A RADIAL IRON-CONSTANTAN THERMALELECTRIC GENERATOR

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PREFACE

In recent years the need of a new approach to the problem of electrical power sources for numerous applications has caused researchers to revaluate the potential of the thermalelectric generator as a source of electric power. Although the merits of a device for converting heat energy directly into electrical energy utilizing the thermoelectric effect have been investigated in the past, the development of the thermalelectric generator, also referred to as a thermopile, has been neglected in favor of the more conventional type power sources, namely, rotating machines.

In the following discussion, the author has dealt with the problem of designing, constructing, testing and evaluating a particular type of thermalelectric generator that has an improved performance as compared to previously designed generators. Included are charts predicting the efficiency of a radial type generator at various operating temperatures and expressed as a function of other parameters such as area ratio, thermal conductance and electrical resistivity of the materials used in the construction of the generator. The work for this thesis is also representative of a portion of a research program sponsored by the Wright Air Development Center, United States Air Force, concerned with the investigation of unconventional power sources.

The author wishes to express his indebtedness to Professor Paul A. McCollum, P.E., project leader of the afore mentioned research project for his invaluable assistance in the experimental work performed and preparation of this paper. Thanks are also extended to Mr. Ralph W. Fisher and the personnel of the Research and Development Laboratory of Oklahoma State University for their assistance in the construction and testing of the experimental generator described herein. To my wife, Wanda, my deepest appreciation for her valuable services as typist of this manuscript.

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CHAPTER I

INTRODUCTION

Serious consideration of the thermalelectric effect as a source of electric power has, in recent years, become a renewed challenge to the engineering science. Although the thermalelectric phenomena is not a new concept, having been investigated by Thomas J. Seebeck in the 19th century[1], its development for power applications has been neglected until recent years in favor of rotating machinery. With the advent of semiconductor devices that require little maintenance and low power, the use of the thermalelectric generator as a low power source has become an increasingly attractive proposal.

As stated in previous publications[2], the thermalelectric generator is characterized by low efficiency, great weight per unit volume and small power output. It is the intent of this paper to describe the development of a thermalelectric generator that will yield an increased power output per unit volume and weight, and to present a collection of data, both theoretical and experimental, depicting performance under typical operating conditions. The particular design chosen for the experimental generator that was constructed and tested was a radial

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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]Thomas N. Ewing, "The Thermopile Generator As A Source of Electrical Energy" (unpub. Master's Thesis, Oklahoma State University, 1956), p. 66.

type consisting of sheets of iron and constantan. This arrangement was considered superior to previous experimental generators in that it provided more active metal per unit volume, which would lead one to believe that it would result in higher efficiency and greater power output per unit volume and weight. It should be realized that further significant improvement in the efficiency of such a generator could be achieved only by an increased study in the field of metallurgy. With significant improvements in the characteristics of materials, namely, thermal conductivity and electrical resistivity, the efficiency of the radial thermalelectric generator could be substantially increased.

Although the efficiency of the thermalelectric generator seldom exceeds 1.0 percent, it should be realized that such a device could utilize waste heat or be used in applications where there is an abundance of heat such that the overall efficiency of the particular combination would be very attractive and thereby overshadow the comparatively poor efficiency of the generator alone. Thermalelectric generators would not be expected to replace modern day power plants or installations that require high efficiency power sources. However, the application of thermalelectric generators to the production of power for homes and industry is not to be entirely discounted in view of the advances being made with devices that collect and concentrate the radiation of the sun[3] and make available a relatively new method of utilizing the heat of the sun.

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[3]Maria Telkes, "Solar Thermoelectric Generators," Solar Energy Project, College of Engineering, New York University, Journal of Applied Physics, Vol. 25, No. 6, June, 1954, pp. 768-770.

CHAPTER II

THEORETICAL EQUATIONS

From previous studies, the general maximum efficiency equation for any thermalelectric generator is stated as[4]

$$\mathcal{E}_{max} = \frac{T_h - T_c}{T_h}\left[1 + \frac{2\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}{e^2\,T_h} - \frac{2\left\{1 + \frac{\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}{e^2\,T_h}\right\}}{\sqrt{1 + \frac{e^2\,T_h}{\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}}}\right] \quad (1)$$

where: T_h = the hot junction temperature in ^oK.

T_c = the cold junction temperature in ^oK.

e = the thermalelectric power output of each junction in μvolts per ^oC.

p' = the resistivity of one metal in the thermocouple in μohm-cm.

p" = the resistivity of the second metal in the thermocouple in μohm-cm.

k' = the thermal conductivity of one metal in the thermocouple in watts per cm-^oC.

k" = the thermal conductivity of the second metal in the thermocouple in watts per cm-^oC.

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[4] Attie L. Betts and Paul A. McCollum, "Unconventional Electrical Power Sources," Wright Air Development Center Technical Report 54-409 (Oklahoma State University, September, 1954) p. I-12.

ℓ' = the length of one metal in the thermocouple in cm.

ℓ'' = the length of the second metal in the thermocouple in cm.

a' = the cross-sectional area of one metal in the thermocouple in cm^2.

a'' = the cross-sectional area of the second metal in the thermocouple in cm^2.

This equation assumes that there is no heat loss through the refractory material of the generator and is therefore referred to as the general theoretical maximum efficiency equation.

If the terms corresponding to the electrical resistance and thermal conductance of the generator in the general equation are expanded, the result will be

$$\left(\frac{\rho'\ell'}{a'}+\frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'}+\frac{k''a''}{\ell''}\right) = \rho'k'+\rho''k''+\rho'k''\left(\frac{a''}{a'}\right)\left(\frac{\ell'}{\ell''}\right)+\rho''k'\left(\frac{a'}{a''}\right)\left(\frac{\ell''}{\ell'}\right)$$

By observing the geometry of a radial thermalelectric generator as illustrated by Figure 1, it is apparent that the active lengths of the different materials in the radial thermalelectric generator will always be equal. Therefore, this portion of the general equation may be further simplified.

When $\ell' = \ell''$

$$\left(\frac{\rho'\ell'}{a'}+\frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'}+\frac{k''a''}{\ell''}\right)=\rho'k'+\rho''k''+\rho'k''\left(\frac{a''}{a'}\right)+\rho''k'\left(\frac{a'}{a''}\right)$$

The ratio $\frac{a''}{a'}$ appearing in this equation is termed the area ratio and is represented by the Greek symbol delta, δ. It is of interest to note that the area ratio is a ratio of the cross-sectional areas of

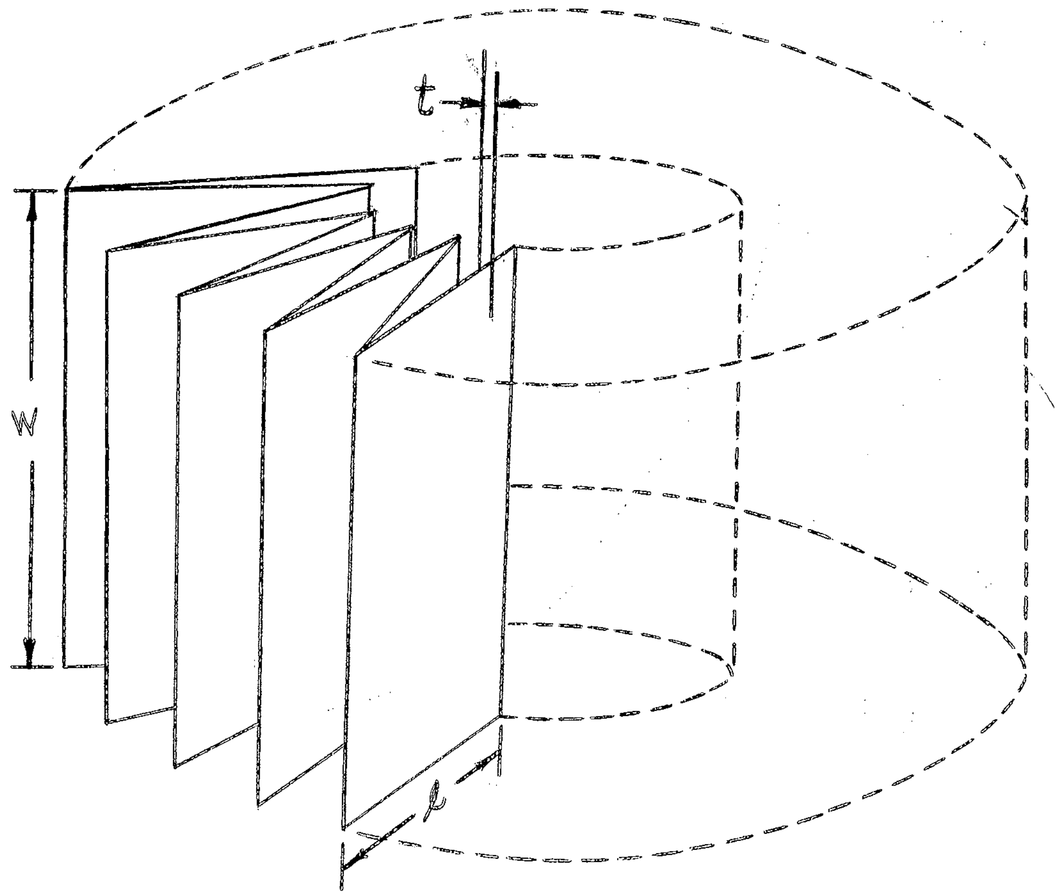

Figure 1. The geometry of a radial thermalelectric generator.

the two materials in the generator and may also be expressed as

$$\delta = \left(\frac{a''}{a'}\right) = \left(\frac{w''}{w'}\right)\left(\frac{t''}{t'}\right) \tag{2}$$

where: w' = the width of one material in the thermocouple in cm.

w'' = the width of the second material in the thermocouple in cm.

t' = the thickness of one material in the thermocouple in cm.

t'' = the thickness of the second material in the thermocouple in cm.

If the simplified portion of the general efficiency equation is now substituted into the general efficiency equation, there results the theoretical maximum efficiency equation for a radial thermalelectric generator. This equation may be written as

$$\mathcal{E}_{max} = \frac{T_h - T_c}{T_h}\left[1 + \frac{2\left(\rho'k' + \rho''k'' + \rho'k''\delta + \frac{\rho''k'}{\delta}\right)}{e^2 T_h} - \frac{2\left\{1 + \frac{\rho'k' + \rho''k'' + \rho'k''\delta + \frac{\rho''k'}{\delta}}{e^2 T_h}\right\}}{\sqrt{1 + \frac{e^2 T_h}{\left(\rho'k' + \rho''k'' + \rho'k''\delta + \frac{\rho''k'}{\delta}\right)}}}\right] \qquad (3)$$

From this equation, it is apparent that for two given materials and a specific operating condition, the theoretical maximum efficiency will vary as the area ratio is varied. In addition, for each change in the operating conditions, T_c and T_h, there will be a corresponding change in the maximum efficiency. This is necessarily true since the electrical resistivity, thermal conductivity and thermal power output of the materials is a function of temperature. Some materials, such as constantan, have relatively stable electrical resistivities in a moderate temperature range[5], but their thermal conductivity and thermal power output are found to vary considerably in the same range of temperatures. The effects of varying the area ratio and operating conditions on the theoretical maximum efficiency of a radial thermalelectric generator are clearly illustrated by Figures 2, 3, 4, 5 and 6. Data for these charts was obtained by writing a program for an IBM 650 Digital Computer using the FLOPS Interpretive System.

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[5]Colins J. Smithells, Metals Reference Book, (New York, 1949) p. 482.

Although this interpretive system of programming offers accuracy to only 8 significant figures, this accuracy was found to be sufficient for the efficiency equation.

It is interesting to note that at elevated operating conditions, above $T_c = 100^oC$ and $\Delta T = 400^oC$, sharp "peaking" occurs on the curves and the area ratio yielding the highest maximum efficiency for that particular operating condition becomes smaller. However, at lower operating conditions, below $T_c = 100^oC$ and $\Delta T = 400^oC$, large variations in the area ratio have little effect on the maximum efficiency.

As a matter of interest, similar curves were plotted for a copper-constantan radial generator and it was found that the optimum area ratio for maximum efficiency varied considerably with this combination of materials. The optimum area ratio for the copper-constantan generator might vary between 6 and 16 as compared to 0.5 and 2.5 for the iron-constantan generator. The large variation of area ratio with respect to the copper-constantan generator can be chiefly attributed to the increased thermal conductivity of copper as compared to iron.

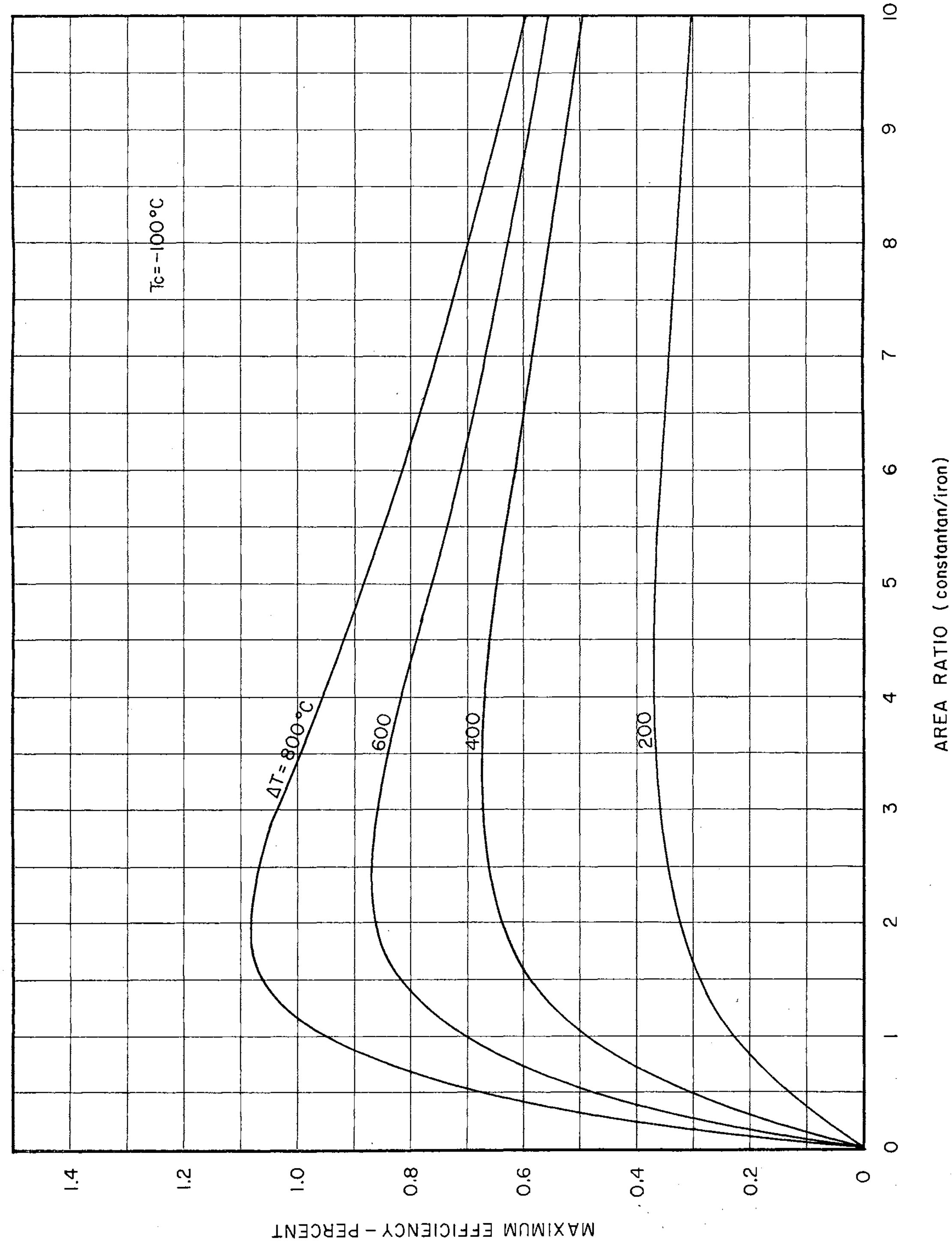

Figure 2. Maximum efficiency versus area ratio, $T_c = -100^{\circ}C$.

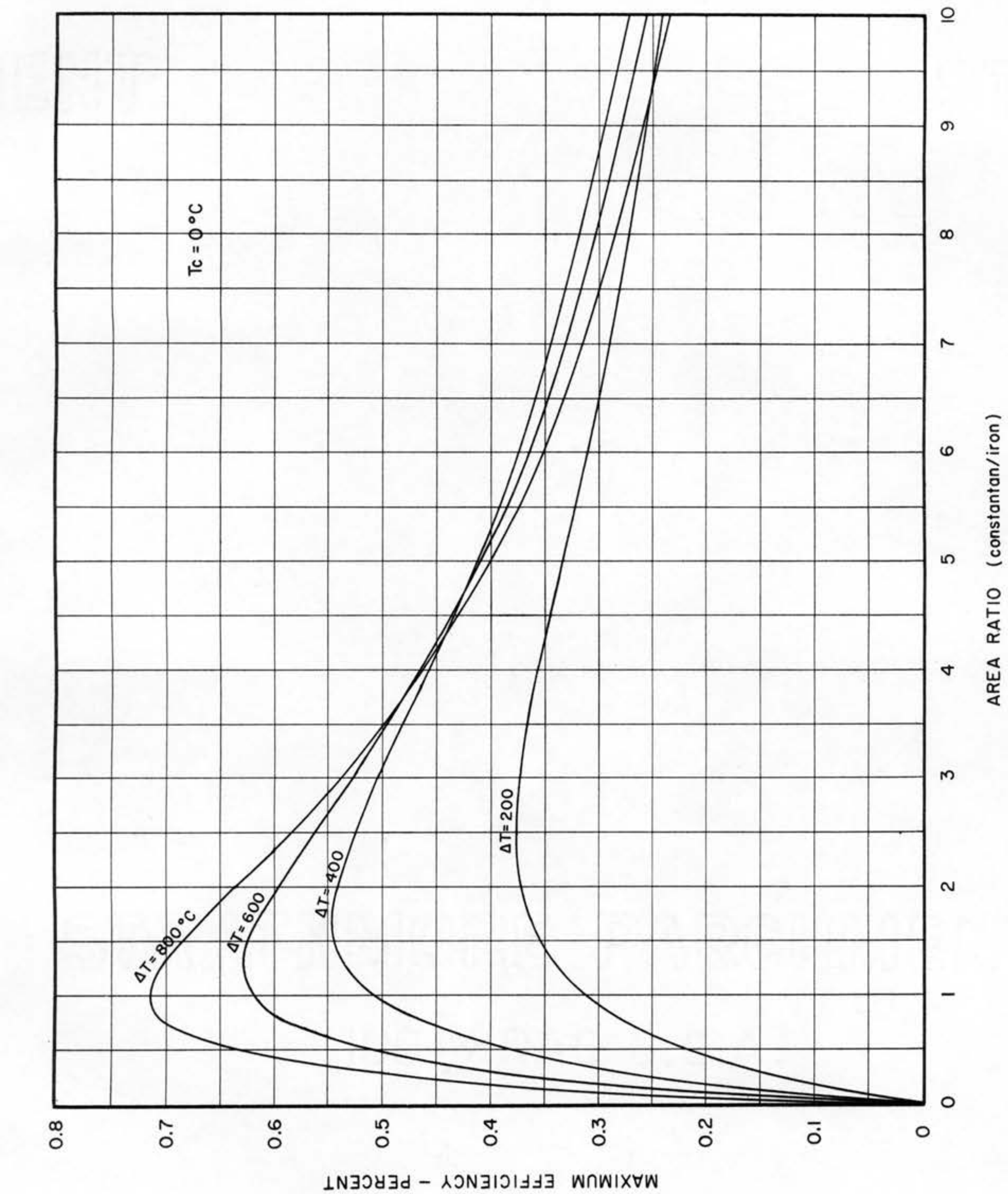

Figure 3. Maximum efficiency versus area ratio, $T_c = 0^{o}C$.

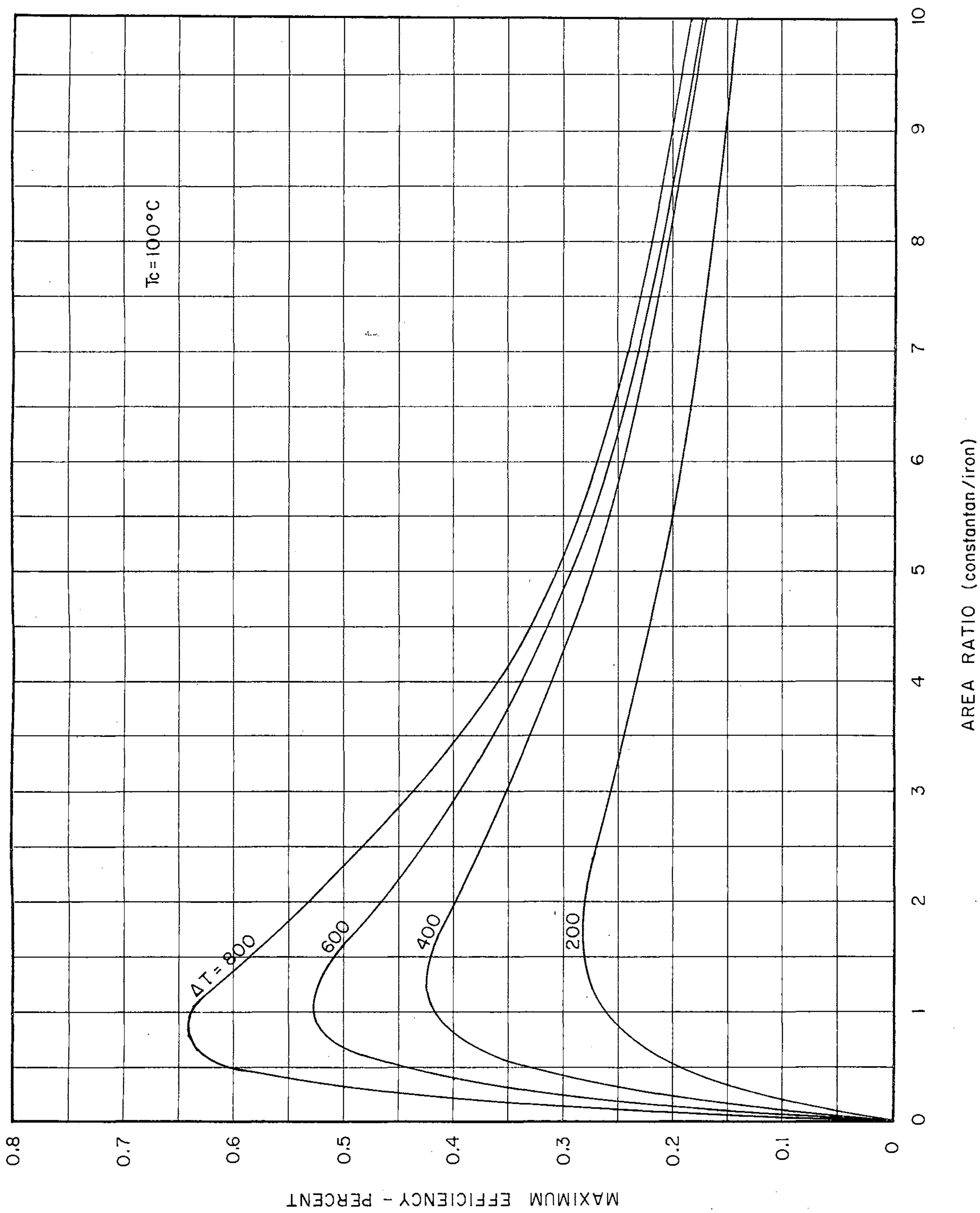

Figure 4. Maximum efficiency versus area ratio, $T_c = 100^{\circ}C$.

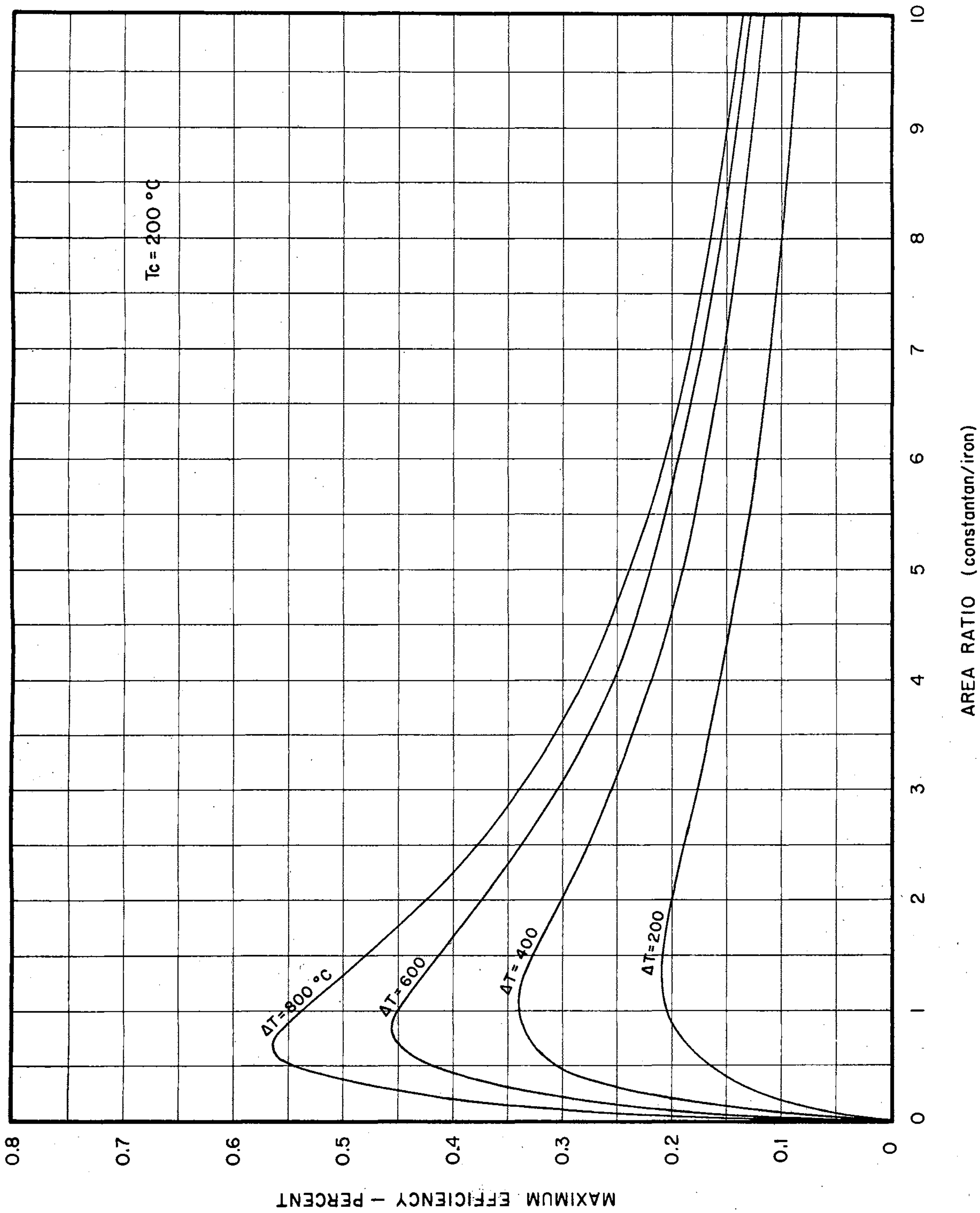

Figure 5. Maximum efficiency versus area ratio, $T_c = 200^oC$.

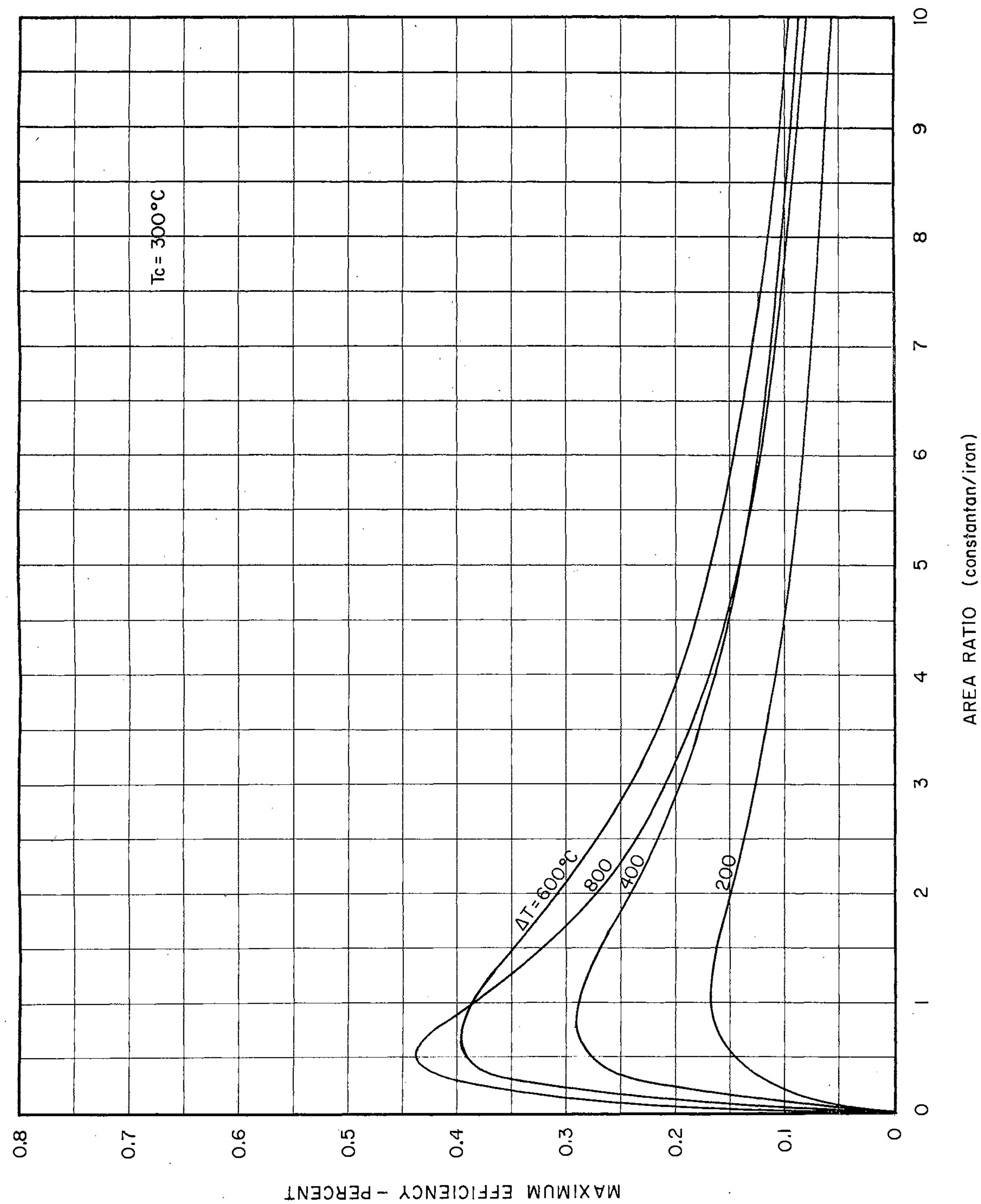

Figure 6. Maximum efficiency versus area ratio, $T_c = 300^oC$.

CHAPTER III

DESIGN AND CONSTRUCTION

In any thermalelectric generator, the power output and the efficiency are greatly influenced by the temperature differential that can be maintained between the hot and cold junctions of the generator. Since both the power output and efficiency are functions of temperature, it is evident that the most propitious operating condition will have associated with it a large temperature differential. In order to maintain a large temperature differential between the hot and cold junctions of a thermalelectric generator, it is necessary to recall a basic law of thermodynamics. Stated briefly, the temperature differential between the ends of a solid conductor is proportional to the heat flow through the conductor.[6] In equation form this may be written as

$$q = \frac{\Delta T}{R} \tag{4}$$

where q = the heat flow through the material, Btu/min

R = the thermal resistance, ^{o}F/Btu/min

ΔT = the temperature differential

This equation is analogous, under linear conditions, to Ohms Law encountered in electrical circuits where the current, I, is proportional to the voltage or potential, V, and inversely proportional to the

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[6] William H. McAdams, Heat Transmission, (New York, 1933) p. 9

resistance, R. In the electrical circuit, the voltage is a function of the current flow through the conductor, and similarly in the heat circuit the temperature differential is a function of the heat flow through the conductor. Applying this theorm to the problem of maintaining a large temperature differential between the hot and cold junctions of a thermalelectric generator, it is necessary to dissipate an amount of heat from the cold junctions equal to the amount of heat that is being absorbed into the hot junctions. However, the limiting factors in this regard are the thermal conductivities of the materials used and the ability to dissipate heat at the cold junctions. Recognizing these two limiting factors, the radial design employing large flat sheets of metal was chosen because it offered a large low resistance path for heat to flow and with the addition of cooling fins on the cold junctions, a convenient method of dissipating heat at the cold junctions. In addition, the radial design was considered superior to previous experimental generators constructed of wire[7] in that the amount of refractory material necessary for insulation purposes was substantially reduced. This factor greatly increased the power output per unit volume and weight.

In the design procedure for a radial thermalelectric generator, two methods of attack are available. If the materials with which the generator is to be constructed have been chosen, in this instance iron and constantan, and if there is available a series of charts such as Figures 2, 3, 4, 5, and 6, a great deal of information concerning the

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[7] Ewing, p. 39.

performance of the generator can be determined, which in turn will assist in the choice of dimensions for the generator. The first method of attack to be described originates from the output considerations of the generator. Let it be assumed that an output voltage of 1.75 volts is desired and the generator is to be operated at a temperature differential of 600°C when the cold junction temperature is 100°C. From the curves of Figure 4 it is seen that with these operating conditions the optimum area ratio is approximately unity and the theoretical maximum efficiency of the generator is approximately 0.526 percent. Let it also be assumed that there is available an input power of 1500 watts. Therefore

$$\begin{aligned} \text{Power output} &= (\text{Power input})\,(\text{Efficiency}) \\ &= (1500)\,(0.00526) \qquad (5) \\ &= 7.89 \text{ watts} \end{aligned}$$

and the current output will be

$$\begin{aligned} \text{Current output} &= \frac{(\text{Power output})}{(\text{Output voltage})} \\ &= \frac{7.89}{1.75} \qquad (6) \\ &= 4.5 \text{ amperes} \end{aligned}$$

and if maximum power transfer is assumed, the total resistance of the generator will be

$$\begin{aligned} \text{Total resistance of the generator} &= \frac{(\text{Output voltage})}{(\text{Output current})} \\ &= \frac{1.75}{4.5} \qquad (7) \\ &= 0.388 \text{ ohms} \end{aligned}$$

Since the materials to be used and the operating conditions have been chosen, the electrical output of each junction may be calculated. The electrical output of a thermocouple junction may be stated as[8]

$$E = e\Delta T \tag{8}$$

where E = the electrical output of a junction in volts

e = the thermal electric power of the materials in μvolts per ^{o}C.

ΔT = the temperature differential in ^{o}C.

Therefore the electrical output of each junction in the generator will be

$$E = (56.0 \times 10^{-6})\ (600)$$

$$= 33.6 \times 10^{-3} \text{ volts}$$

Since an output voltage of 1.75 volts at maximum power transfer is desired, the necessary number of junctions will be

$$\text{Number of junctions} = \frac{(2)\ (\text{Desired output voltage})}{(\text{Electrical output of each junction})}$$

$$= \frac{(2)\ (1.75)}{(33.6 \times 10^{-3})} \tag{9}$$

$$= 104 \text{ junctions}$$

Knowing the total resistance of the generator and the required number of junctions necessary to obtain the desired output, the resistance of each junction may be calculated as

$$\text{Resistance of each junction} = \frac{(\text{Total resistance of the generator})}{(\text{Number of junctions})} \tag{10}$$

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[8]Betts, p. I-11.

$$= \frac{0.388}{104}$$

$$= 0.00373 \text{ ohms}$$

In addition, the resistance of each junction may also be written as the resistance of the iron and constantan sheets for that junction. In equation form this is

$$\text{Resistance of each junction} = \frac{\rho' l'}{a'} + \frac{\rho'' l''}{a''} \qquad (11)$$

At the particular operating conditions chosen, the characteristics of the two materials are found and the resistivities are given as[9]

$$p' = 46.5 \ \mu\text{ohm-cm}$$

$$p'' = 49.0 \ \mu\text{ohm-cm}$$

By setting equation 11 equal to the resistance of a single junction in the experimental generator, an expression may be derived which yields a relationship between the length, width and thickness of the materials to be used in the construction of the generator. When $l' = l''$ and the area ratio is unity or $a' = a''$, equation 11 may be modified to give

$$\text{Resistance of each junction} = \frac{l}{a}(\rho' + \rho'') \qquad (12)$$

and

$$0.00373 = \frac{l}{a}\left(46.5 \times 10^{-6} + 49.0 \times 10^{-6}\right)$$

and since the cross-sectional area of the material is equal to the thickness of the sheets multiplied by the width of the sheets,

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[9]Smithells, p. 482.

equation 12 may be rewritten as

$$wt = 0.0256\ell \tag{12a}$$

where w, ℓ, and t are expressed in centimeters. With this relationship an infinite number of dimensions may be calculated for the proposed generator. If the thickness of the materials is taken as 0.02 inches, equation 12a will yield

$$w = 0.504\ell \tag{13}$$

where w and ℓ may now be expressed in either inches or centimeters. Considering equation 13, the length and width may be adjusted to suit the particular application of the generator. In the case of the experimental generator constructed for this study, an active length of 6 inches and a width of 3 inches was chosen as convenient dimensions for laboratory testing purposes.

The second method of design to be described has its origin with the heat flow requirements of the generator. As stated previously, the temperature differential between the hot and cold junctions of the generator is proportional to the heat flow through the conductors. If an incremental area of a conductor is considered and a heat flow equation is written for this area, there will be[10]

$$q = -ka\frac{\Delta T}{\Delta \ell} \tag{14}$$

where - ka represents the thermal conductivity, k, of the material and the cross-sectional area, a. The term $\Delta\ell$ represents the incremental length of the conductor being considered and ΔT the temperature differential between the ends of the conductor. Now if the sum is

[10]McAdams, p. 11

taken of all these incremental areas along the length of the conductor, there will result

$$\int_0^{\ell} q\,d\ell = \int_{T_h}^{T_c} -ka\,dT$$

$$q\ell = -ka\left(T_c - T_h\right) \qquad (14a)$$

$$q = \frac{ka}{\ell}\left(T_h - T_c\right)$$

The total heat flow in the generator will be equal to the product of the total number of junctions in the generator and the heat flow from one junction. Since each junction consists of two materials, equation 14a may be modified to yield

$$q = \left(\frac{k'w't'}{\ell'} + \frac{k''w''t''}{\ell''}\right) N\Delta T \qquad (14b)$$

where

N = the total number of junctions in the generator

If the same operating conditions and desired output are chosen as in the first example, namely,[11]

T_c = 100°C	N = 104	p' = 46.5 μohm-cm
ΔT = 600°C	$\ell' = \ell''$	p" = 49.0 μohm-cm
δ = 1	w' = w"	k' = .4578 watts per cm-°C
q = 1500 watts	t' = t"	k" = .481 watts per cm-°C

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[11]International Critical Tables, (New York, 1929) Vol. 6, p. 214.

and the appropriate values are substituted into equation 14b, there will result

$$1500 = \frac{w}{\ell}(0.0508)\ (0.4578 + 0.481)\ (104)\ (600)$$

and

$$w = 0.504\,\ell \qquad (15)$$

and it is evident that equation 15 compares very favorably with equation 13.

The two dimensions of the generator that have thus far been neglected are the inside and outside diameters of the generator. However, these dimensions are relatively simple to determine and may on occasion assist in the choice of the thickness of the materials to be used. Considering first the inside diameter, D_i, the geometry of a radial thermalelectric generator indicates that the circumference of the inside diameter will be

$$\text{Circumference of } D_i = \pi D_i = N(t' + t'' + t_s)$$

Therefore

$$D_i = \frac{N}{\pi}\left(t' + t'' + t_s\right) \qquad (16)$$

where

t_s = the thickness of the insulating material in cm.

If the area ratio is introduced and $w' = w''$, then $t'' = \delta t'$ and equation 16 may be rewritten as

$$D_i = \frac{N}{\pi}\left[t'(1+\delta) + t_s\right] \qquad (16a)$$

Also from the geometry of the generator the ouside diameter D_o, may be written as

$$D_o = D_i + 2\ (\ell + \ell_f) \qquad (17)$$

where

$\ell =$ the length of the materials in cm.

$\ell_f =$ the length of the cooling fins in cm.

In the construction of the experimental generator, the iron sheets were allowed to extend 1 inch beyond the length of the constantan sheets to act as cooling fins for the cold junctions. The 1 inch length of the cooling fins was considered sufficient to maintain a cold junction temperature of 100°C when the generator was operated at a temperature differential of 600°C. In the actual operation of the generator the average cold junction temperature never exceeded 70°C and no single cold junction temperature ever exceeded 73°C.

In the construction of the radial generator, the iron and constantan sheets were joined at both the hot and cold junctions by a resistance welding process. The sheets thus joined were shaped into a circle which had an inside diameter, D_i, of 2 inches and outside diameter, D_o, of 16 inches. Sheets of paper asbestos were used as insulating material between the hot junctions and a commercial refractory material, "Kast-o-lite", was used as insulating material along the lengths of the metals and at the cold junctions. Two 14 inch disks each 3 inches in thickness were molded of a different commercial refractory material, "Alfrax" No. 58, and placed on the top and bottom of the generator to limit lateral heat losses during the operation of the generator. Experimental results indicated this insulation was insufficient suggesting that the thickness of the disks should have been substantially increased in order to keep the lateral heat losses at a minimum and therefore improve the experimental results of the generator. As a source of input power, an electrical heating element consisting

PLATE I

THE RADIAL THERMALELECTRIC GENERATOR

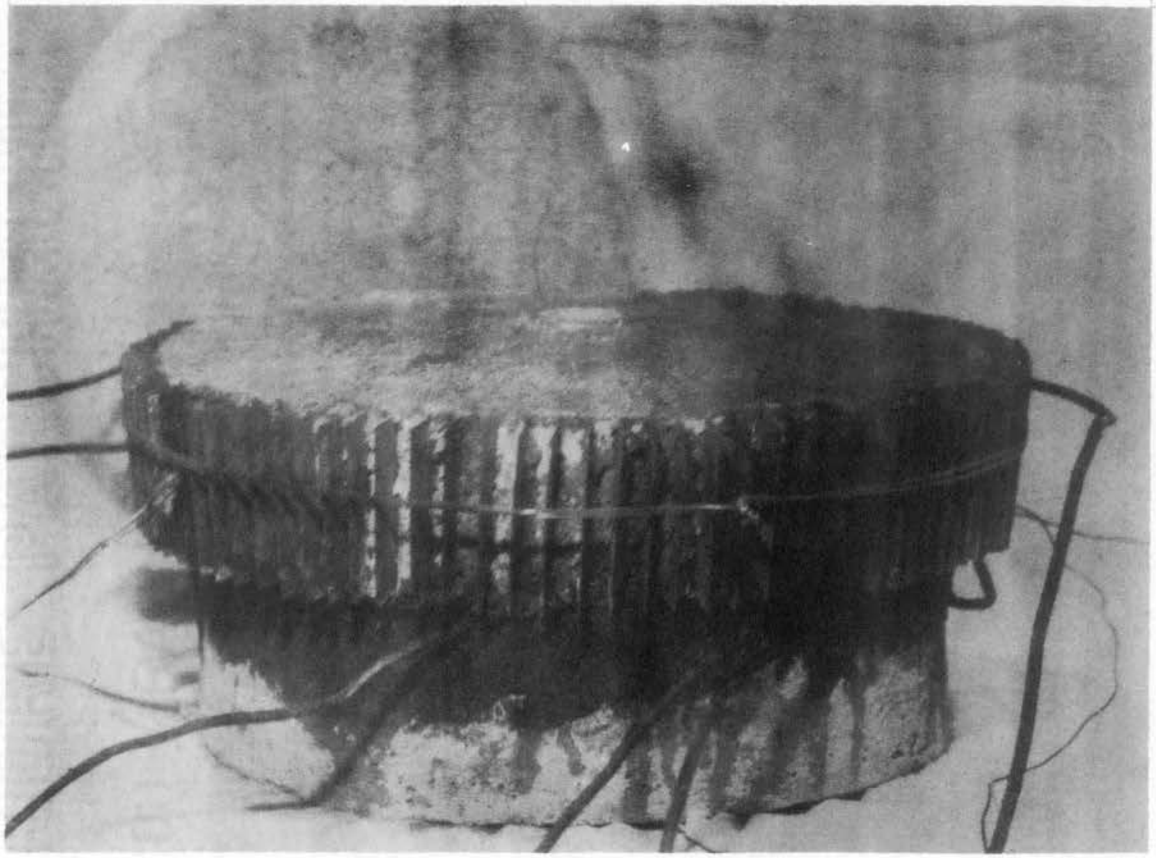
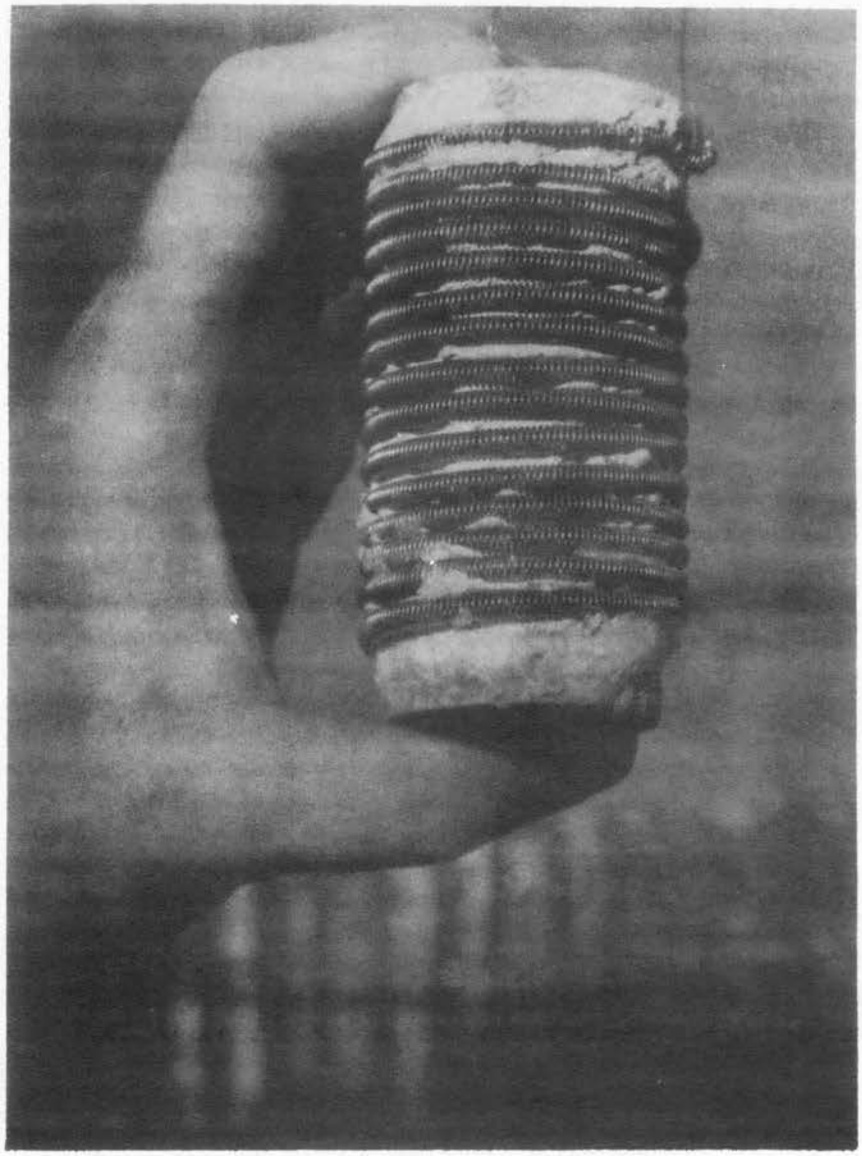


PLATE II

HEATING ELEMENT USED AS SOURCE OF INPUT POWER



of 36 inches of B&S 22, nickel chromium, 3/16 inch coiled wire was wound around a ceramic cylinder 3 inches long and 1 1/2 inches in diameter. With a heating element of this type, a maximum sustained input power of 1735 watts was obtained before excessive surface temperature of the coiled wire caused failure. Iron-constantan measuring thermocouples were attached at 3 positions around the circumference of the inside diameter to measure the hot junction temperatures and at 4 positions around the outside diameter to measure the cold junction temperatures during the operation of the generator.

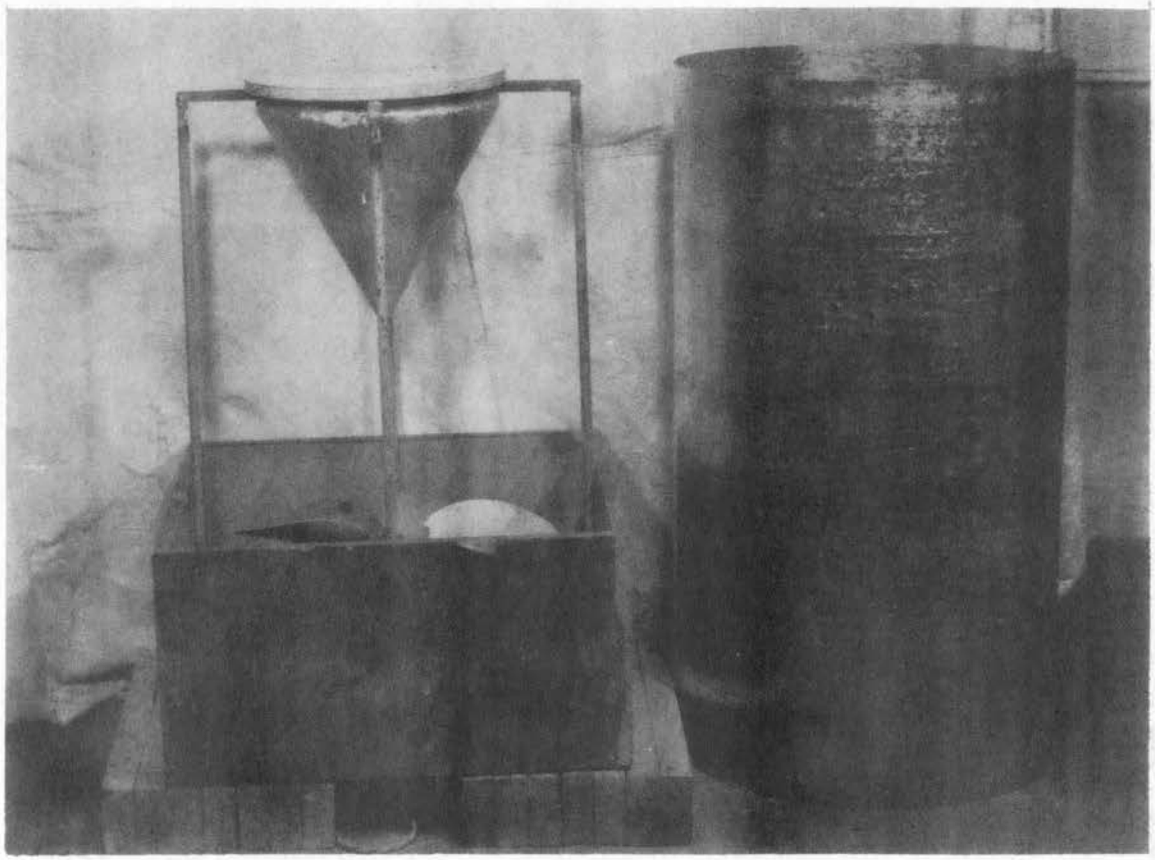
CHAPTER IV

TESTING AND EVALUATION

During the development of any device, the testing and evaluation of experimental results constitutes an important phase of the engineering science. It is the testing and evaluation of a new device that culminates all previous endeavor. In the case of the radial generator, no unusual problems were encountered in testing and evaluation, and a satisfactory program of experimental results was obtained. By using an electrical heating element as a source of input power and a slide wire rheostat as an electrical load, a convenient means of measuring both the input and output power was afforded. A schematic diagram of the test arrangement is illustrated by Figure 7. In the operation of the generator, the input current I_i, input voltage V_i, output current I_o and output voltage V_o were measured and recorded as were the temperatures of both the hot junctions T_h, and cold junctions T_c. In addition, a four-blade 18 inch fan, driven by a 1/8 horsepower electric motor, furnished a flow of room temperature air across the cooling fins of the generator. The power necessary to drive this cooling device was not included as part of the input power of the generator. This cooling arrangement is illustrated by Plate III. During the test operations, the generator was allowed to operate at each particular magnitude of input power for a period of 2 hours or more in order for the temperatures throughout the generator to stabilize. Hot and cold junction temperature readings were taken and recorded immediately before and

PLATE III

COOLING ARRANGEMENT FOR EXPERIMENTAL GENERATOR



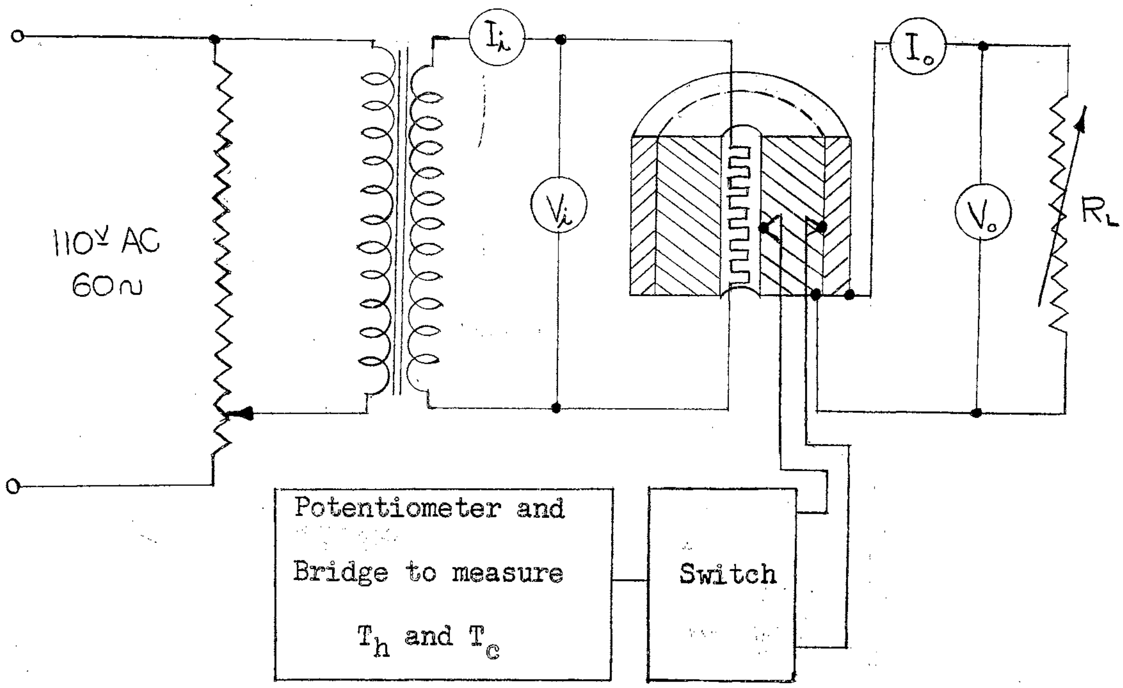


Figure 7. Schematic diagram of the test arrangement.

after the input and output currents and voltages were measured and recorded. This procedure proved to be quite adequate in that only slight variations were noted between the initial and final junction temperature readings.

After the testing of the generator was completed, calculations of the theoretical maximum efficiency at each test operating condition were made. These results are compared with the measured efficiency of the generator in Figure 8. It is apparent from Figure 8 that as the operating temperatures increased, the lateral heat losses which are not taken into account in the theoretical calculations, increased proportionally resulting in a more significant difference between the

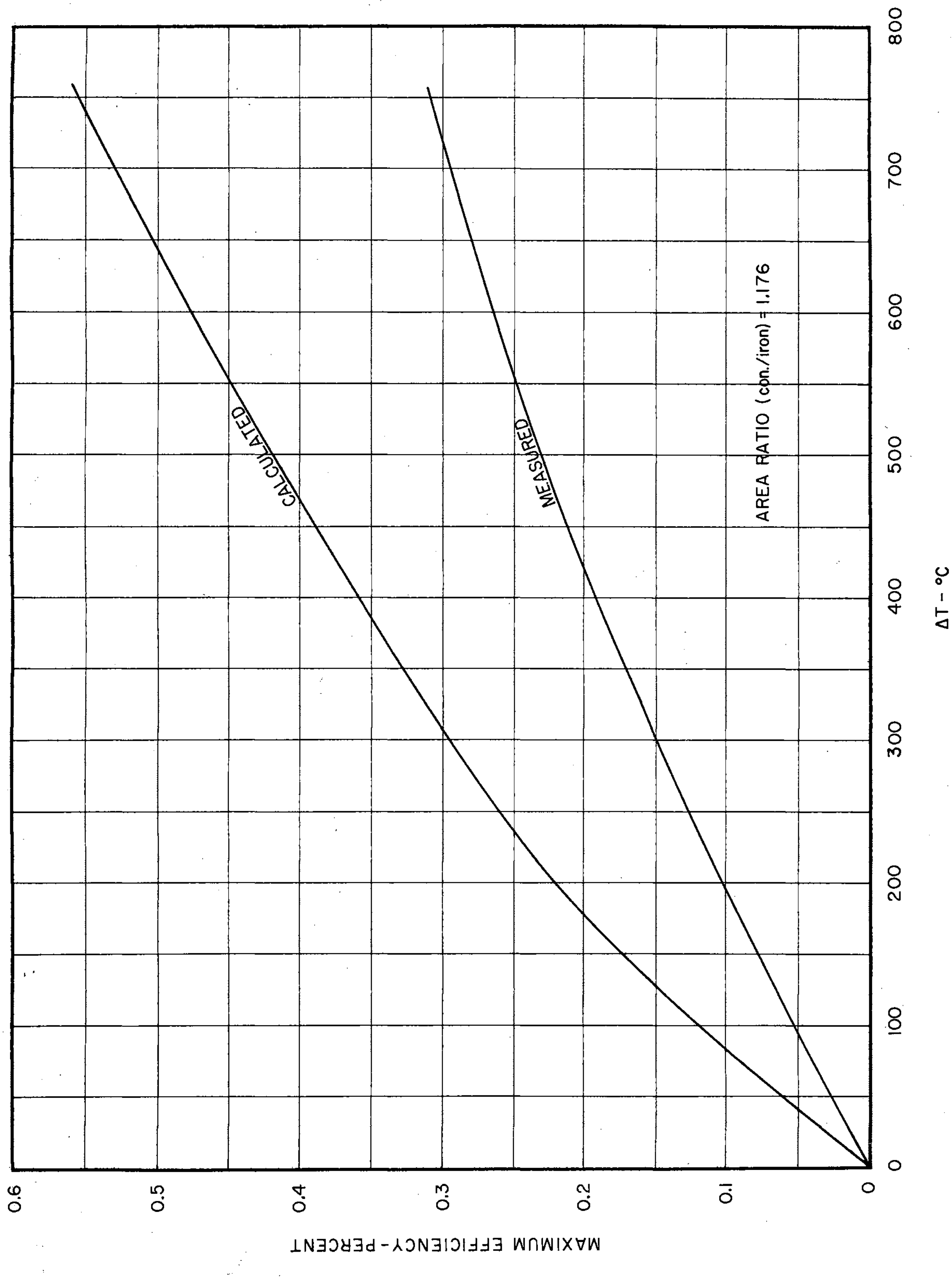


Figure 8. Comparison of measured and calculated efficiency.

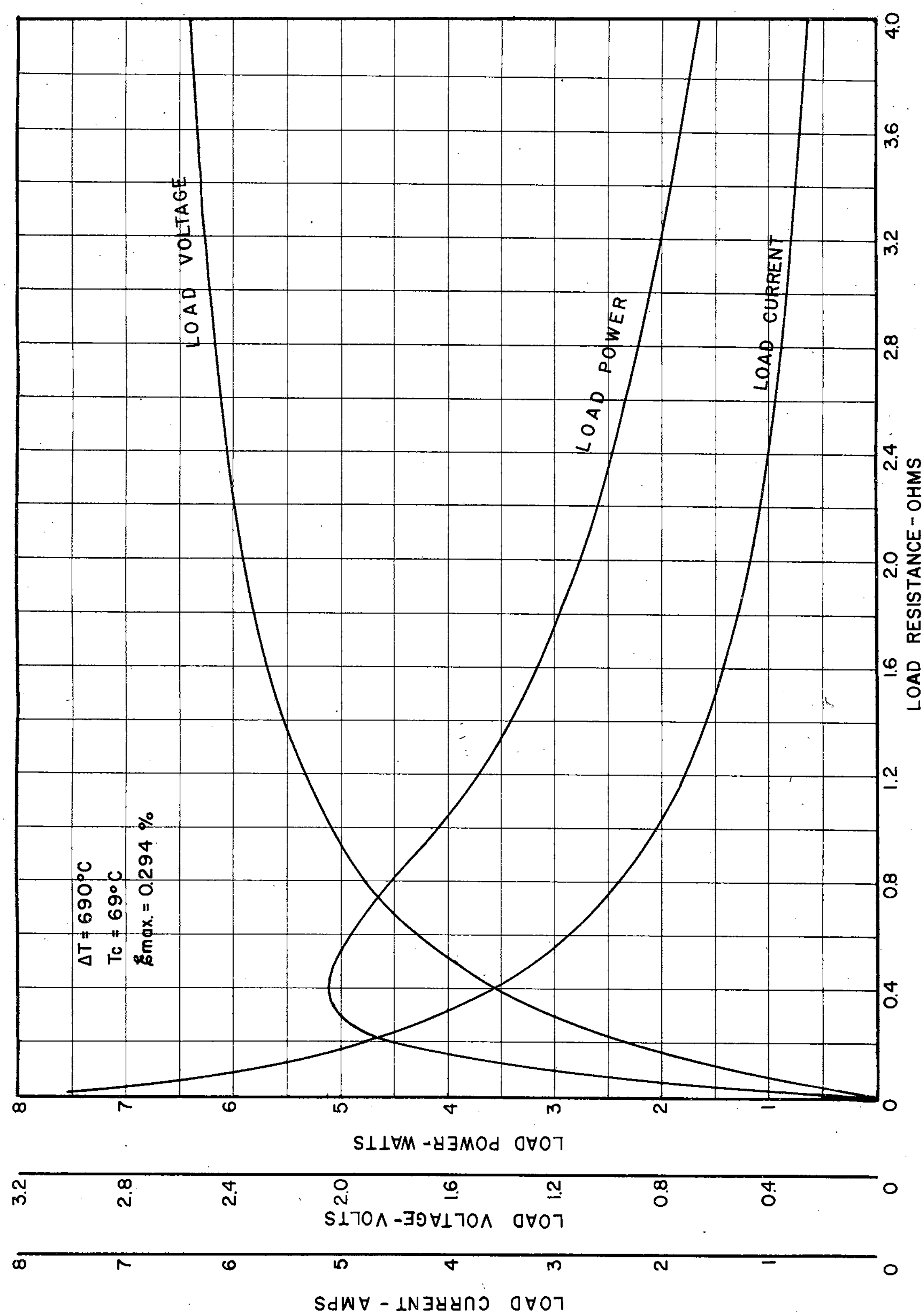


Figure 9. Current, voltage and power output of radial generator.

measured and calculated efficiency of the generator. Figure 9 depicts the measured output voltage, current and power of the generator as a function of load resistance. At maximum power output, the resistance of the generator was determined to be 0.40 ohms which compared most favorably with the calculated resistance of 0.388 ohms. Both the calculated and measured values of the input power, output power, current and voltage, resistance of the generator, efficiency, temperature differential and cold junction temperature, are listed in Table I. Table II compares the general performance of the radial generator with the performance of previously constructed wire generators.[12]

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[12]Paul A. McCollum, "Unconventional Electrical Power Sources," Wright Air Development Center Technical Report 54-409, Part II, (Oklahoma State University, September, 1955) p.20.

TABLE I

COMPARISION OF CALCULATED AND MEASURED RESULTS

	MEASURED	CALCULATED
Temperature differential, ΔT, ^{o}C	689.2	600
Cold junction temperature, T_c, ^{o}C	68.4	100
Output voltage, V_o, volts	1.38	1.75
Output current, I_o, amperes	3.7	4.5
Resistance of the generator, R_g, ohms	0.40	0.388
Power output, P_o, watts	5.11	7.89
Power input, P_i, watts	1735	1500
Efficiency, E_{max}, percent	0.294	0.526

TABLE II

COMPARISION OF PERFORMANCE CHARACTERISTICS

OF RADIAL AND WIRE GENERATORS

	RADIAL GENERATOR	WIRE GENERATOR
Volume per kilowatt, cubic feet/kilowatt	67.2	100.2
Weight per kilowatt, pounds/kilowatt	9,390	11,034

CHAPTER V

DEVELOPMENT OF DESIGN CHARTS

Several attempts have been made in previous studies to develop a series of charts and outline a procedure whereby the dimensions, characteristics of materials, and performance of a proposed thermalelectric generator could be conveniently specified. However, these attempts have been incomplete and failed to indicate many of the variable factors involved. Most noticeably absent from these studies is the area ratio which apparently influences to a great extent the performance of the generator. As illustrated by the design procedures described in Chapter III, the existence of charts such as shown in Figures 2, 3, 4, 5, and 6 can greatly reduce the labor involved in the design of a radial thermalelectric generator by indicating those conditions which will yield the most attractive results. However, the charts illustrated by Figures 2, 3, 4, 5, and 6 are particular to only a radial generator constructed of iron and constantan and are therefore of no value in a general sense. It would be impractical if not impossible to construct charts of this nature for every possible combination of materials and operating conditions which might be encountered now and in the future. Therefore there arises the need for charts of a more general nature, and applicable to a range of operating temperatures most likely to be encountered.

As stated in Chapter II, the general theoretical maximum efficiency of any thermalelectric generator may be expressed as

$$\mathcal{E}_{max} = \frac{T_h - T_c}{T_h}\left[1 + \frac{2\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}{e^2 T_h} - \frac{2\left\{1 + \frac{\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}{e^2 T_h}\right\}}{\sqrt{1 + \frac{e^2 T_h}{\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right)}}}\right] \quad (1)$$

If only a radial generator is considered, then $\ell' = \ell''$ and $\frac{a''}{a'} = \delta$ and the terms containing the electrical resistance and thermal conductance of the generator may be expressed as

$$\left(\frac{\rho'\ell'}{a'} + \frac{\rho''\ell''}{a''}\right)\left(\frac{k'a'}{\ell'} + \frac{k''a''}{\ell''}\right) = \left(\rho'\delta + \rho''\right)\left(\frac{k'}{\delta} + k''\right) = CD$$

where

$$C = \rho'\delta + \rho'' \quad (18)$$

$$D = \frac{k'}{\delta} + k'' \quad (19)$$

If parameters "C" and "D" are substituted in the general equation the result will be

$$\mathcal{E}_{max} = \frac{T_h - T_c}{T_h}\left[1 + \frac{2CD}{e^2 T_h} - \frac{2\left\{1 + \frac{CD}{e^2 T_h}\right\}}{\sqrt{1 + \frac{e^2 T_h}{CD}}}\right]$$

This equation may be further simplified by specifing a parameter "B" as

$$B = \frac{2CD}{e^2} \quad (20)$$

then

$$\mathcal{E}_{max} = \frac{T_h - T_c}{T_h}\left[T_h + B - \frac{B + 2T_h}{\sqrt{\frac{B + 2T_h}{B}}}\right] \tag{21}$$

With the parameters "B", "C", and "D" thus developed, charts were constructed that graphically express their relationship to each other. Data for these charts was obtained with the aid of an IBM 650 Digital Computer and the FLOPS Interpretive System of programming. The data shown in Figure 10 expresses the parameter "B" as a function of the thermalelectric power of each junction and the product of the "C" and "D" parameters. The charts depicted by Figures 11, 12, 13, 14, 15, 16, and 17 represent the theoretical maximum efficiency of a radial thermalelectric generator as a function of the parameter "B", temperature differential and the cold junction temperature. It should be understood that these charts may be used for any combination of materials for which there is available the electrical and thermal characteristics of the materials. In addition, the charts are independent of the physical dimensions of the generator and may be used in reverse order. For example, at a particular efficiency and operating temperatures the parameter "B" may be determined which in turn will specify the characteristics of the materials necessary to realize these conditions. Conversely, for any combination of materials the parameter "B" may be determined and may then be used to find the efficiency at the particular operating conditions.

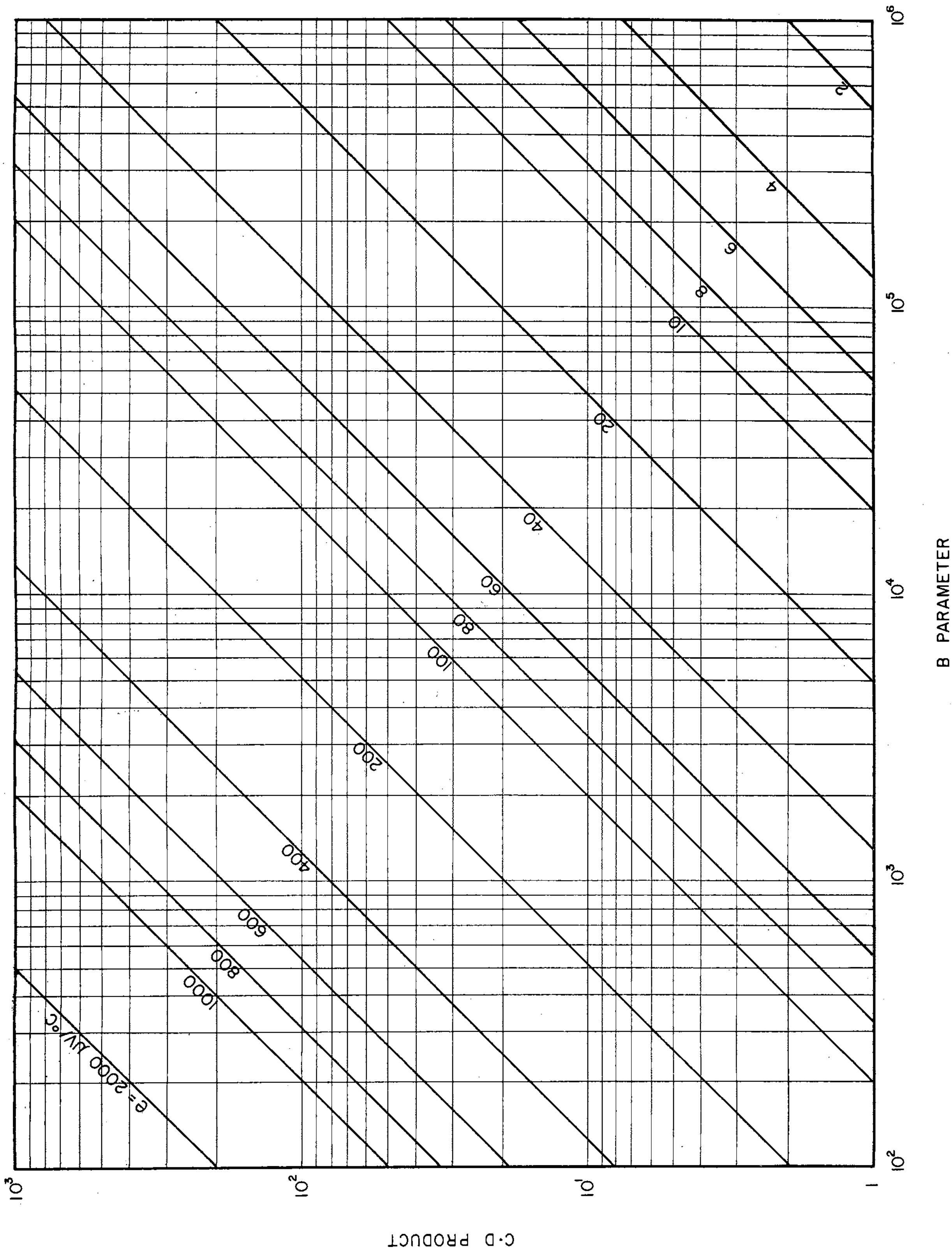

Figure 10. Relationship of "B", "C" and "D" parameters.

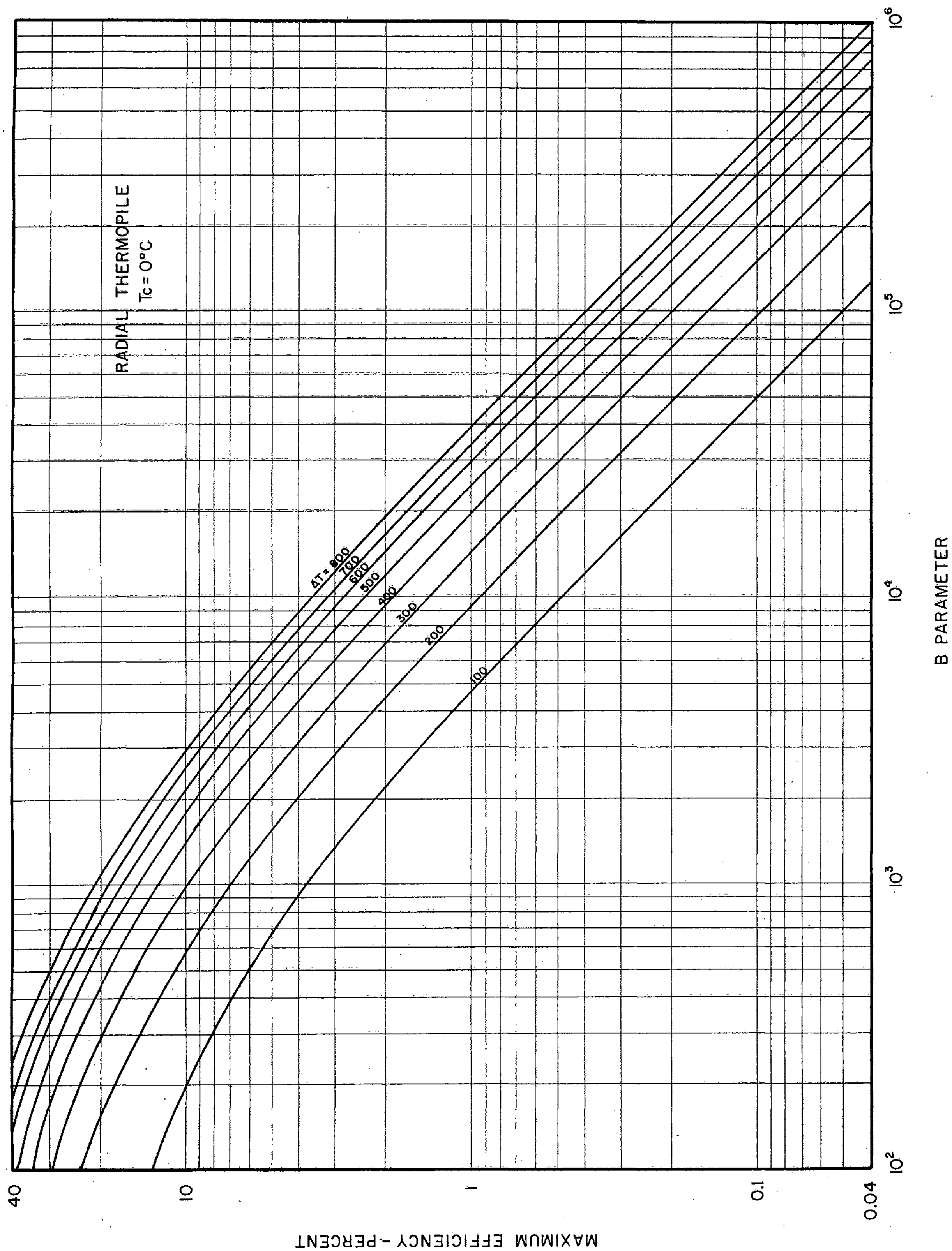

Figure 11. Maximum efficiency versus "B" parameter, $T_c = 0^{O}C$.

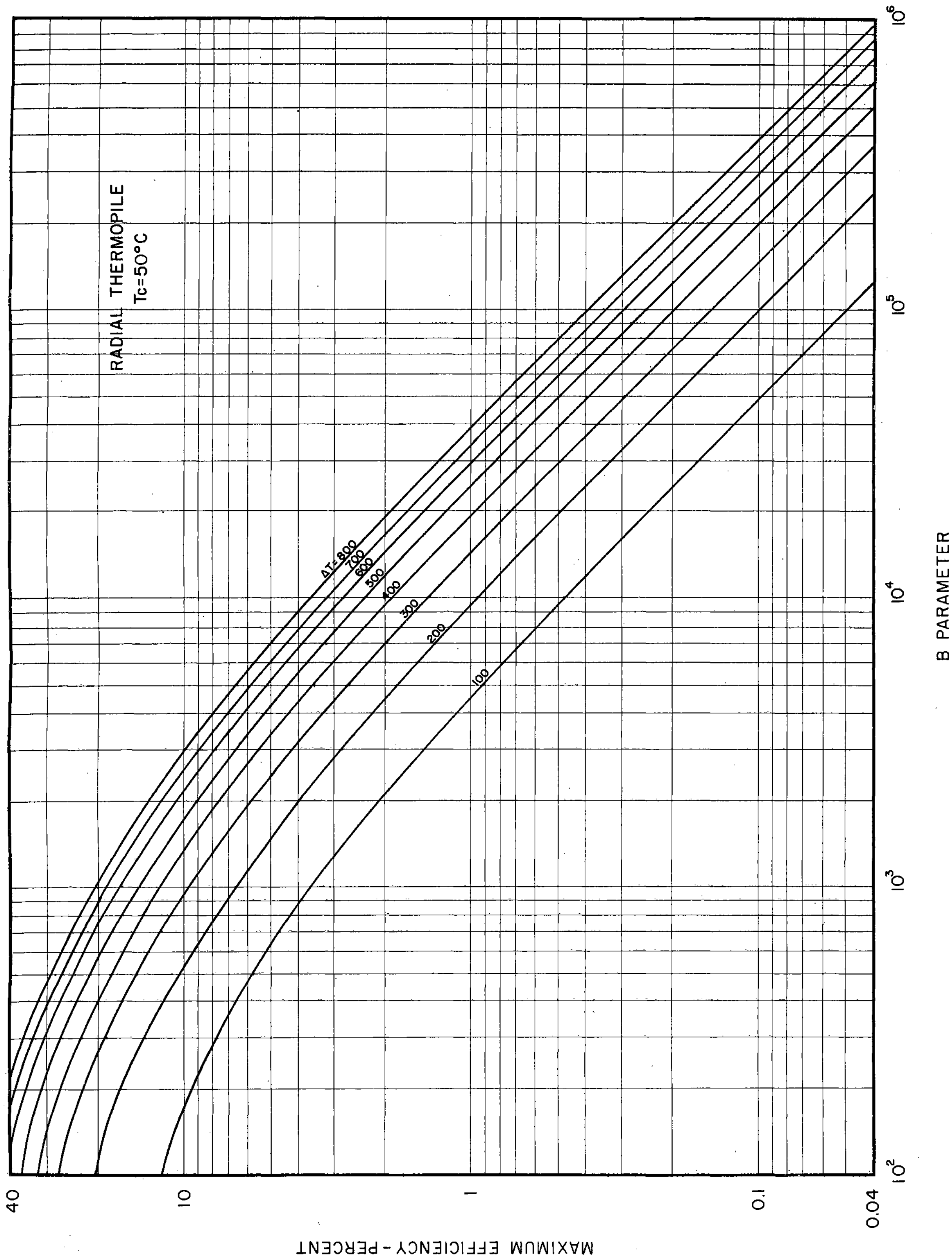

Figure 12. Maximum efficiency versus "B" parameter, $T_c = 50^oC$.

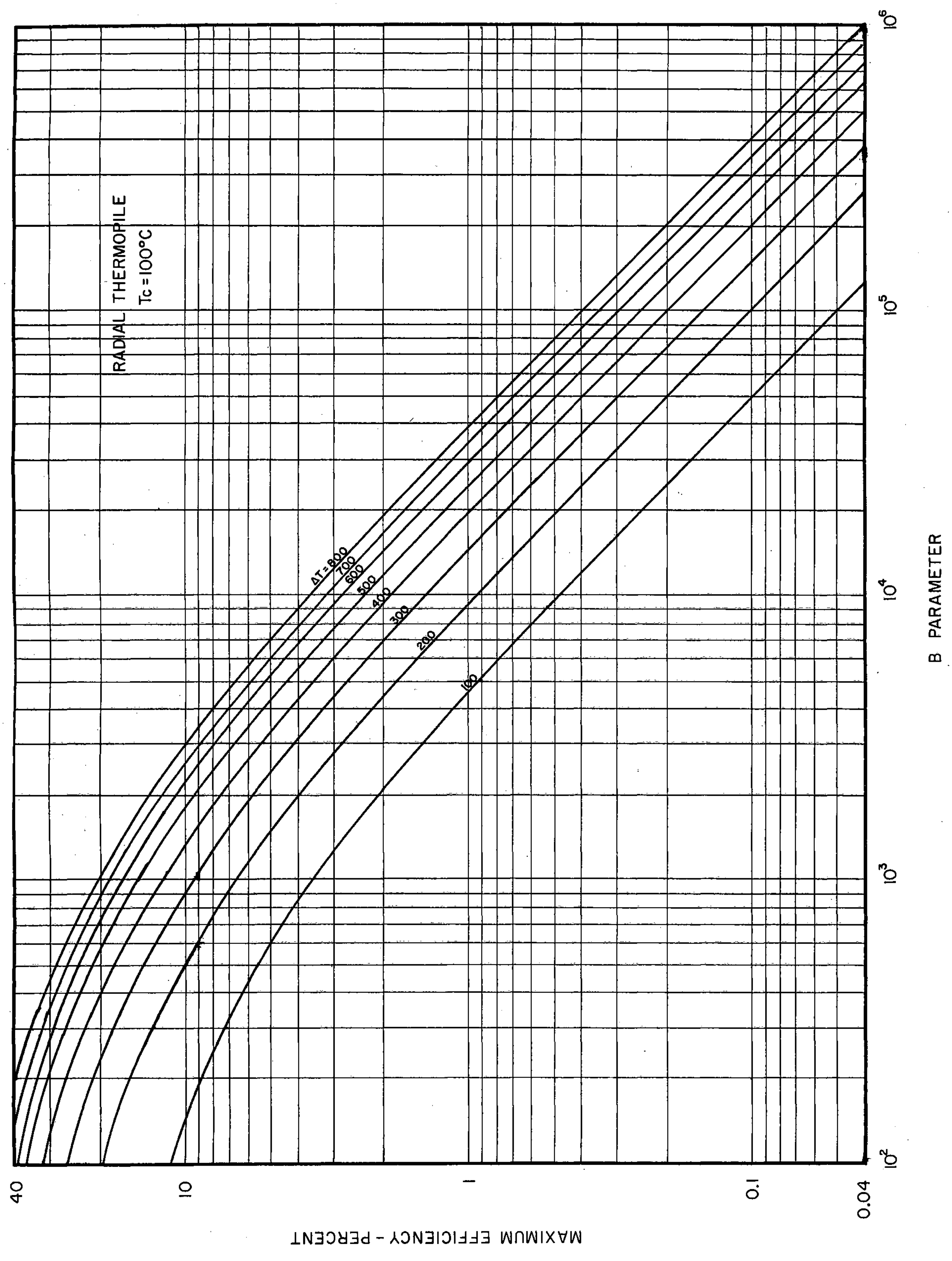

Figure 13. Maximum efficiency versus "B" parameter, $T_c = 100^oC$.

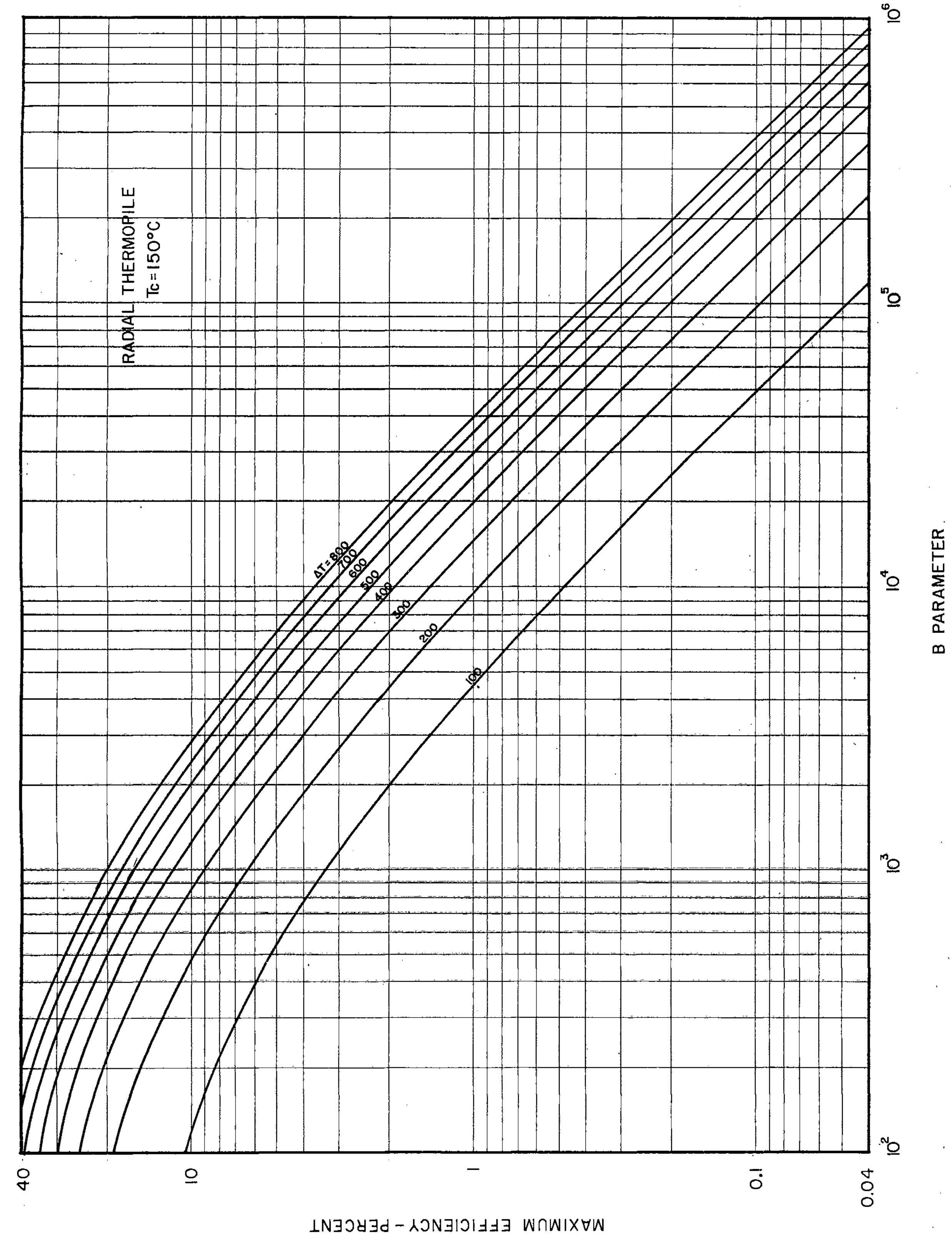

Figure 14. Maximum efficiency versus "B" parameter, $T_c = 150^oC$.

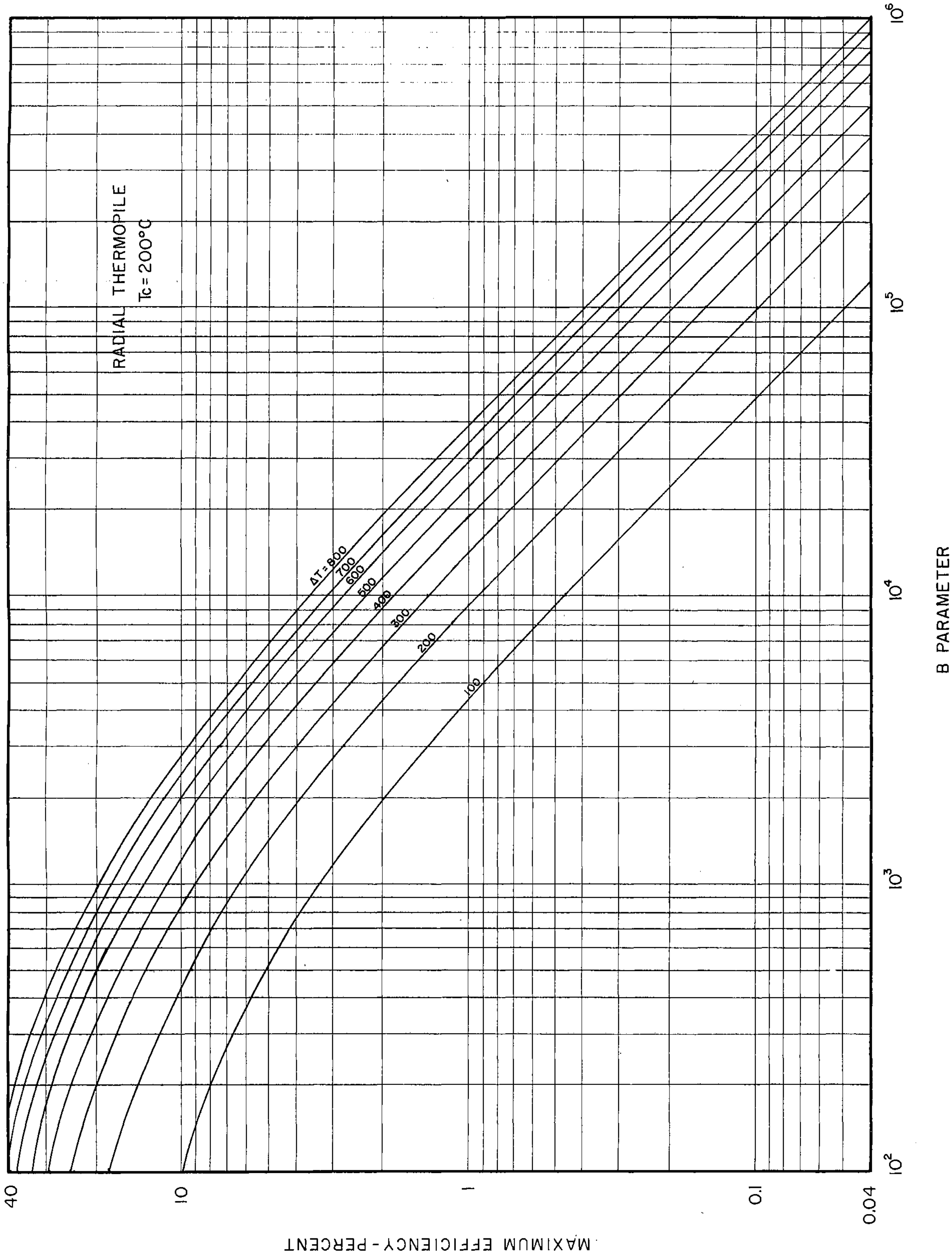

Figure 15. Maximum efficiency versus "B" parameter, T_c = 200°C.

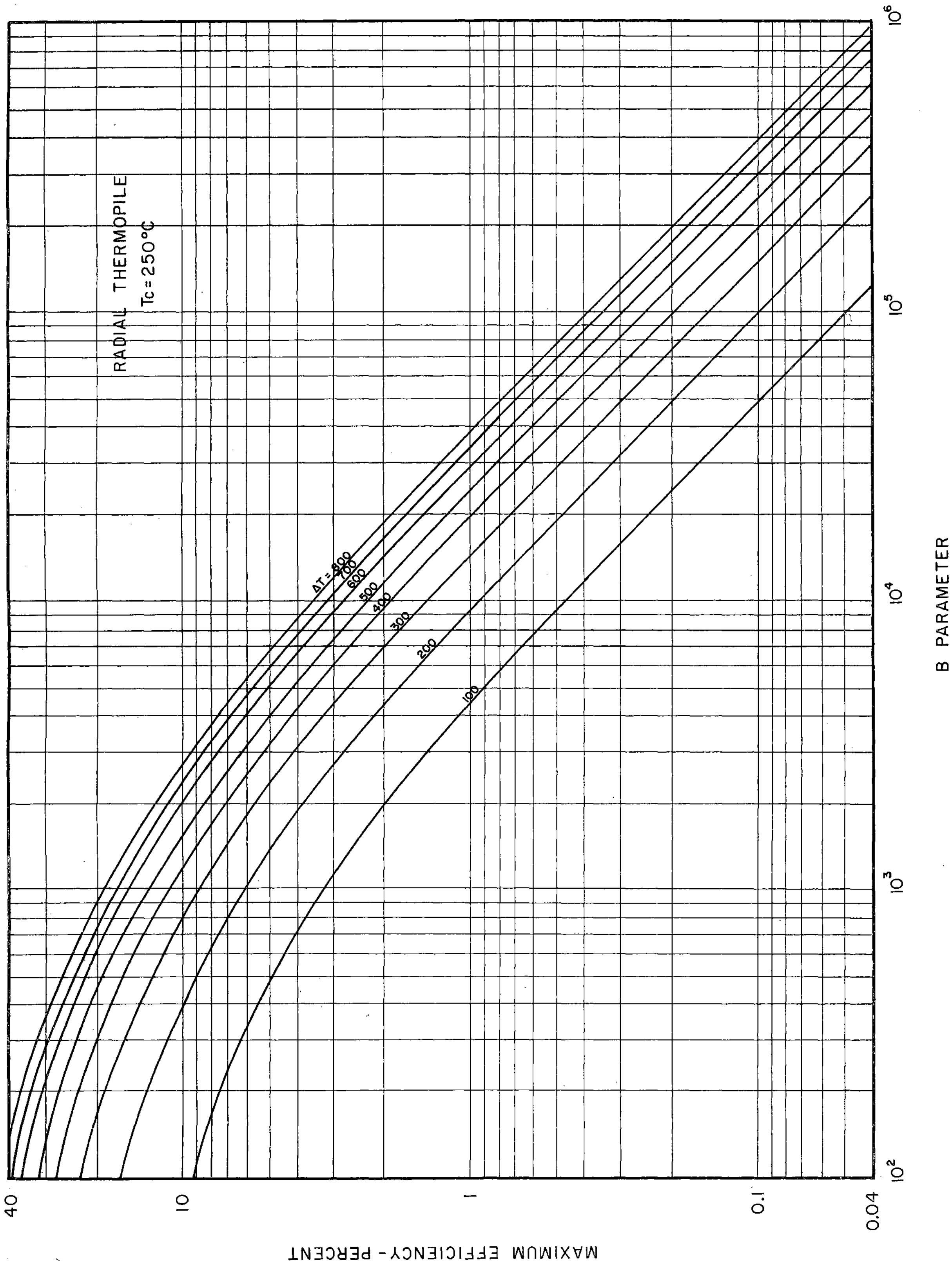

Figure 16. Maximum efficiency versus "B" parameter, $T_c = 250^oC$.

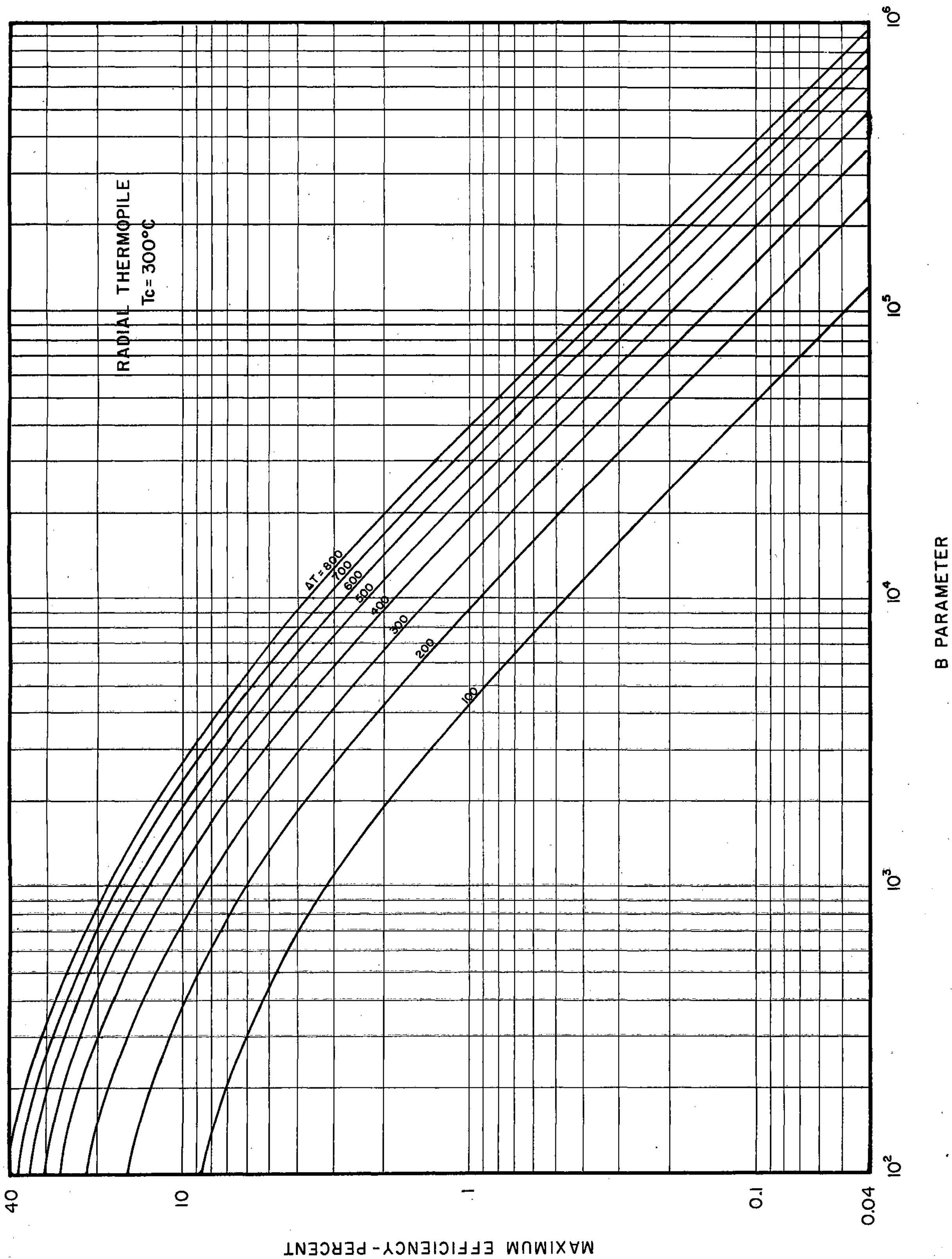

Figure 17. Maximum efficiency versus "B" parameter, $T_c = 300^\circ C$.

In practice, these charts should be used to aid in making an intelligent choice of materials. After the materials have been chosen, a series of charts similar to those of Figures 2, 3, 4, 5, and 6 could be constructed to show in greater detail the influence of the area ratio and the operating temperatures on the theoretical maximum efficiency of the generator. The use of manual computation in this regard might prove to be prohibitive, however, with the increased popularity and availability of electronic digital computing devices, this problem is not considered to be serious. With a satisfactory choice of materials, area ratio, and operating temperatures, a procedure similar to either of the methods described in Chapter III may be used to determine the physical dimensions of the generator.

CHAPTER VI

SUMMARY AND CONCLUSIONS

The applications in which a thermalelectric generator might be used in the future are of course open to much speculation. With technology advancing in ever increasing strides, it sometimes seems that the impossible of today is but a commonplace fact of tomorrow. If there was available an efficient thermalelectric generator comparable in size and output to an automobile storage battery, and operated by waste heat from possibly a nuclear reactor, its applications would indeed be widespread. Although such a device is not now available, its development and ultimate existence should be recognized as within the realm of possibility. Nevertheless, the thermalelectric generator as we know it today, as a bulky mass with low efficiency and low power output, still has several possible applications.

One, seemingly apparent application, is in high altitude aircraft and ballistic missiles. The radial thermalelectric generator might use the exhaust gases as a source of heat and supply electrical power for communications equipment, guidance system and fire control apparatus. Because of the low power output and large weight and volume of the generator, the devices utilizing the power of the generator should be designed around semiconductor devices which are characterized by small power requirements and small weight and volume as compared to similar circuits employing vacuum tubes. It is probable that the savings in volume and weight made possible with circuits utilizing semiconductors would partially at least, offset the additional weight and volume required for the thermalelectric generator. Another important application of the thermalelectric generator involves solar energy as a source of heat. A home,[13] located 30 miles from Tucson, Arizona, is equipped with a solar-heat collector which furnishes air heating for the home during cold weather. This is accomplished by collecting and concentrating heat energy from the sun on a rockpile located several feet underground. If this heat-storage rockpile were surrounded by a radial type thermalelectric generator, electric power for lighting and appliances would be furnished in addition to home heating. Such an arrangement would use the heat-storage rockpile as the hot junctions and the earth as the cold junctions. Since the entire system would be a permanent installation located underground, the size of the thermalelectric generator would be of little consequence, and its low efficiency would cause no problem due to the abundance of solar energy.

The objective of this thesis has been to present a discussion of the development of a thermalelectric generator of varied design, and also to predict the performance of this generator under typical operating conditions. The problem of efficiency has been given serious consideration, and charts depicting the influence of various parameters such as area ratio and operating temperatures on the efficiency of the generator have been presented. Although some of the charts presented in this thesis apply only to a combination of iron and constantan, the equations used to calculate data for these charts are general in nature.

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[13]Raymond W. Bliss, Jr., "Solar House Heating, A Panel," Proceedings World Symposium on Applied Solar Energy, Phoenix, Arizona, November, 1955 pp. 151-158.

With these equations it is possible to evaluate the merits of any combination of thermocouple metals and establish their relative worth when used in a radial type generator. In addition, it is also possible to predict the characteristics of a combination of materials that will yield the maximum efficiency and output for a given set of operating conditions. These charts are presented in Chapter V and apply to all combinations of materials. From these charts it is evident that certain characteristics of materials will yield efficiencies that far exceed the efficiencies encountered with the experimental generator constructed and tested.

Several photographs have been included to illustrate the relative size and shape of the radial generator design as well as the scheme for cooling the cold junctions and furnishing heat for the hot junctions. The particular method of supplying heat to the experimental generator described in this paper involved an electrical heating element which resulted in some limitations in the operating temperatures attainable. Due to high surface temperatures on the windings of the heating element during the operation of the generator, the ceramic core on which the element was wound fractured, causing the element to become short-circuited. The highest average hot junction temperature obtained using the electric heating element was 757°C. This yielded an average temperature differential of 690°C. The theoretical efficiency equation indicates that the efficiency increases as the temperature differential increases, therefore more detailed information about the operation of the radial thermalelectric generator at temperatures in excess of 1000°C is most desirable.

Subsequent testing of the experimental generator indicated that excessive lateral heat losses through the refractory disks caused the calculated and measured efficiencies to differ considerably. Since the efficiency of the generator derived from an empirical formula does not take into account any heat losses, it is apparent that all efficiency predictions are, in general, ideal efficiencies, and discrepancies between measured and calculated results should be expected. However, with adequate heat insulation losses through the refractory of the generator could be substantially decreased and therefore increase the operating efficiency of the generator.

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