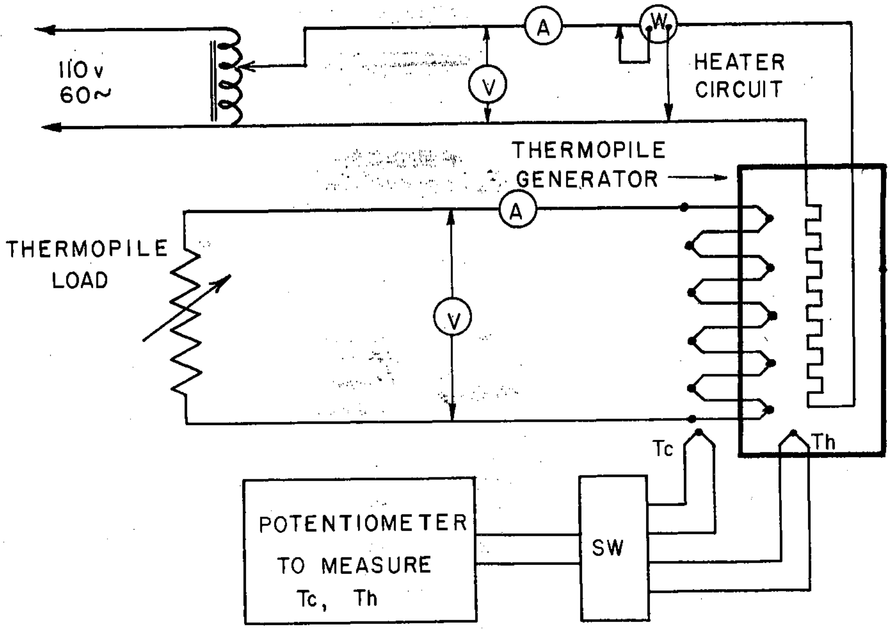


Figure 7. Schematic diagram of test setup.

setup in operation. The photograph shows the thermopile generator with cooling fins. It should be remembered that the first test runs were made without cooling fins, the thermopile being packed with dry ice instead. About 150 pounds of this coolant were used per day of operation.

The following equipment was used in the performance tests:

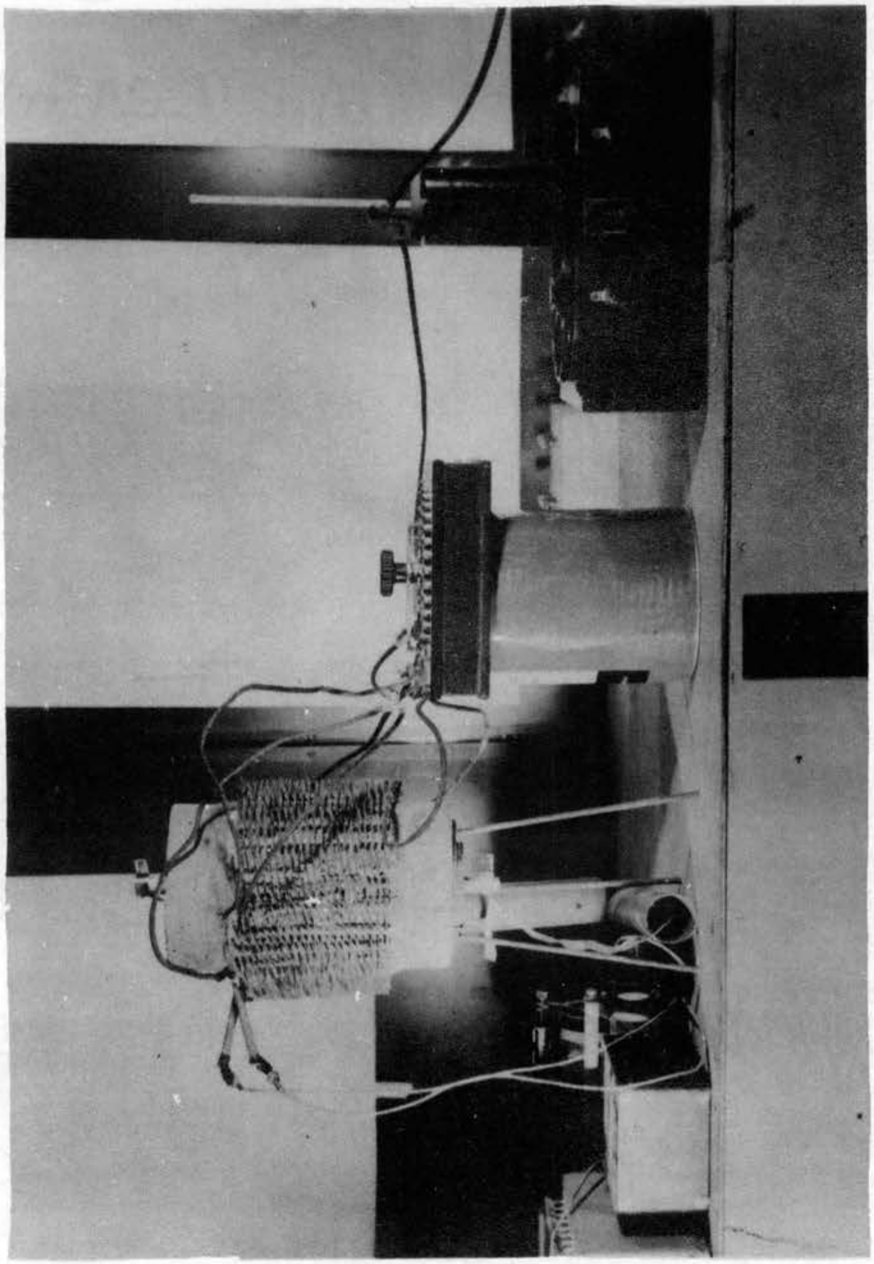
HEATER CIRCUIT

Voltage Regulator, 0-115 volts @ 100 amps., Transtat, No. 29145.
A. C. Voltmeter, 0-150 volts, Weston, Model 155., No. 36955.
A. C. Ammeter, 0-50 amps., Weston, Model 115., No. 55259.
A. C. Wattmeter, 0-3.75 kilowatts, Weston, Model 16, No. 1221.
Current Transformer, 5 to 50 ratio, Westinghouse, Type PC-137., No. 3310142., (Used with wattmeter).

The heater circuit provided a controlled source of current through the heating rod in order that the input heat may be accurately regulated. Data of input voltage, current, and power were recorded.

Plate IV

Laboratory Test Setup



THERMOPILE LOAD

Rheostat, 0-180.0 ohms, Cenco, (Number not given),(Preliminary adjustment).
Rheostat, 0-13.7 ohms, Biddle, No. 75664., (Final adjustment).
D. C. Voltmeter, 0-7.5-30 volts, Weston, Model 430., No. 5496.
D. C. Ammeter, 0-1-10-50-250 milliamps., Triplett, Model 1220F., No. 15156., (Small readings of current).
D. C. Ammeter, 0-1.5 amps., Weston, Model 45., No. 29648., (Large readings of current).

The thermopile load provided a means of obtaining performance data of the thermopile generator output. Data of output voltage and current as a function of load resistance were recorded.

TEMPERATURE MEASURING EQUIPMENT

Thermocouple Potentiometer, 0-6-30-60 millivolts, General Electric, Type PJ-84., No. 3246091.
Transfer Switch, General Electric, Cat. 2855639GR1.

The temperature measuring equipment provided a means of accurately measuring the temperatures of the hot and cold junctions. The potentiometer was used to measure the emf's of the temperature measuring thermocouples. The individual thermocouple leads were brought out to the multi-point transfer switch before connecting to the potentiometer.

Thermocouples used for temperature measurements should have a constant cold junction temperature. The cold junctions were placed in melting ice water in order that changes in the ambient room temperature would not introduce errors.

It should be pointed out that the balance type manually operated potentiometer, such as the G. E. Type PJ-84., is a widely used means of measuring thermocouple voltages. The circuit diagram in Figure 8 shows this potentiometer to consist of a dry cell, control rheostat, series milliammeter, standardized resistor, and a galvanometer. In use, the unknown thermocouple output is balanced against the voltage drop across the standard resistor, with the galvanometer used as a detector of equal potentials. Therefore, the current through the series

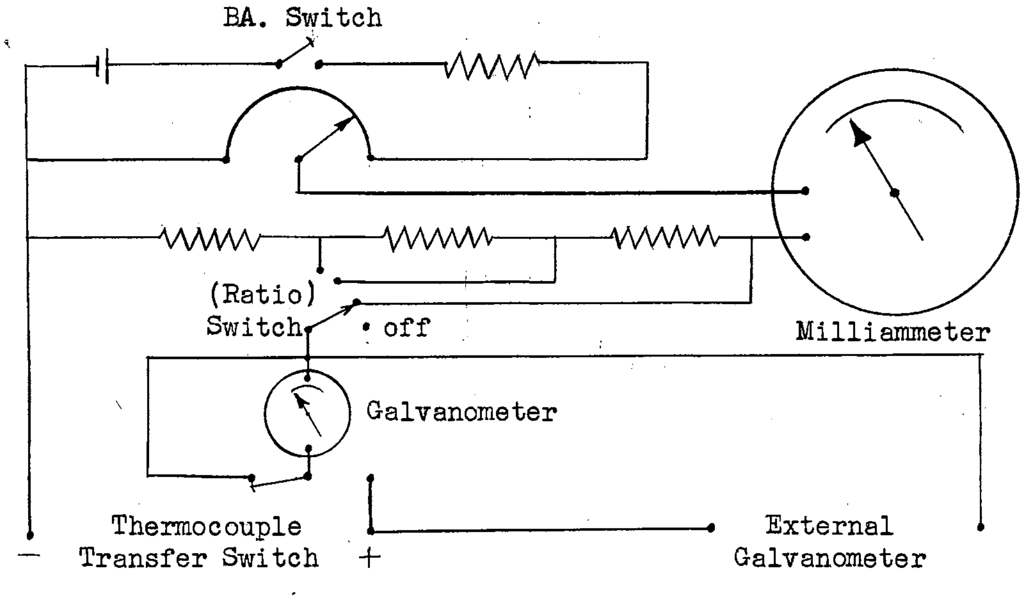


Figure 8. Internal Connections of the G. E. Potentiometer, Type PJ-84.,(General Electric Manual, GET-1087B).

milliammeter is directly proportional to the drop across the standardized resistor and to the thermocouple emf when the galvanometer shows zero potential difference. The potentiometer instrument reads the temperature difference between the thermocouple junction and the cold junction (melting ice in this case).[25]

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[25] "Specialized Instruments to Measure Nonelectrical Quantities", Manual of Electrical Instruments; General Electric Manual GET-1087B, (Schenectady, N. Y., 1952), p. 120.

CHAPTER V

THE COPPER-CONSTANTAN THERMOPILE GENERATOR

The first of the two generators to be built and tested was the thermopile using copper and constantan as the thermocouple elements. These materials were chosen first because of the lower melting point of copper, the ease of handling this softer metal, and the lower electrical resistance. This chapter deals with the theoretical calculations and the actual performance of this generator.

In order to determine the accuracy of the thermocouple calibration curves of Figure 1, a thermoelectric emf test was made of the voltage output of one thermocouple at a time. Several copper-constantan thermocouples were constructed for this purpose. One junction was placed in boiling water and the other in melting ice. A potentiometer measured the thermoelectric power as .0428 millivolts per degree centigrade which compared favorably with .04276 millivolts per degree centigrade found in the General Electric Tables of Thermocouple Characteristics. All the thermocouples tested were found to have the same voltage output which would indicate good uniformity in the construction of the junctions.

Theoretical calculations of the heat flow of the system were made in order to determine the size and type of equipment that would be needed to furnish the required power input. It was determined from these calculations that there would be about 880 calories per second of heat, or about 3.7 kilowatts of electrical power, required to maintain a desired constant temperature differential of 400 degrees centigrade in the thermopile. However, the required power input was slightly less than the calculated value. This difference was due to the value used for the thermal conductivity (k), of the refractory material. The value used in the calculations, obtained from the manufacturer, was for the refractory material after it had been fired. The refractory material used in these experiments was allowed to cure at room temperature only, thereby causing the value for'k' to be inaccurate.

Calculations of the theoretical internal thermopile resistances were made so that the theoretical output power, voltage, and current could be determined. The results of these calculations are given in Table IV for a temperature differential of 356 degrees centigrade.

TABLE IV

THEORETICAL INTERNAL RESISTANCES OF THE COPPER-CONSTANTAN THERMOPILE GENERATOR. ($\Delta T = 356^{\circ}C$)

Resistance of the constantan wire	8.340000 ohms
Resistance of the copper wire	0.658000 ohms
Resistance of the junctions	0.001175 ohms
Resistance of the segment connections	0.003460 ohms
Resistance of the segment junctions	0.000056 ohms
Total	9.002691 ohms

This temperature differential was the highest measured differential of the test runs. The total of 9.002691 ohms compares favorably with the total internal resistance at room temperature ($\Delta T = 0$), which was found to be 8.710 ohms by actual measurement.

Several test runs were made with the copper-constantan thermopile generator. These test runs were made at increasing temperature differentials up to 356 degrees centigrade. The temperature limiting factor was the melting point of the silver solder used in the thermocouple junctions as mentioned previously.

Theoretical power output, efficiency, load voltage, and load current calculations were made using the 356 degree centigrade temperature differential. Figure 9 shows the power output of the generator, and Figure 10 shows the efficiency results. Figure 11 shows the voltage and current relations. These graphs indicate the measured results to be slightly less than the calculated values in all cases. This difference is largely due to the excessive heat loss through the walls of the refractory cylinder, a factor which is not considered in the theoretical calculations. Another source of error was in the junctions of the thermocouples. These junctions were silver soldered by an oxyacetylene flame in air which caused a slight oxidation in the junctions. This not only increased their resistance, but also lowered the thermoelectric power slightly.

Since the efficiency of the thermopile is of great interest, a graph has been drawn in Figure 12, showing the maximum efficiencies at different temperature differentials. The major differences between the calculated and measured results have been mentioned previously. The maximum efficiencies found experimentally agree with the results made by other experimentors. Again it should be pointed out that if efficiencies are to be improved, metals and alloys with a lower Wiedemann-Franz-Lorenz constant must be found.

A noted disadvantage with the copper-constantan thermopile generator was the large quantities of input power needed to produce the input heat. The copper element was the cause of this with its very large thermal conductivity factor. Also, this caused the efficiencies to be small, in the order of .07% maximum. These disadvantages led to the development of the iron-constantan thermopile generator described in the following chapter.

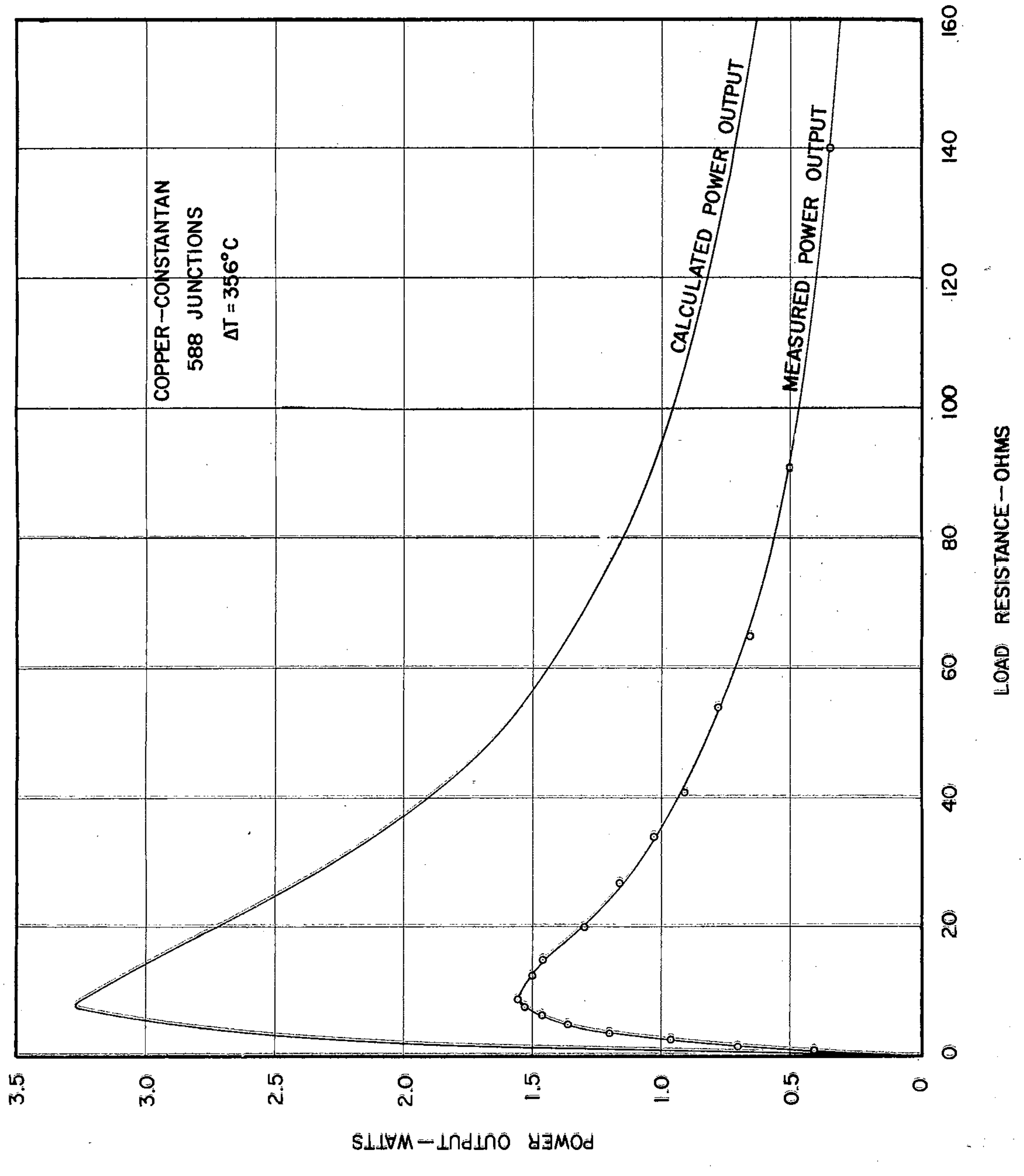


Figure 9. Power Output of the Copper-Constantan Thermopile.

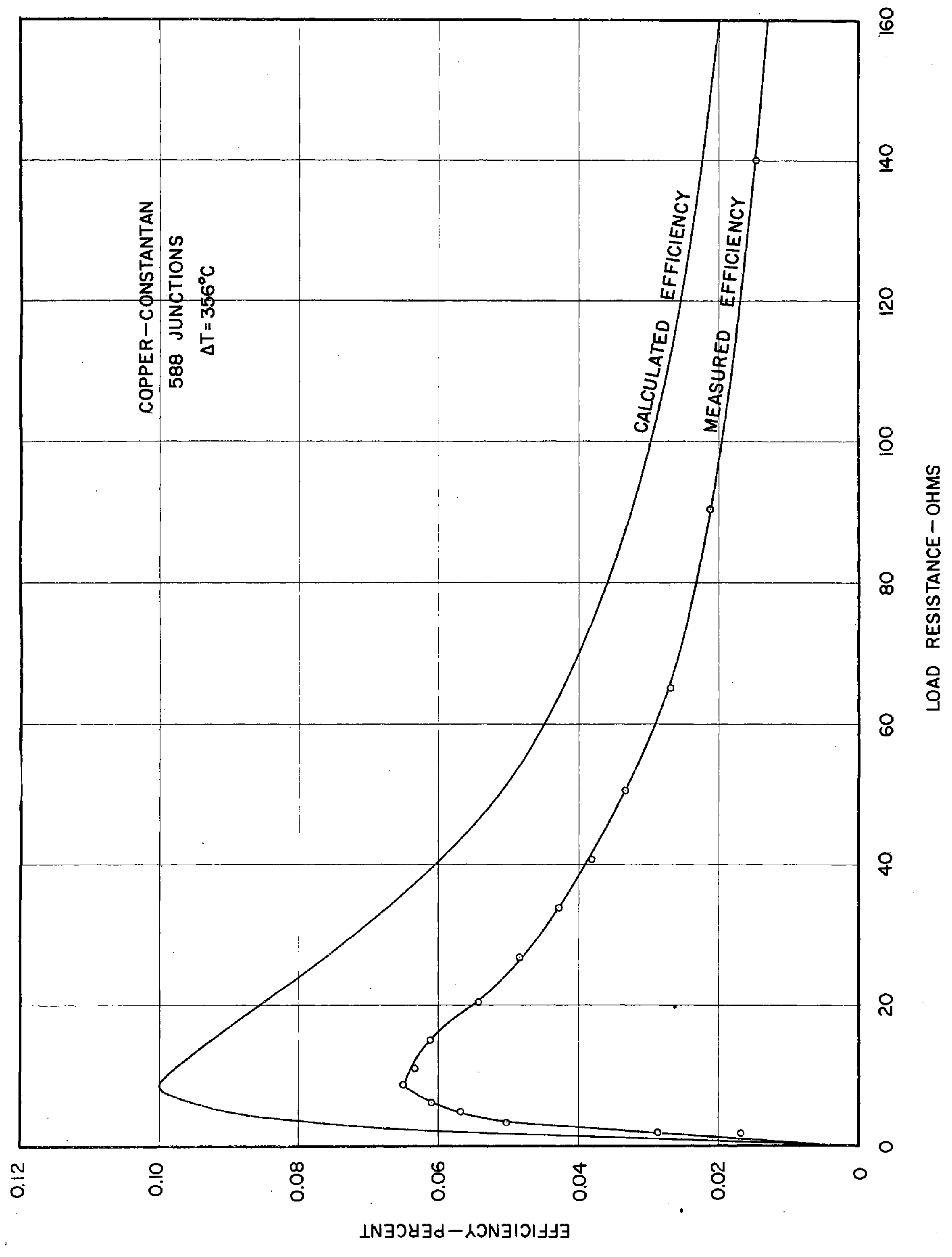


Figure 10. Efficiency of the Copper-Constantan Thermopile.

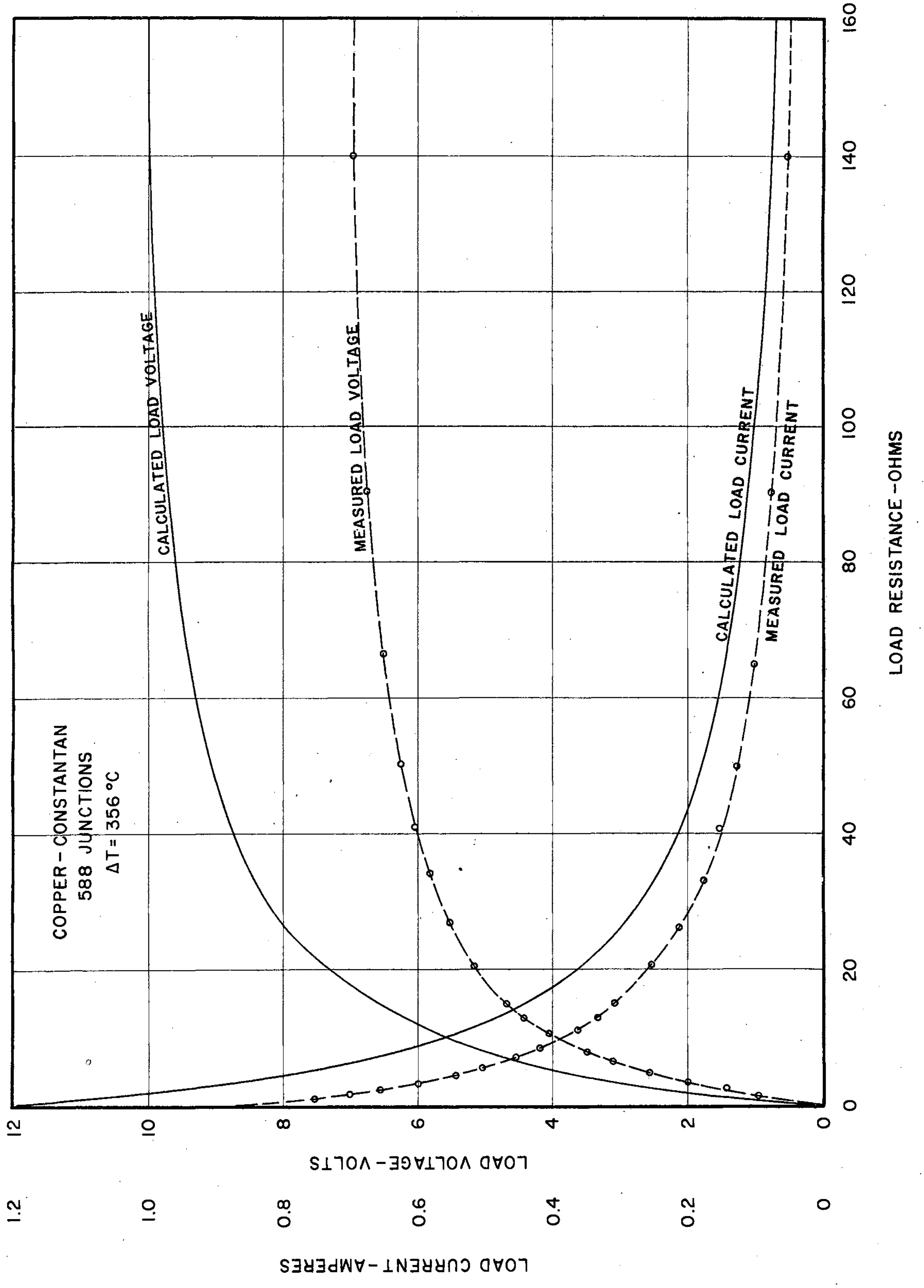


Figure 11. Voltage and Current of the Copper-Constantan Thermopile.

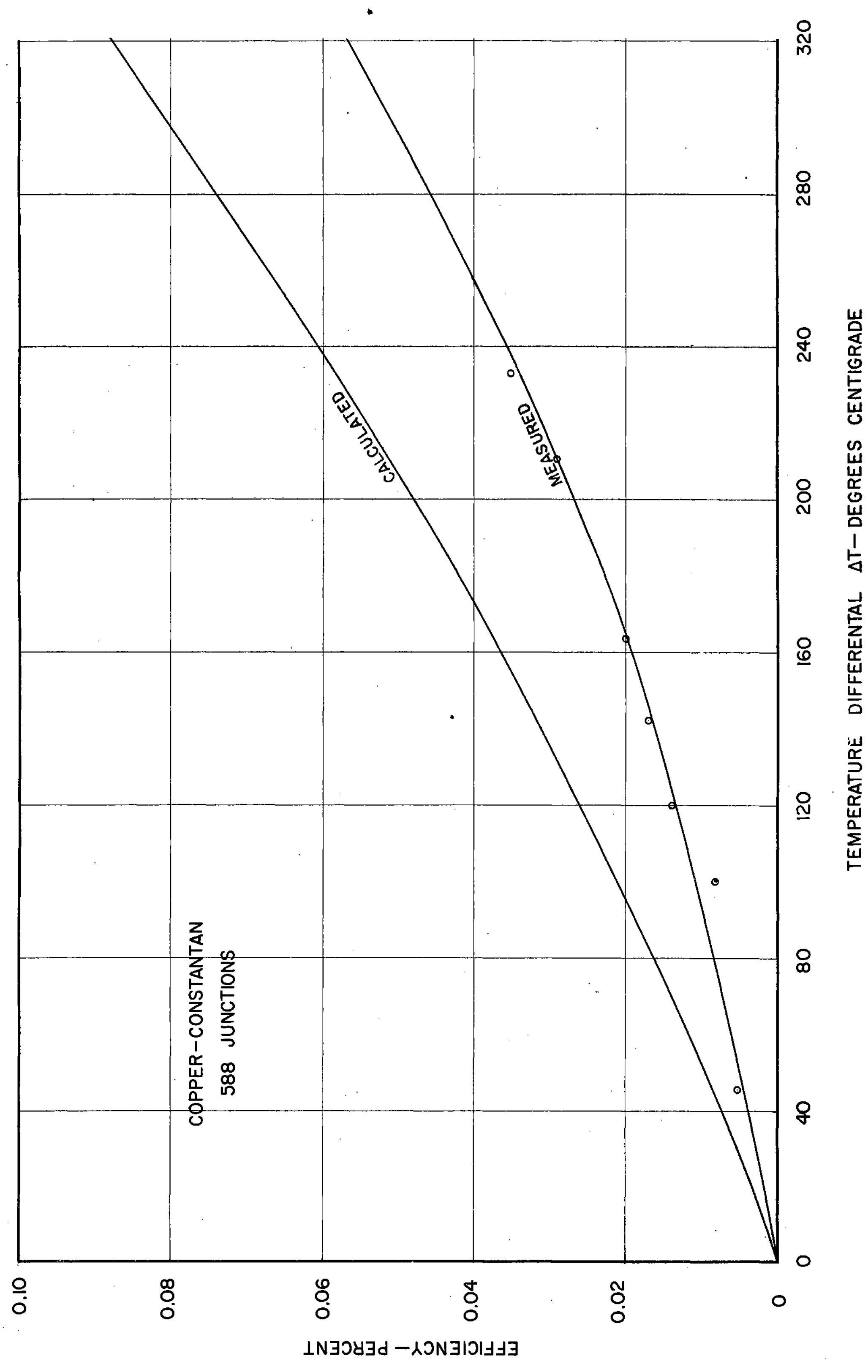


Figure 12. Maximum Efficiency of the Copper-Constantan Thermopile

CHAPTER VI

THE IRON-CONSTANTAN THERMOPILE GENERATOR

The iron-constantan thermopile generator was built in order to overcome some of the disadvantages of the copper-constantan thermopile. Theoretical calculations indicated that the main advantage of this generator over the one using copper and constantan was that the heat required to maintain a given temperature differential would be reduced to less than one-fourth. Although this was at the expense of some increase in internal resistance, the efficiency was increased by several times. Also there was an increase in the thermoelectric power. This chapter deals with the theoretical calculations and the actual performance of the iron-constantan thermopile generator. Also, the results of the fin design and construction are given.

As before, the calculations of the theoretical internal thermopile resistances were made so that other theoretical calculations could be determined. Table V lists the individual internal resistances. The

TABLE V

THEORETICAL INTERNAL RESISTANCES OF THE IRON-CONSTANTAN THERMOPILE GENERATOR. ($\Delta T = 356^{\circ}C$)

Resistance of the constantan wire	8.340000 ohms
Resistance of the iron wire	3.377260 ohms
Resistance of the junctions	0.001175 ohms
Resistance of the segment connections .	0.003460 ohms
Resistance of the segment junctions ...	0.000056 ohms
Total	11.721951 ohms

above summation compares favorably with the total resistance at room temperature ($\Delta T = 0$), which was found to be 9.70 ohms by actual measurement.

To more easily observe the advantages of the iron-constantan thermopile over the copper-constantan thermopile, the information shown in Table VI was calculated. This table shows the theoretical calculations of heat flow, power input, internal resistance, and thermoelectric power for both thermopile generators. It reveals the decided advantage of the iron-constantan generator.

TABLE VI

A THEORETICAL COMPARISON OF TWO THERMOPILE GENERATORS

GENERATORS @400°C ΔT	HEAT FLOW Cal./sec.	POWER INPUT Watts	INTERNAL RES. Ohms	THERMOELECTRIC POWER mv/juction
Cu-Copnic	878.8	3,680.0	9.0030	20.90
Fe-Copnic	202.8	849.0	11.7220	22.10

Several test runs on this generator were made at increasing temperature differentials. Again, the silver solder limited the use of higher temperatures at the hot junctions. Theoretical power output, efficiency, load voltage, and load current calculations were made using a 356 degree centigrade temperature differential. A comparison between these calculations and the actual test data is represented in Figures 13, 14, and 15. The difference between calculated and measured results were discussed in Chapter V. Figure 16 shows the maximum efficiencies at different temperature differentials.

Tests of the two generators were made with dry ice in order to further increase the temperature differential necessary to produce larger

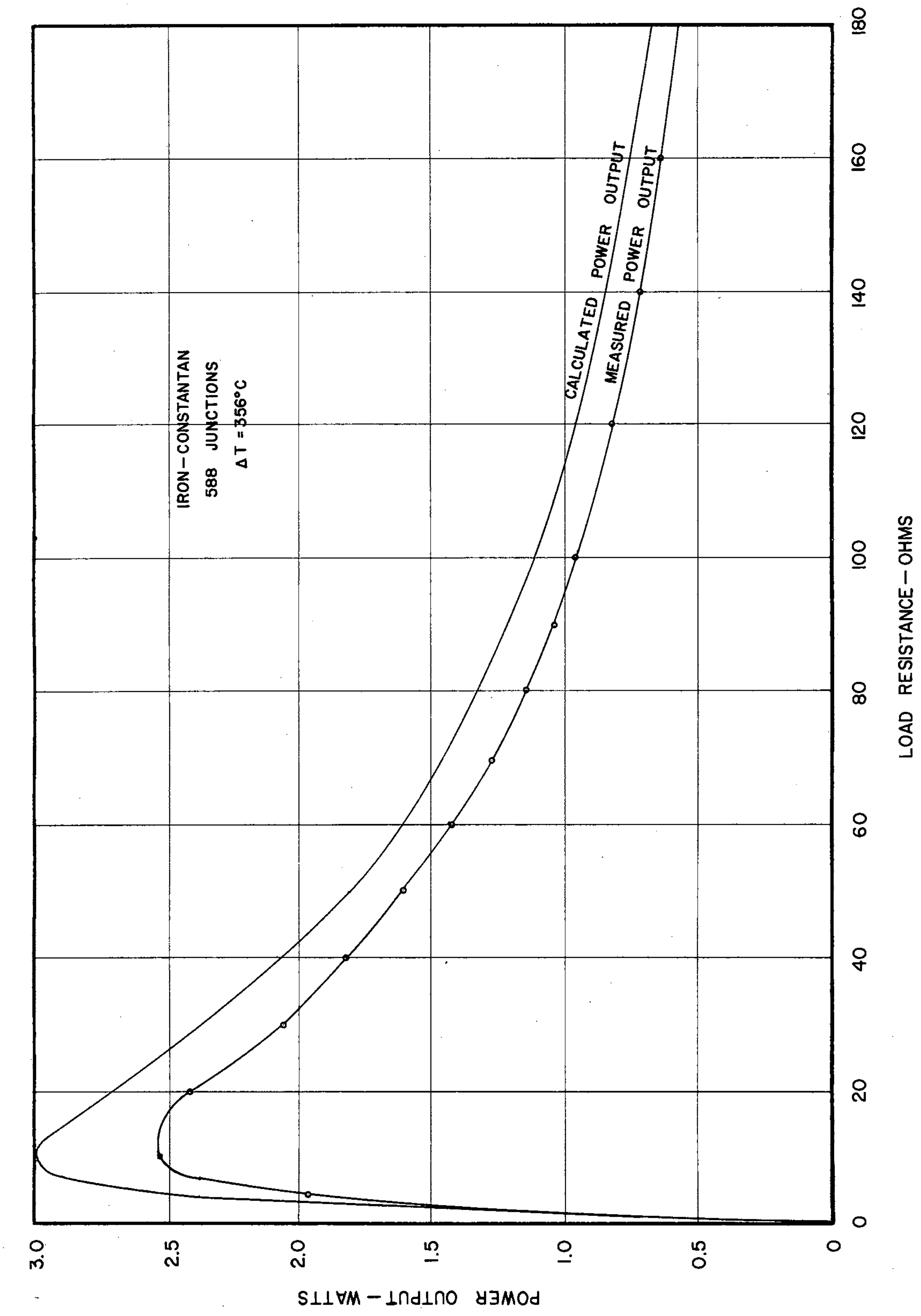


Figure 13. Power Output of the Iron-Constantan Thermopile.
(Dry ice cooling T_h = 356°C)

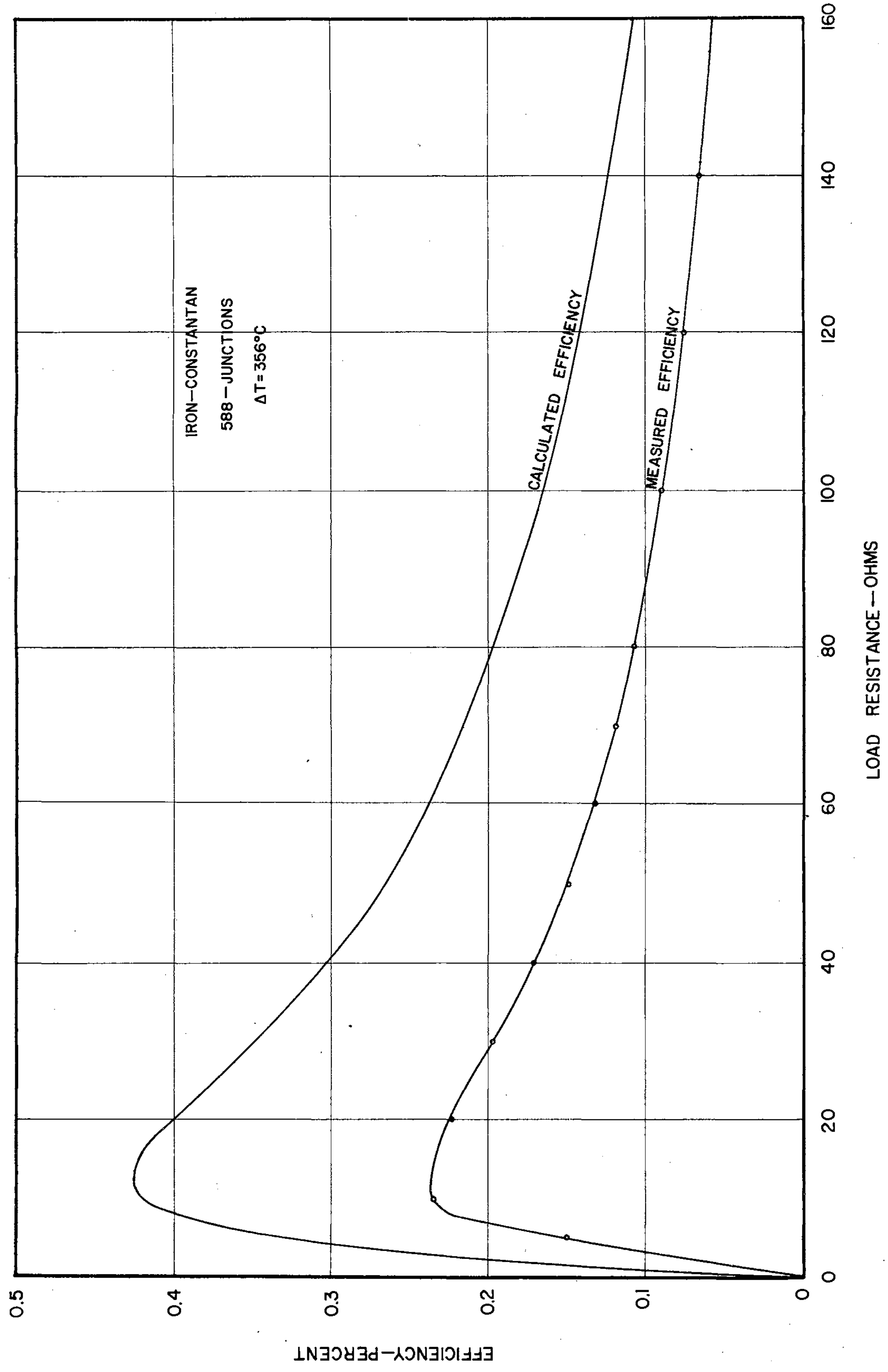


Figure 14. Efficiency of the Iron-Constantan Thermopile.
(Dry ice cooling $T_h = 356^{\circ}C$)

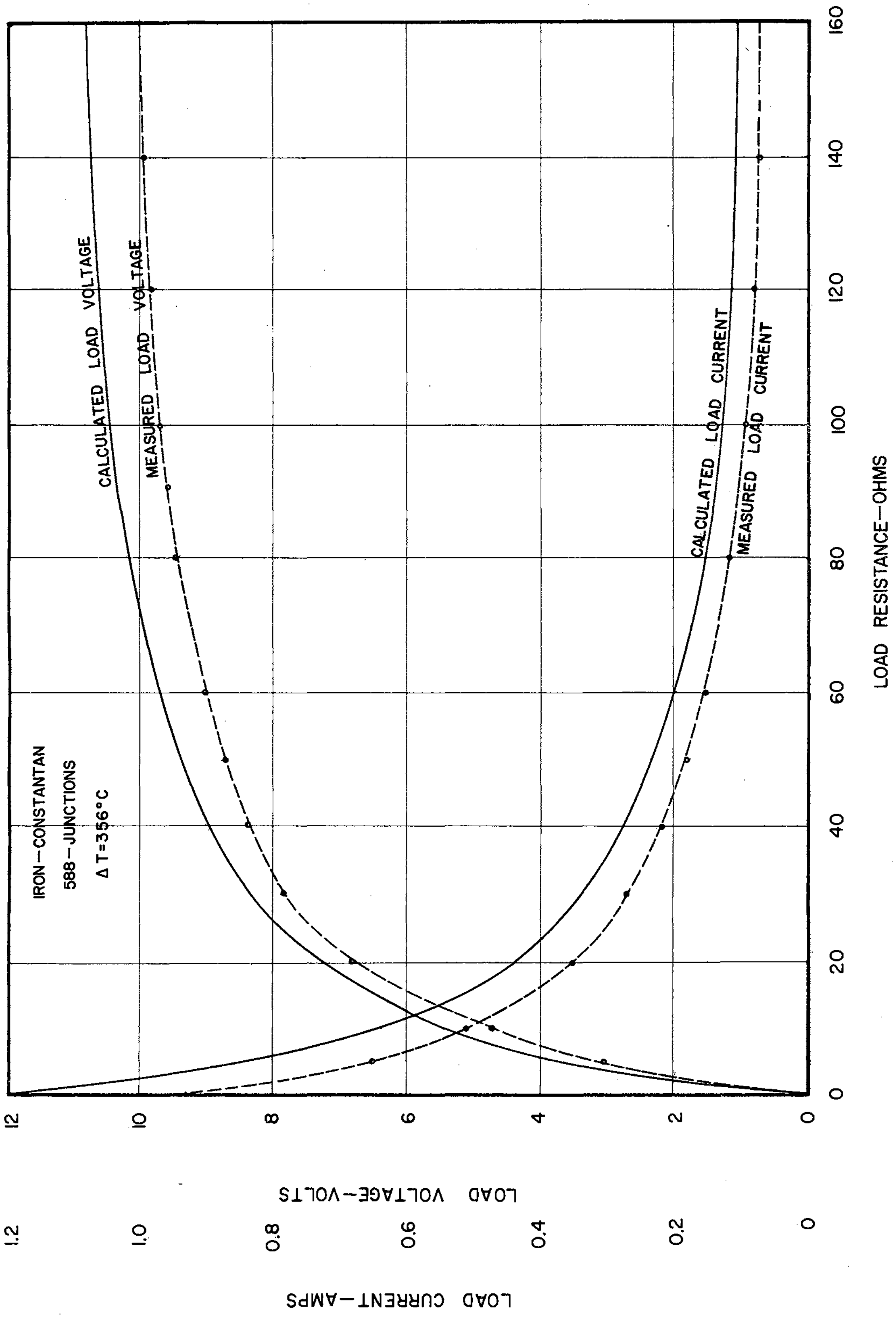


Figure 15. Voltage and Current of the Iron-Constantan Thermopile
(Dry ice cooling $T_h = 356^{\circ}C$)

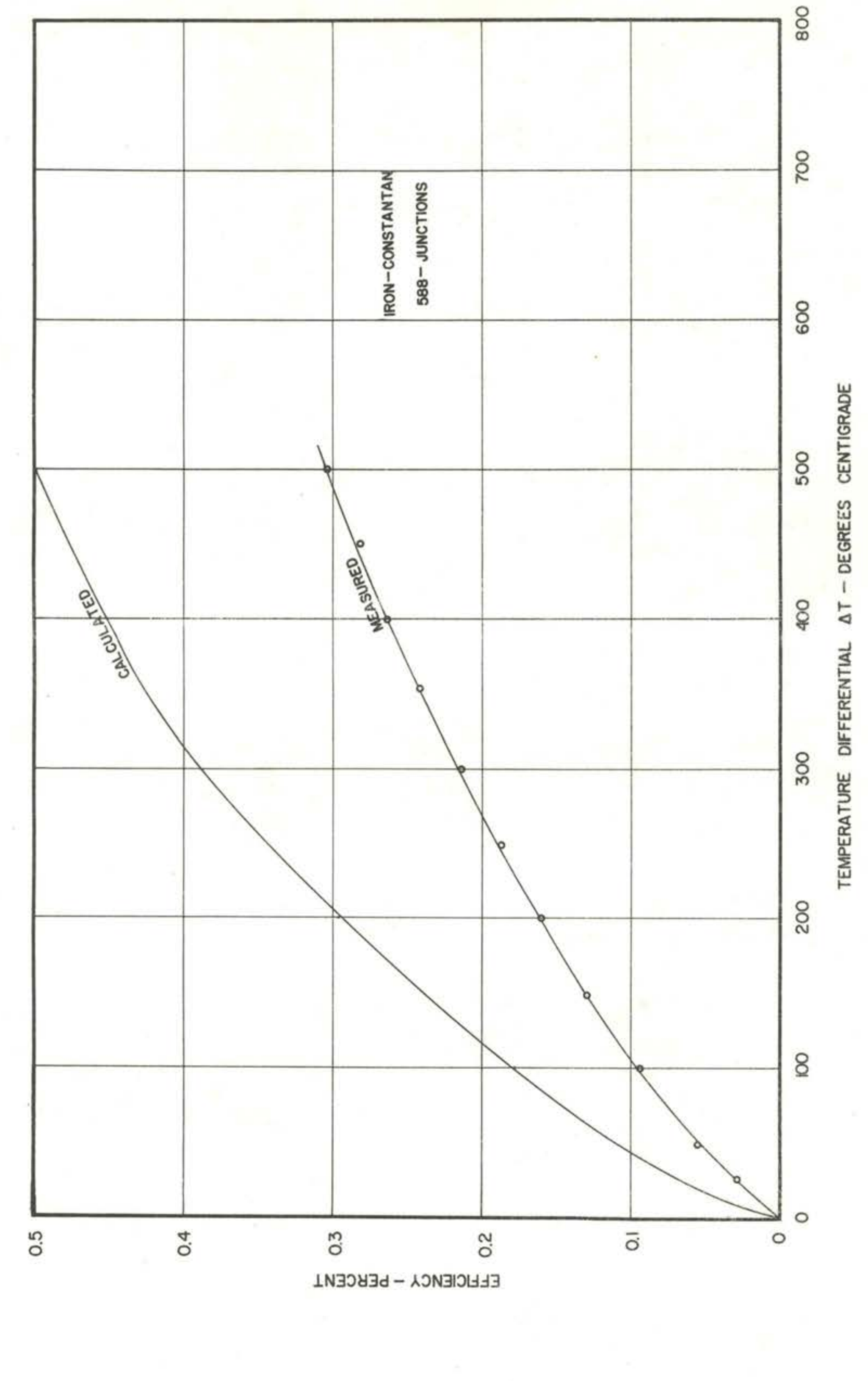


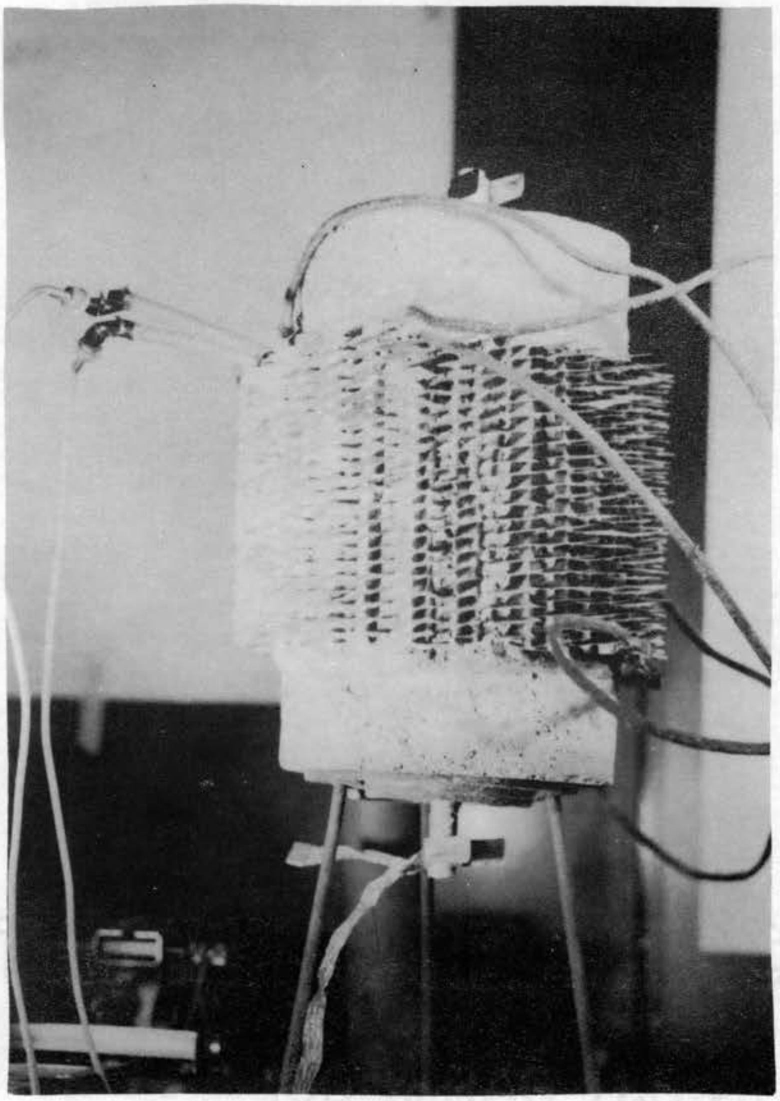
Figure 16. Maximum Efficiency of the Iron-Constantan thermopile. (Dry ice cooling $T_h = 356^{\circ}C$)

emf's. Naturally, the use of such a coolant is expensive and impractical. After the tests were completed with the use of dry ice, cooling fins were added to the iron-constantan generator and circulating air was provided which resulted in a more practical device. The cooling fins were constructed of copper strips, 1/2" x 1/2" x 1/32", and were silver soldered directly to the outside junctions. Plate V shows the iron-constantan thermopile generator with the cooling fins attached. Air at room temperature, 28.5 degrees centigrade, was blown across the thermopile at several different velocities. The results of these test runs are shown in Figures 17 and 18.

It is obvious from these results that the addition of cooling fins on the thermopile generator are a necessity if the generator is to be a practical one. It should be noted here that the cost of the cooling fin material was far less than the price of the dry ice used in one day of operation.

Plate V

The Thermopile Generator With Cooling Fins



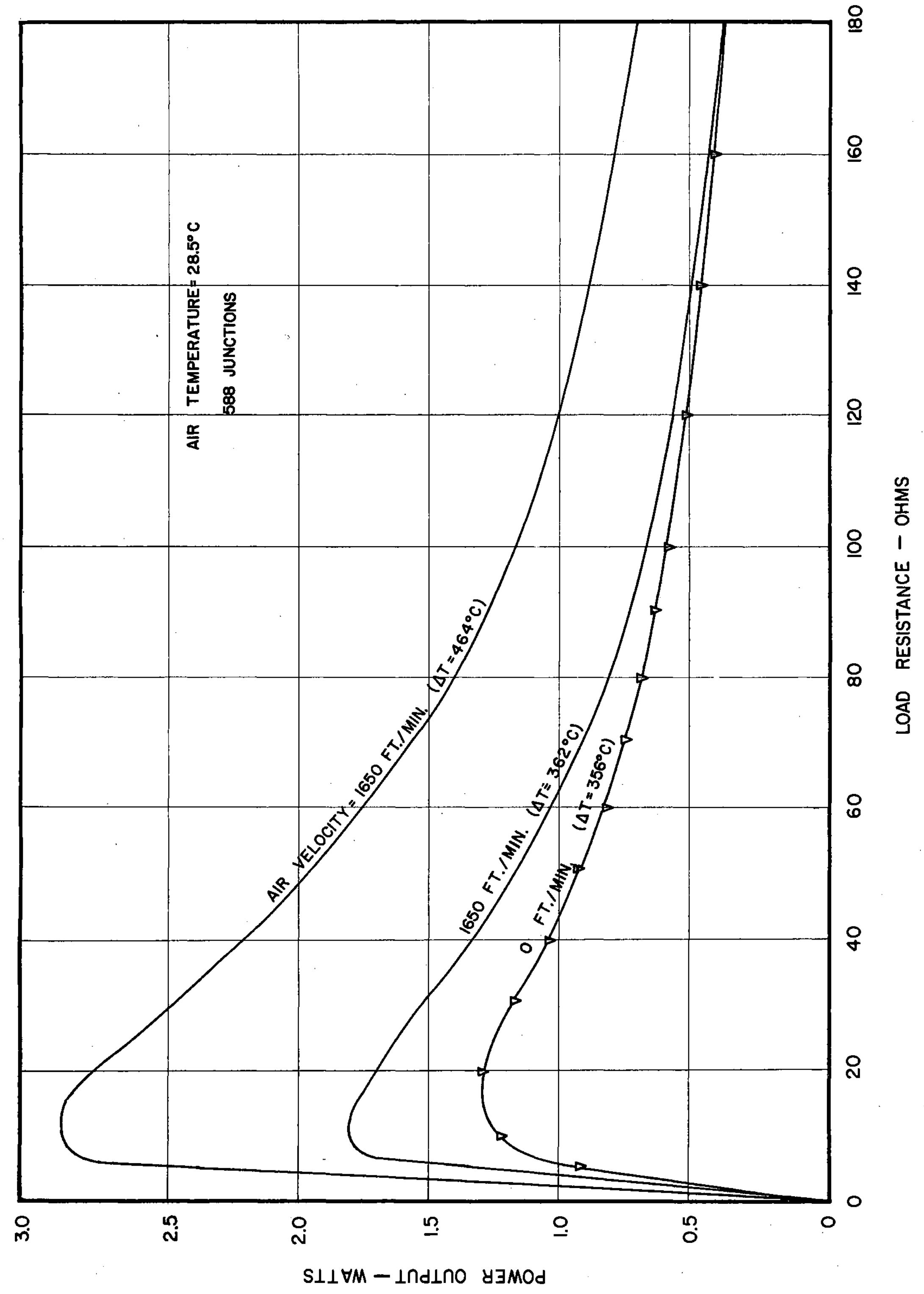


Figure 17. Power Output of the Iron-Constantan thermopile Generator with cooling fins.

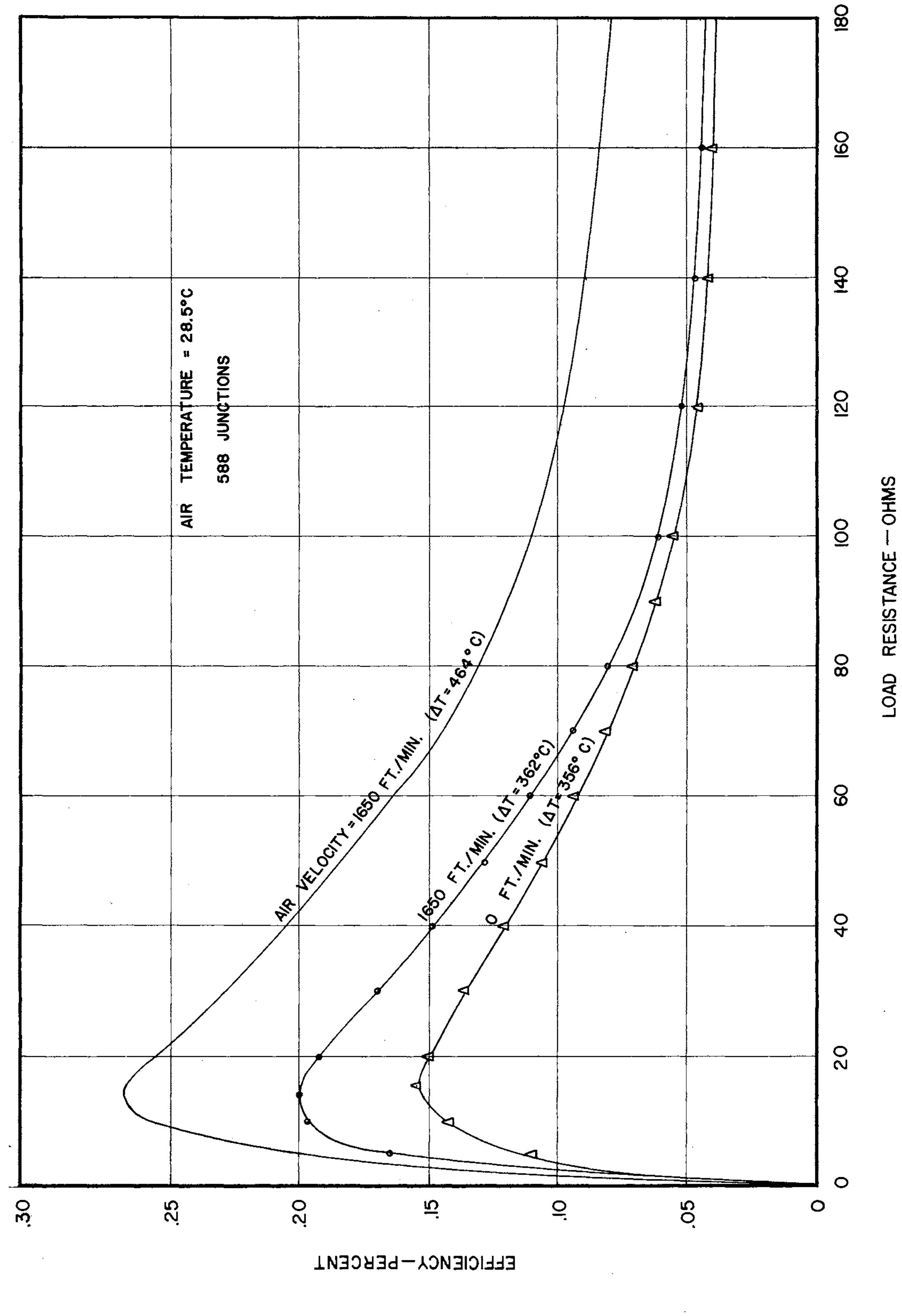


Figure 18. Efficiency of the Iron-Constantan Thermopile Generator with cooling fins.

CHAPTER VII

COMPARISON OF THE GENERATORS TESTED

This chapter was written for the purpose of comparing the measured results of the two generators and the effect produced by the addition of cooling fins. According to Table VI, it was expected that the iron-constantan thermopile would excel in all-round performance, except for a slight increase in the internal resistance. Even though it does have this higher resistance, it still out-performed the copper-constantan generator in all respects. Figures 19, 20, 21, and 22 show the output voltage, current, power, and efficiency, respectively, as a function of load resistance for both generators. From these performance curves it may be seen that the iron-constantan generator with cooling fins but no air velocity even outperformed the copper-constantan using dry ice as a coolant.

In Figures 23 and 24, power input and the maximum efficiencies are shown as functions of the temperature differential. It is interesting to observe that the power input for the thermopile with cooling fins is slightly less than that of the same generator using dry ice as a coolant.

The performance curves shown in this chapter supply more definite proof that the addition of cooling fins to any practical thermopile generator is a necessity.

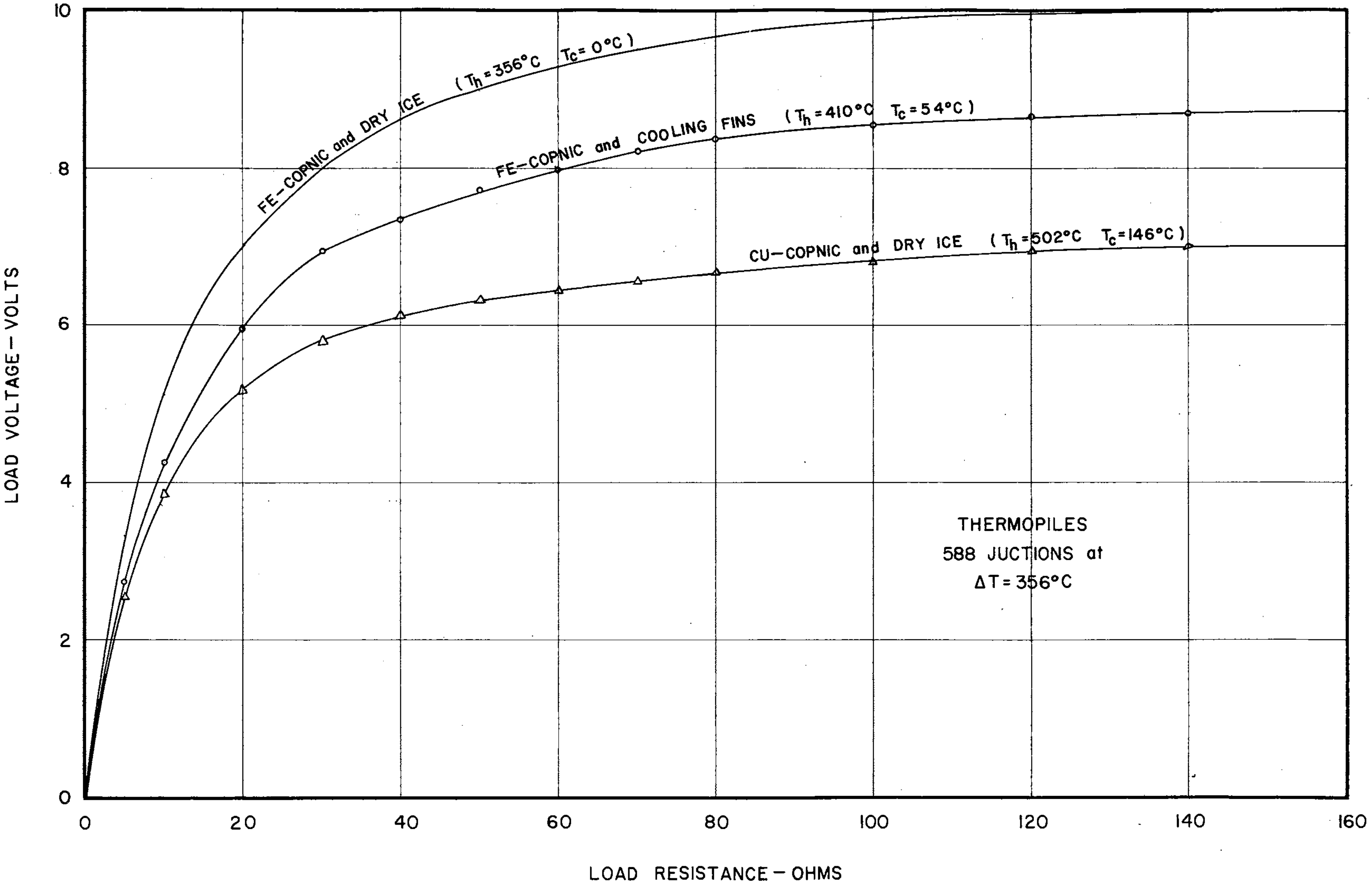


Figure 19. Voltage output comparison.

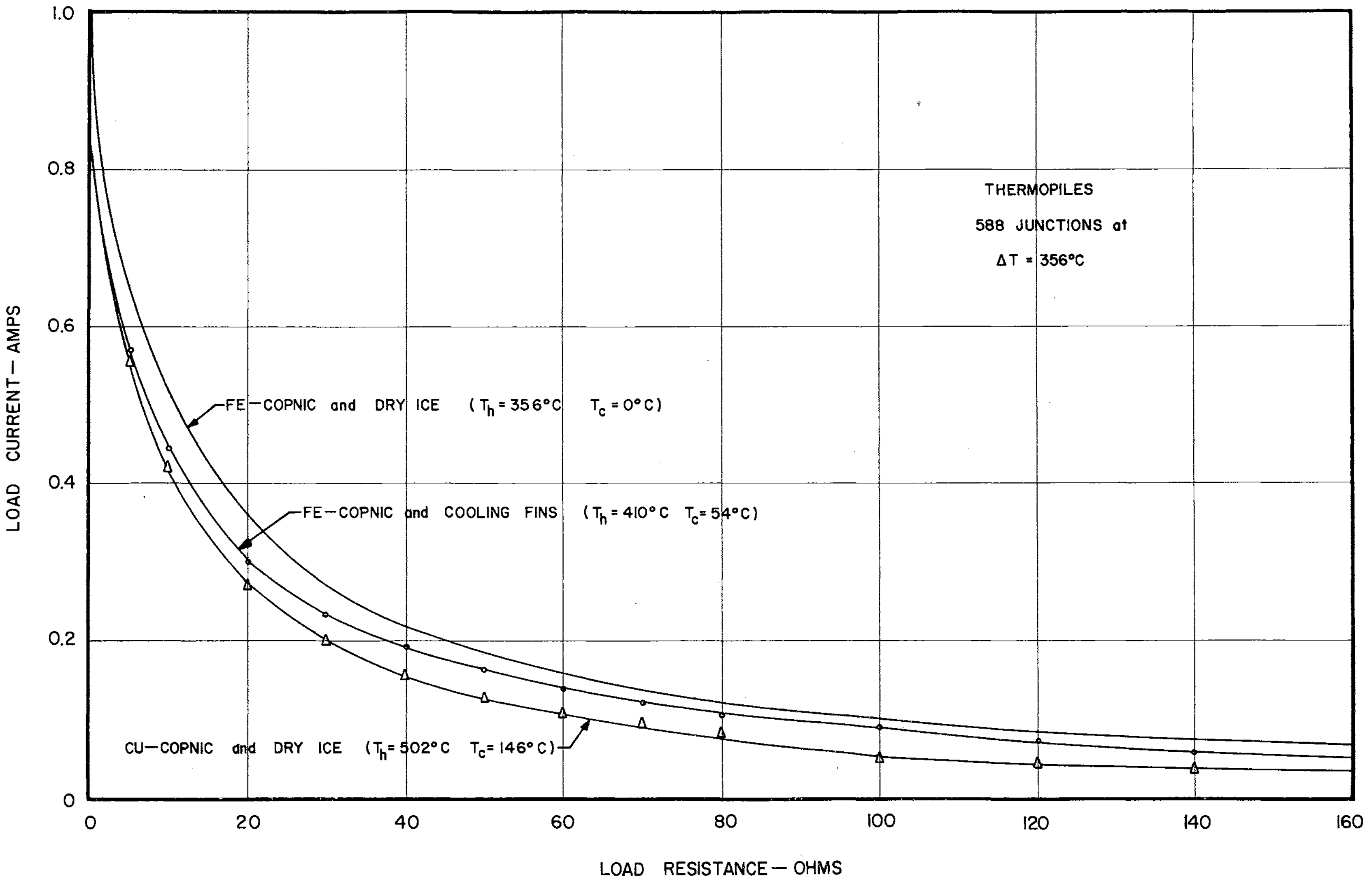


Figure 20. Current output comparison.

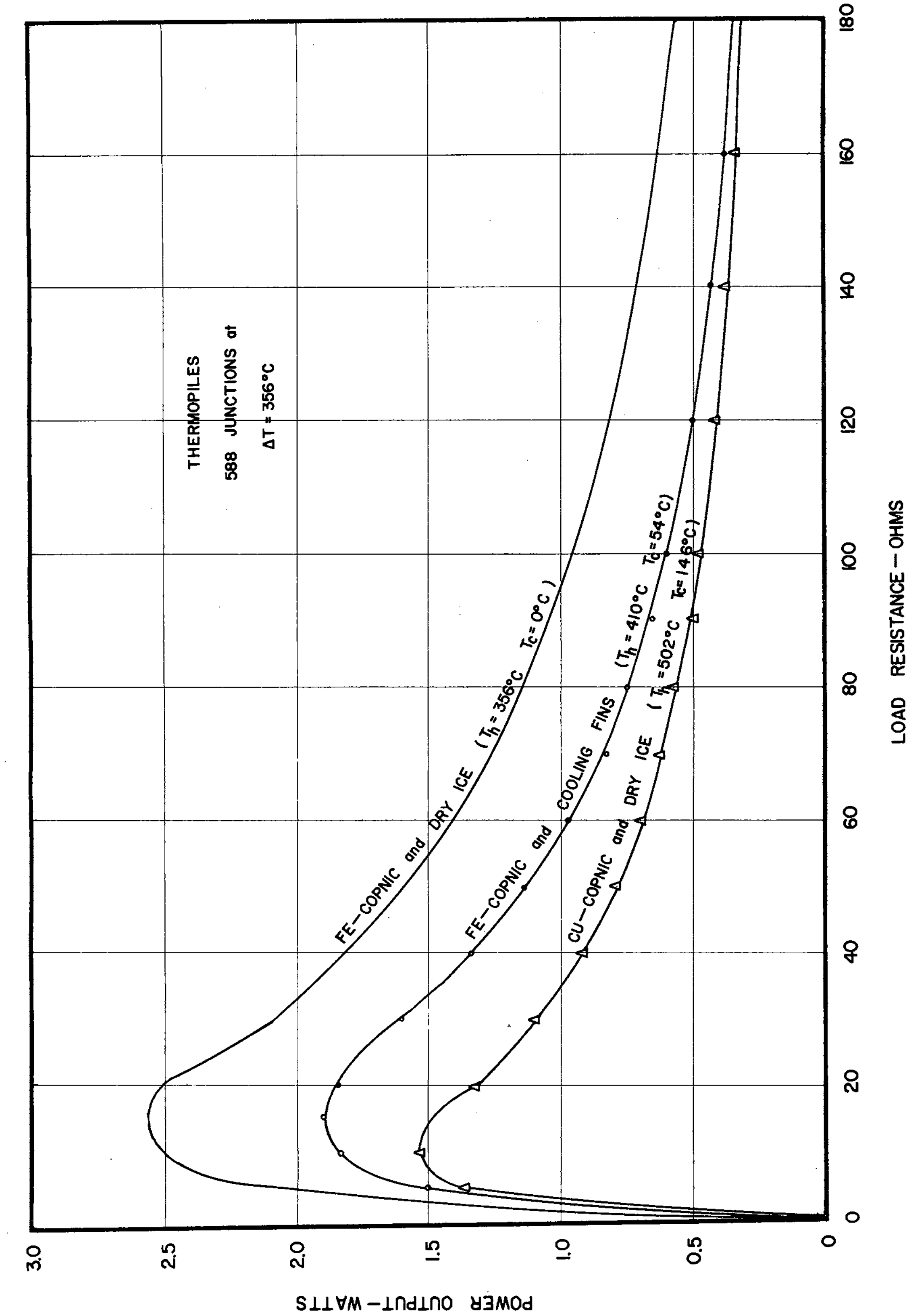


Figure 21. Power output comparison.

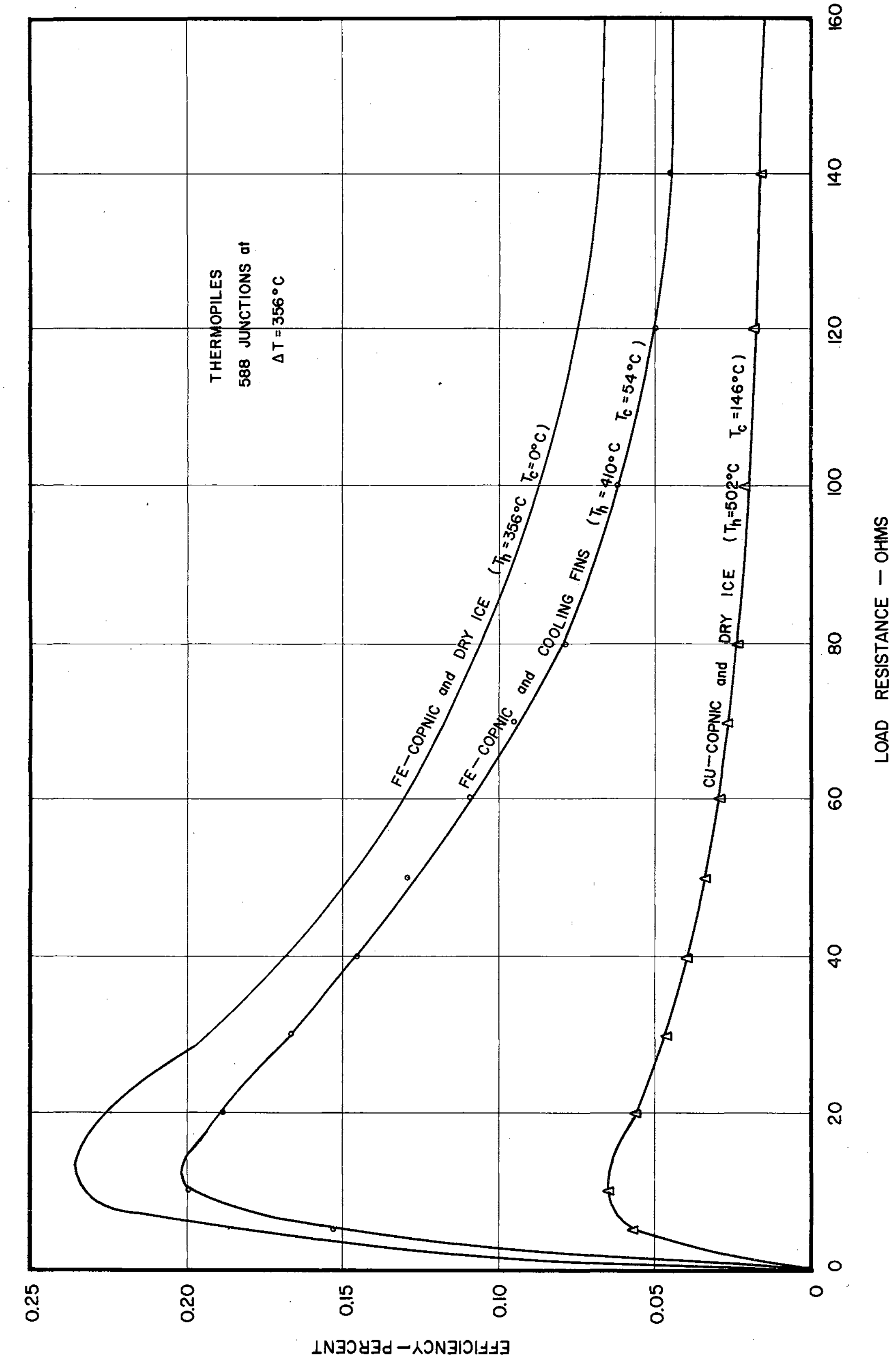


Figure 22. Efficiency comparison.

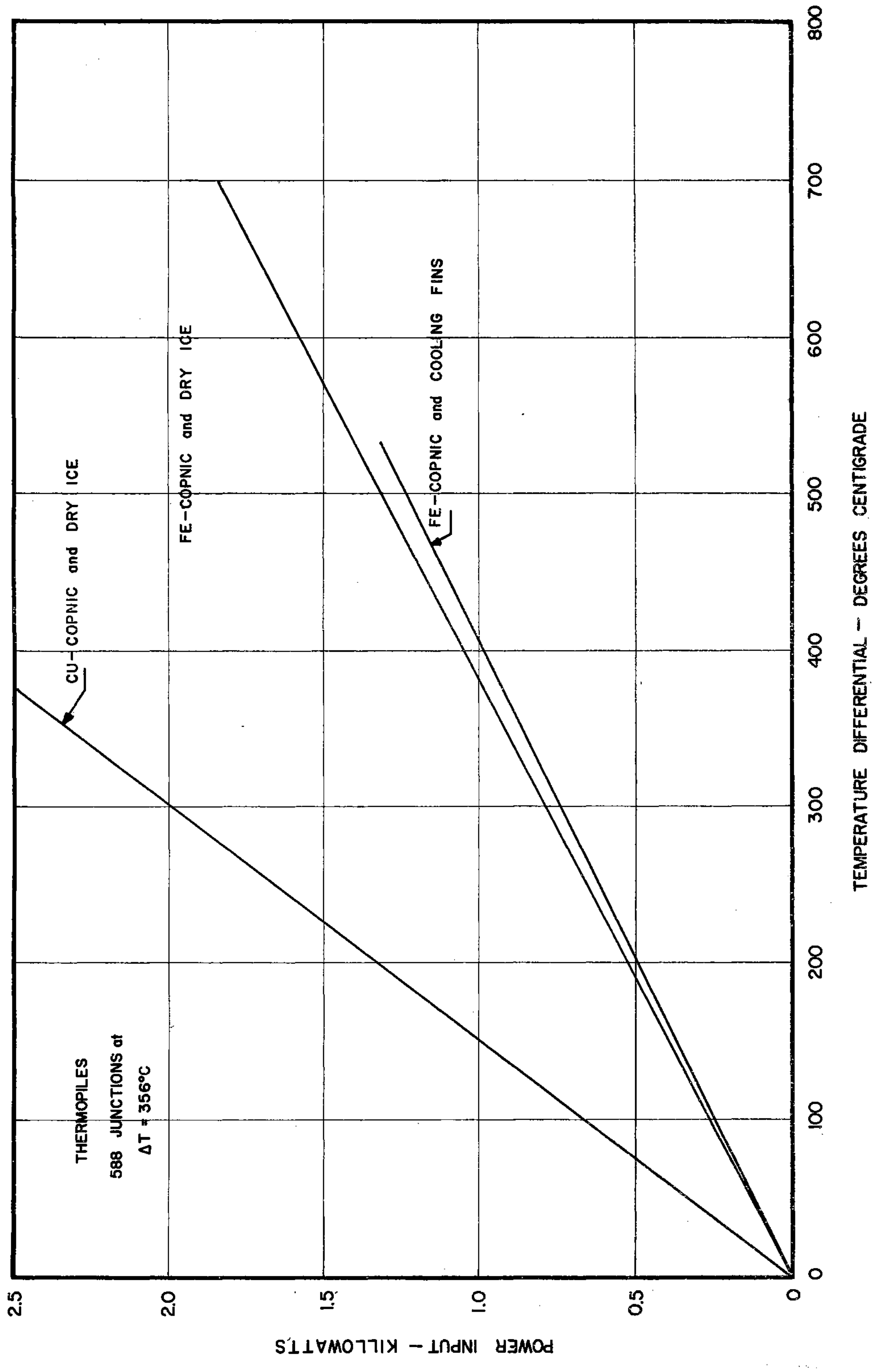


Figure 23. Power Input comparison.

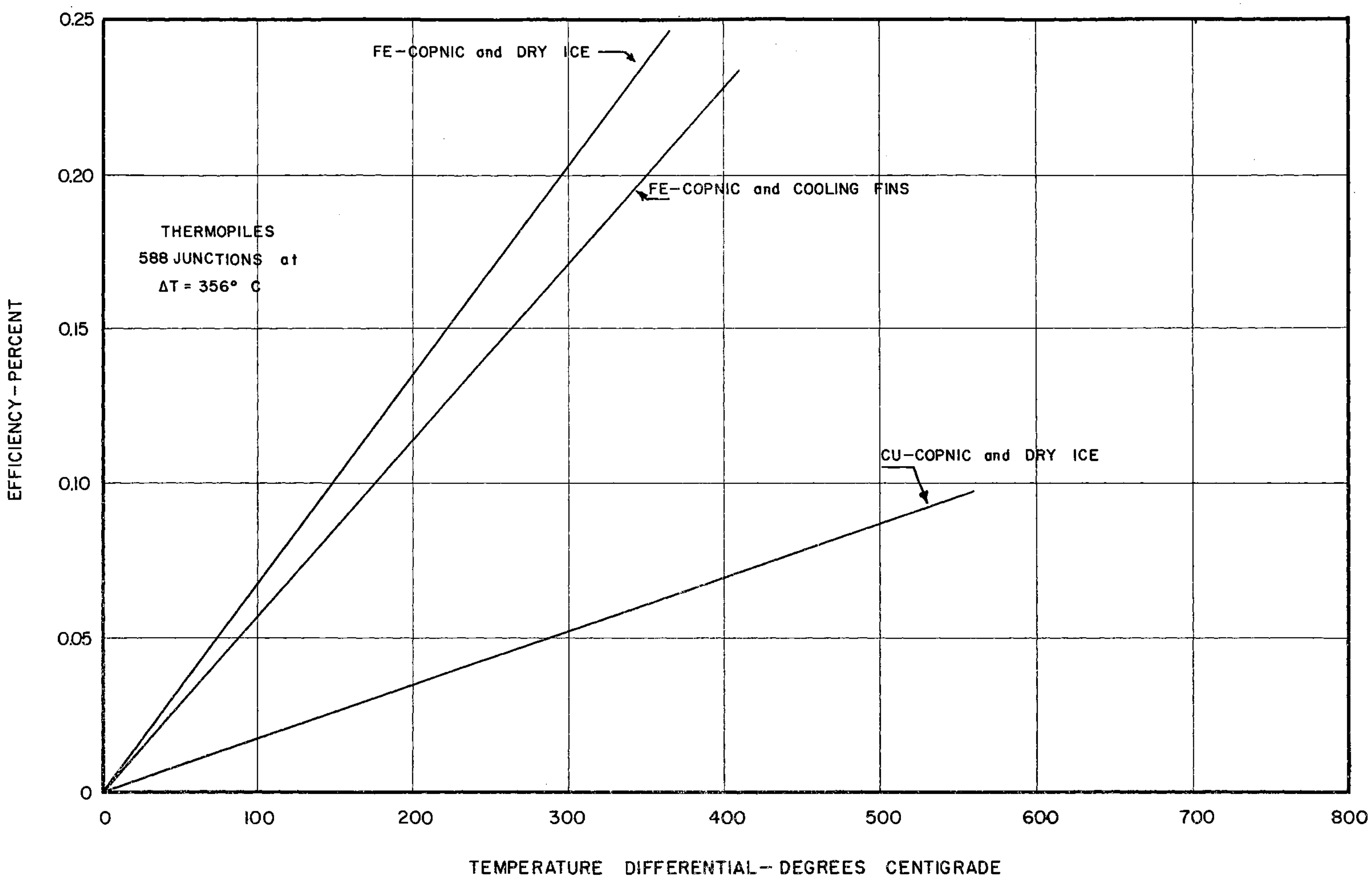


Figure 24. Maximum Efficiency comparison.

CHAPTER VIII

ADDITIONAL PRACTICAL CONSIDERATIONS

The problem of reducing the thermal conductivity of the refractory insulating material by firing proved to be a major one. This chapter presents a practical solution to this enigma.

The manufacturer of the refractory material recommends the firing of his product at 1600 degrees fahrenheit to successfully obtain a low thermal conductivity. Since it is necessary to embed the thermocouple wires during the casting process it would also be necessary to expose these metallic wires to the high firing temperatures. A "Kast-o-lite" wafer with the thermocouple wires was fired in the presence of air, at 1600 degrees fahrenheit, to observe the amount of oxidation produced on the wires. This intense heat produced an objectionable amount of scaling at the thermocouple junctions.

The solution to this oxidation problem was found when the wafers were fired in the presence of an inert gas. A wafer was placed in an iron container through which nitrogen gas was allowed to flow during the firing process. A small escape hole was provided in the container to allow the gas to flow and also prevent the possibility of an explosion of the expanding gas at the higher temperatures. Figure 25 shows a diagram of this firing process. The experiment proved very sucessful in that it allowed no appreciable oxidation of the junctions.

After the wafer had been successfully fired, a few of the junctions were silver soldered and others were fused. Table VII is a chart of

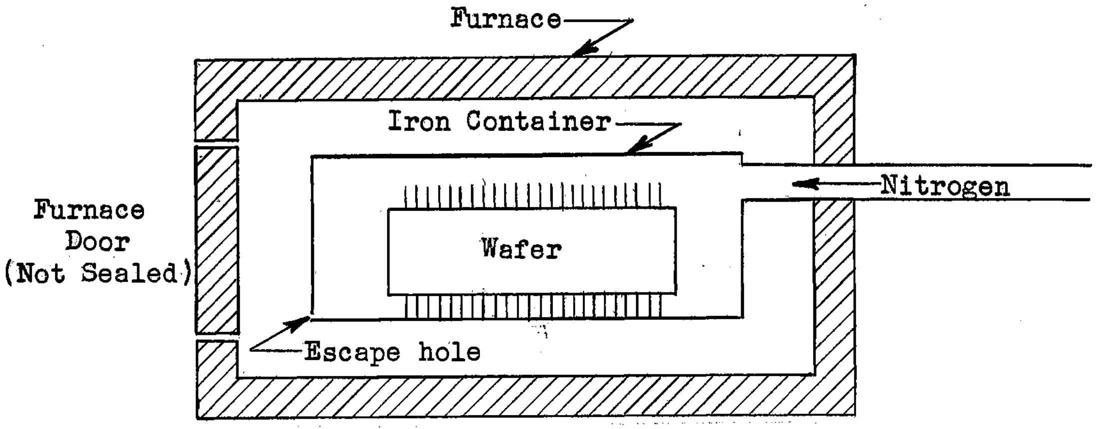


Figure 25. Firing Process using inert gas.

TABLE VII

RESULTS OF FIRING REFRACTORY WAFERS.

Resistance (Before Firing) Ohms per junction		Resistance (After Firing) Ohms per junction	
Silver Soldered	Fused	Silver Soldered	Fused
0.01465	0.01486	0.01635	0.01795

the junction resistances before and after firing. It is readily seen that it would be feasible to fire the wafers in an inert gas and then fuse the junctions. Although this would increase the internal resistance, it would decrease the thermal conductivity of the refractory material, and also allow the hot junctions to be operated closer to melting temperatures of the thermocouple materials. This would allow a much greater temperature differential as well as increasing the efficiency considerably. Firing of the "Kast-o-lite" material made it noticeably lighter and stronger. A suitable furnace could not be located that was large enough to fire the complete thermopile generator.

Since oxidation of the thermocouple metals is of great importance, it was theorized that prolonged operation of the thermopile might cause scaling of the hot junctions which would eventually ruin the generator. The iron-constantan thermopile with cooling fins was operated continually with the hot junctions at 500 degrees centigrade for a period of 48 hours. It was then tested and found that there was no increase in the internal resistance from oxidation. This is a good indication of the durability of the generator.

CHAPTER IX

PRACTICAL CONSIDERATIONS OF THE THERMOPILE GENERATOR

This chapter is concerned with various heat sources, some applications, and a regulating system for the thermopile. These factors must be considered if a practical generator is to be attained.

It would be desirable if waste or by-product energy could be utilized in producing the heat required by the thermopile generator. Such energy sources as jet aircraft exhaust, missile air friction heat, waste industrial heat, and solar energy are just a few examples of readily available waste heat that could be used.

For an immediate use of the thermopile generator, a study of its application in high altitude jet air craft is being made. The adverse affect of high altitude upon rotating types of generators creates a problem that thermopiles would easily solve since they contain no moving parts. Therefore, in the advent of aircraft manufacturers utilizing transistors and other low powered semi-conductor devices in all of the electrical and electronic equipment, the thermopile generator could play an important role as an aircraft power supply. The jet engine exhaust would provide abundant amounts of heat for these generators and large temperature differentials could be achieved using the cold atmosphere of high altitudes. This same situation would also exist in the case of rockets and guided missiles.

Industry could well make use of the thermopile generator because of the many exhaust stacks on large furnaces, machinery, and boilers.

The thermopile could operate many control devices and could be used in many cases as a safety device. For example, in the case of gas furnaces, if the pilot light should accidentally be extinguished, the cessation of current generated by the thermopile could cause appropriate equipment to cut off the gas supply and prevent the dangerous escape of unburned gas. Heat rising in the exhaust stacks could supply heat energy to the hot junctions while the outside air would circulate through the cooling fins, producing an adequate temperature differential for the thermopile. The thermopile generators could conceivably be used as exhaust stacks, thereby serving two purposes.

In using the thermopiles as portable or stand-by power supplies for communication and electronic equipment, there are two natural sources of energy available: solar energy, found almost universally; and the sub-freezing temperatures of the polar regions and in higher altitudes. For an example of the use of solar energy, it is conceivable that thermopiles could be used in the newly developed artificial earth satellites to be launched during the forthcoming International Geophysical Year, 1958.[26] It has been suggested that mercury batteries be used as a source of power in the satellites. However, solar energy and equipment heat could be harnessed along with atmospheric cooling to energize a thermopile generator that would last almost indefinitely.

Another possible use of the thermopile would be as a source to supply power to equipment carried by polar expeditions into the arctic and antarctic regions. Temperature differentials would easily be obtained from the sub-freezing temperatures of the climate and from the heat generated by

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[26] "Questions About the Minimoons", <u>Popular Science Monthly</u>, August, 1956, pp. 122-124.

cooking and heating stoves and other equipment.

It is apparent from the above discussions that many sources of natural and waste energy are readily available for use in a thermopile generator. It has also been mentioned that there are many uses of the thermopile as a source of electrical power. As discussed previously, it is because of the lower efficiency of these devices that make them especially well suited for the utilization of wasted energy.

When using a source of waste heat, it will, in most cases, be necessary to provide a control device for regulating the heat input to the generator. Otherwise, the hot junctions could be permanently damaged from an excessive heat flow, and also the increased electrical output would continually be activating circuit protective devices. Figure 26 shows one type of feedback system that could be used as a heat input control for constant power output. One apparent disavantage

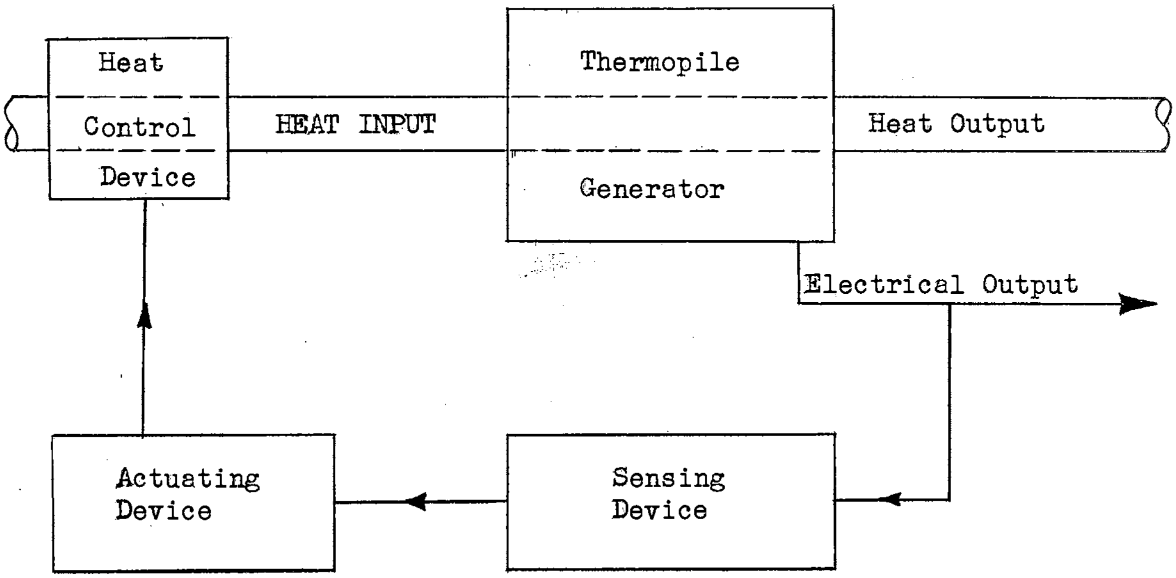

Figure 26. A Regulated Output - System A.

of System A is that it uses part of the power output for energizing the heat control equipment, thereby reducing the maximum possible power output. A seemingly better solution is shown in Figure 27. By using a

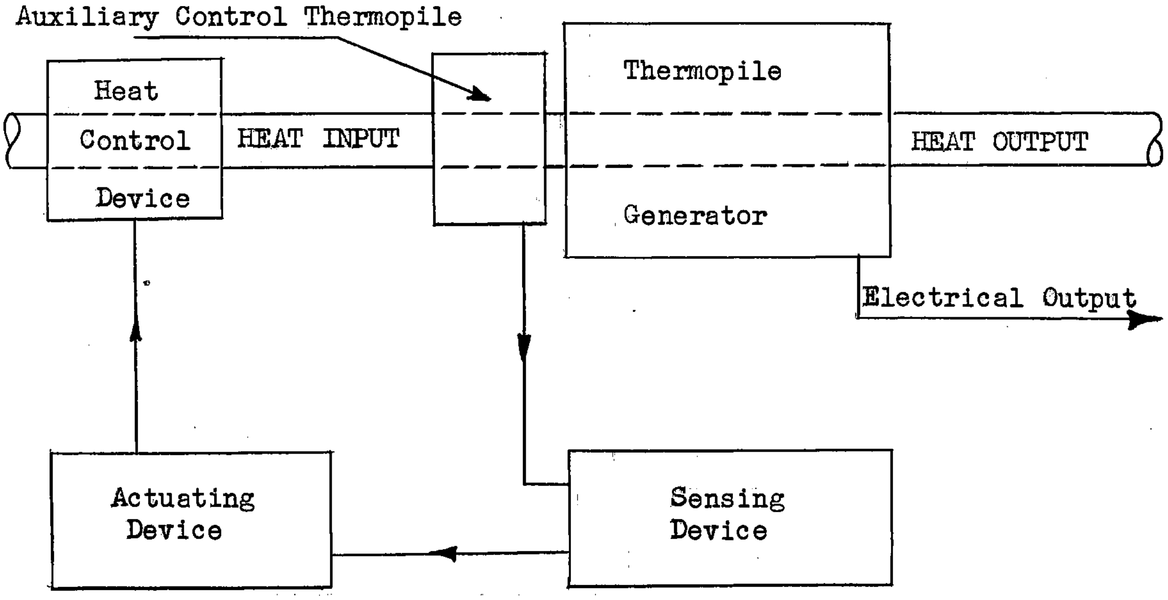

Figure 27. A Regulated Output - System B.

small auxiliary thermopile to independently control the heat input, System B would allow the thermopile generator to supply the maximum possible power output.

Certain specifications might call for the use of a "noiseless" power supply where no source of waste energy was available. In this case, some type of fuel would have to be burned to provide the required input heat for the thermopile generator. Many fuels are readily obtainable such as coal, wood, oil, kerosene, gasoline, and natural gas. When using such fuels as kerosene, oil, and gasoline a properly designed gravity feed system would be required to produce a controlled heat input to the generator. Coal, wood, natural gas, and many other fuels could be considered without the need for a forced draft. The selection of the fuel and heat transfer system would depend largely on the temperature at which the hot junctions are to be maintained. Where efficiency is to be sacrificed because of cheap fuel or other conditions exist which do not depend on economy, the solution is only influenced by the safe operating temperature of the hot junctions. An example of a thermopile using a fuel for input heat would be a portable field power unit for the operation of electronic equipment, or for charging batteries, where quietness could be a factor of operation.

It should be remembered that there is a disavantage in producing heat by the use of a fuel. Because of the low overall efficiency of this device, large amounts of fuel would be needed for continous operation. If at all possible, the thermopile should have a secondary purpose such as providing warmth for personal comfort, or for cooking.

CHAPTER X

SUMMARY AND CONCLUSIONS

The object of this thesis was to present the design, selection of materials, construction, performance, an analysis of the results, and a study of the practical considerations of the thermopile generator. Mention was made to the past and present accomplishments with a device of this nature.

Theoretical considerations disclosed many of the problems encountered with thermopiles. Special attention was given to the efficiency problem. It was found that any new materials used in the thermocouple elements would have to have a lower ratio of thermal to electrical conductivity to have any great effect on the efficiency. Also, the problem of the thermal conductivity of the refractory material was studied. This was successfully solved by firing samples of the materials in the presence of an inert gas.

A detailed analysis of the design and construction of the thermopile along with a discussion of the instrumentation and testing equipment was furnished. Several photographs of the actual construction were inserted to aid in the understanding of the written material.

Two thermopile generators were constructed and tested to prove their practicability as a source of electrical energy. The iron-constantan thermopile proved to be far superior to the copper-constantan thermopile in all respects, although it did have a slightly higher internal resistance. Special emphasis was placed on the addition of cooling fins to further show how a practical generator can be obtained. All the generators where graphically compared and discussed, again proving the superiority of the iron-constantan thermopile.

It was found that the thermopile generator is best suited for the utilization of waste heat. Several sources of natural and waste energy were discussed along with many practical uses for the generator. It was found that the thermopile would have particular application in the field of high altitude aircraft and in industry. Block diagrams were included for a regulating system for constant emf output.

It was concluded that the thermopile generator, despite its low efficiency, has several commerical prospects. Particular attention should be focused on the material selected for the generator. It is recommended that a further study be made of the thermocouple elements. The theoretical calculations indicate that the problem of producing thermopile generators of higher efficiency can be solved only by a continuing search for materials of high thermoelectric power, low specific electrical resistance, and low specific heat conductivity. The best approach to this problem may be in the field of semiconductors incorporating trace elements to properly adjust the thermal and electrical conductivity and structural characteristics. The application of quantum mechanics and a complete review of materials by the application of the electron theory may result in a thermocouple whose lattice structure has the optimum desired characteristics.

It is interesting to note that the United States is not the only nation investigating the potential of the thermopile generator. Only recently Moscow, Russia, announced the commerical development of a thermopile generator to power a low-drain communication receiver. The thermopile is powered by a kerosene lamp which also serves as a light source and produces a temperature differential of 480 degrees centigrade. Cooling fins are provided for the cold junctions.[27]

The theoretical and practical study of the thermocouples and generator design has suggested certain parameters which indicate the physical and electrical characteristics. These must be satisfied before a thermopile generator could be considered seriously as a power source. Some of the most important are (1) Maximum hot junction temperatures of over 500 degrees centigrade, (2) Potential characteristics of over 60 microvolts per degree centigrade, (3) A mechanically strong structure, (4) Low internal resistance, and (5) Resistance to oxidation over prolonged periods of operation. It can be stated generally from the practical considerations of the system design that the efficiency will have a direct ratio to the temperature required at the hot junctions.

It might be of interest to present a brief cost analysis of the iron-constantan generator with cooling fins. The materials of this particular generator amounted to approximately $37.00, with the constantan wire being 60% of the sum. The total weight of this generator was 21 pounds, making the pounds per horsepower ratio in the order of 5,980 which is very good for a thermopile of this size.

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[27] "What's New in Communist Countries," Popular Science Monthly, June, 1956, pp. 112-113.

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