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TELEDYNE ISOTOPES

THERMOELECTRIC GENERATOR DESIGN MANUAL

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LIST OF SYMBOLS

Symbol	Definition	Units
A	Cross section of N element plus P element	in^2
A/L	Element shape factor	in.
C_T	Total contact resistivity per couple	$\mu\Omega\text{-}cm^2$
$C_{T/L}$	Total contact resistivity per couple divided by element length (length of N element = length of P element)	$\frac{\mu\Omega\text{-}cm^2}{in}$
D_N	N element diameter	in.
D_P	P element diameter	in.
E_o	RTG instantaneous open circuit voltage	volts
E_{oc}	Couple instantaneous open circuit voltage	volts
I	Current	amps
k	Thermal conductivity	Btu/hr-ft-°F
L	Element length	in.
L_{SnTe}	SnTe segment length in TAGS segmented couple	in.
m	External resistance divided by internal resistance	
N	Number of couples in RTG	
N_s	Number of couples in series in RTG	
N_p	Number of parallel circuits in RTG	
P	Gross electrical power generated by elements	watts(e)
P_n	Net power delivered to RTG terminals	watts(e)
$\frac{PL}{NA}$	Power parameter for a given material, temperatures, and contact resistivity	watts(e)/in.
Q_{HS}	Heat source thermal inventory	watts(t)
Q_L	Parasitic heat losses	watts(t)

LIST OF SYMBOLS (Cont.)

Symbol	Definition	Units
$\frac{QL}{NA}$	Heat parameter for a given material, temperature and contact resistivity	watts(t)/in.
Q_{rej}	Heat rejection requirements	watts(t)
$Q_{T/E}$	Heat which enters the thermoelectric elements at the hot junction	watts(t)
R_E	Extraneous electrical resistance in the RTG electrical circuit (this includes all resistance in the RTG except the elements)	ohms
T_C	Cold junction temperature	°F
T_H	Hot junction temperature	°F
V_c	Load voltage per couple	volts
V_s	RTG voltage	volts
z	Figure of merit	$°F^{-1}$
α	Seebeck coefficient	V/°F
η	Thermoelectric efficiency	%
η_s	System efficiency	%
ρ	Electrical resistivity	Ω-in.

INTRODUCTION

This manual presents the salient features of thermoelectric generator design and analysis from the viewpoint of heat and charge transport. To this end, it contains a basic description of the thermoelectric phenomenon as well as the properties of important materials used for energy conversion. Chapters I, II, and III illustrate the fundamentals of thermoelectric effects, the characteristics of materials yielding these effects and their pertinence to practical generator design. The properties of materials used in current space and terrestrial generators and parametric performance characteristic of these materials working as thermoelectric couples are given in Chapters IV and V. Finally, use of the parametric characteristics is explained by means of conceptual design calculations given in Chapter VI.

At this point it is appropriate to mention that the scope of this manual does not include chemical and structural characteristics of materials and interfaces vital to generator design. Indeed, these subjects represent formidable challenge to the designer and even at present much is left to the art of fabrication rather than to quantitative formulation of procedure by theoretical means.

CHAPTER I

The Thermodynamics of Thermoelectricity

Many texts begin the discussion of thermoelectricity from the historical viewpoint of discovery by Seebeck, Peltier, and Thomson continuing through the Kelvin relationships. A second approach is to discuss thermoelectricity through direct particle flow and thermodynamic considerations. Since these approaches are well-treated in the literature, this report will present a modified explanation, one that is believed of more immediate appreciation by the designer of practical devices.

The fundamental property of thermoelectricity is the Seebeck coefficient, popularly labeled "α", which characterizes the voltage produced across a material experiencing a temperature gradient and no electrical current flow. Specifically, the open-circuit voltage, E_o is given by:

$$E_{o_{T_1,T_2}} = \int_{T_1}^{T_2} \alpha(T)\, dT \qquad \text{(Eq. I-1)}$$

where the integral is evaluated over the temperature range experienced. Note that the temperature distribution through the material has no effect on E_o, only the temperatures at the two points between which the potential difference is defined affect the value of E_o. In general, α is a strong function of temperature, so that precise integration of $\alpha(T)$ is necessary.

The other important fact of thermoelectric phenomena is that the heat transport by normal conduction and the energy transport by electric current flow may be considered independent. Thus, the thermal and electric processes may be added simply with no interaction other than that

caused by temperature distribution alteration. This enables separation of the electric phenomena as:

$$P_{out} = E_o I - I^2 R_i \qquad \text{(Eq. I-2)}$$

where P_{out} is the electric power available, E_o is the generated voltage (open-circuit or Seebeck), R_i is the generator internal resistance and I, the electric current.

Now let us examine the first term on the right, $E_o I$. As stated, above,

$$E_o = \int_{T_1}^{T_2} \alpha(T)\, dT \text{ and therefore } E_o I = I \int_{T_1}^{T_2} \alpha(T)\, dT.$$ If

the integral is evaluated by parts,

$$E_o I = I \left[\alpha(T_2)\, T_2 - \alpha(T_1)\, T_1 - \int_{T_1}^{T_2} T\, d\alpha \right] \qquad \text{(Eq. I-3)}$$

Equation (I-3) is more than simply a mathematical expression. The terms on the right hand side have a definite physical significant and correspond to real thermal effects. The first term, $I\ \alpha(T_2)\, T_2$, represents the total electrical induced energy flux into the material at position 2 corresponding to T_2. The second term, $I\ \alpha(T_1)\, T_1$, represents the total electrical induced energy flux leaving the material at position 1 corresponding to T_1. These terms are identified in the literature as the Peltier heat terms in honor of their discoverer. The remaining term, $I \int_{T_1}^{T_2} T\, d\alpha$, is likewise readily related to the effect discovered thermodynamically and verified experimentally, the Thomson heat. It may be added that it is more common to see this term as $I \int \tau\, dT$ where $\tau = T\, d\alpha / dT$ (Thomson coefficient). It is apparent

that "Thomson heating" occurs whenever the Seebeck coefficient varies with temperature. In practice, this is the case in all thermoelectric materials.

As stated above, linear superposition applies to the thermal and electric processes so that in order to obtain the total heat supplied, the conduction heat, $q = kA\, dT/dX$, at the surface (hot junction) is added to the Peltier heat.

$$Q_{T/E} = I\alpha(T_1)\,T_1 + kA\frac{dT}{dX}\Bigg|_{\text{at } T_1 \text{ position}} \qquad \text{(Eq. I-4)}$$

Of course, to evaluate the conduction heat, the temperature gradient must be known, and this must be calculated by considering all heat transport effects (i.e., conduction, Joule heating, and Thompson heating). Thus, all thermoelectric design and analysis is based upon evaluation of the differential equation for temperature distribution:

$$\frac{d}{dX}\left(kA\frac{dT}{dX}\right) + I^2\frac{\rho}{A} + \tau I\frac{dT}{dX} = 0 \qquad \text{(Eq. I-5)}$$

where:

- X = length variable
- k = thermal conductivity
- A = cross-sectional area
- T = absolute temperature
- I = current
- ρ = resistivity
- τ = Thomson coefficient

Methods of evaluating this equation, and the significance of the terms will be presented in detail in Chapter III.

The preceding discussion implies that the significant properties affecting conversion efficiency are the Seebeck coefficient, thermal conductivity, and electrical resistivity. From the electrical energy balance (Eq. I-2), it is apparent that a large Seebeck coefficient and small electrical resistance yield high power output. Inclusion of the conduction heat in the total heat input suggests that low thermal conductivity yields the highest efficiency. These quantities are combined in the figure of merit defined as: $Z = \alpha^2/\rho k$. Good thermoelectric materials have large α and low ρ and low k values throughout the operating temperature range, and hence exhibit high values of Z.

A quantitative measure of the significance of Z is commonly demonstrated by a simplified thermoelectric design process. The details will be presented in Chapter III, and it will be stated simply here that an approximation of conversion efficiency is:

$$\eta = \frac{\Delta T}{T_H} \frac{m}{(1+m) - \frac{\Delta T}{(2T_H)} + \frac{(1+m)^2}{(ZT_H)}} \qquad \text{(Eq. I-6)}$$

where: ΔT = temperature difference across thermoelectric material

T_H = hot junction temperature (absolute)

m = optimum load ratio = $\frac{R_L}{R}$ opt.

Z = figure of merit evaluated assuming α, ρ, and k are independent of temperature

Since the optimum load ratio is nearly unity (that is, less than 2), substituting m = 1 yields:

$$\eta = \frac{\Delta T}{T_H} \frac{ZT_H}{(2ZT_H - \frac{\Delta T Z}{2} + 4)} \qquad \text{(Eq. I-7)}$$

Now if we are interested in demonstrating the lower limit performance, that is where ZT_H is small compared to unity, this expression may be simplified to:

$$\eta = \frac{\Delta T}{T_H} \left[\frac{ZT_H}{4} \right] \qquad \text{(Eq. I-8)}$$

The quantity $\Delta T/T_H$ referred to as the Carnot efficiency, may be considered of order unity (at least between 0.25 and 0.75 for practical materials consideration). Thus, $ZT_H/4$ represents the order of thermoelectric efficiency, and it is apparent that if efficiency is to be of order 10%, ZT_H must be at least of order 0.5. Considering practical temperatures, T_H may be between 700 and 1400°K and thus Z must have a magnitude of order 10^{-3}/°K to yield significant conversion efficiency. The next chapter will present the type of materials having such figure of merits as to be worthwhile producers of electrical power.

One final introductory note is appropriate here, and, that is, both negative and positive polarity thermoelectric materials exist. That is, some materials yield a voltage gradient in the direction of the temperature gradient (p material) while others exhibit the negative effect (n material). The advantage of such characteristics is obvious when circuit completion in a practical device is considered.

CHAPTER II

Thermoelectric Materials

Until quite recently the lead tellurides were used almost exclusively for thermoelectric power generation particularly in Radioisotope Thermoelectric Generators (RTG's). This was so for two reasons: 1) there was no suitable substitute for the lead tellurides, p or n, and 2) the unavailability of a radioisotopic heat source that could safely increase the hot junction temperature over the optimum requirement for lead tellurides, about 600°C. For these reasons the lead tellurides will be discussed first.

Lead telluride has a face centered cubic crystalline structure with a melting point of 922°C. The stoichiometric compound contains 38.113 weight percent tellurium. Stoichiometric excesses of Pb or Te in the order of a few hundredths of one percent induce n-type or p-type electrical properties, respectively, and also improve some of the mechanical properties. The carrier concentrations induced by the slight excesses of Pb or Te are about 3×10^{17}/cc. An analysis of the parameters which make up the figure of merit shows that the optimum n-type and p-type charge carrier concentration is in the range of 10^{18}/cc. Small additions of certain foreign compounds which have specific cationic or anionic species can be used to adjust the charge carrier concentration to at least one magnitude beyond the desired level. Thus PbI_2 in minute concentrations is used to adjust the charge carrier concentrations in n-type PbTe thermoelectric materials and Na_2Te in minute concentrations is used to adjust the charge carrier concentration in p-type PbTe thermoelectric materials. The materials PbI_2 and

Na_2Te, and other materials that produce analogous effects, are commonly referred to as dopants. The figure of merit maxima can be varied with temperature as a function of the dopant concentration.

A typical composition for an n-type PbTe thermoelectric material is 37.95 weight percent tellurium, 62.05 weight percent lead and about 0.1 mol percent PbI_2. A typical composition for a p-type PbTe contains 38.3 weight percent tellurium, 61.70 weight percent lead and about 1.0 atomic percent sodium. Most of the lead telluride thermoelectric materials used for power generation are compositions patented by 3M Company, including those just discussed.

Most thermoelectric materials are extremely sensitive to environmental impurities. This is true particularly of the lead tellurides. Careful attention must be given to the extraneous materials which are permitted to contact lead tellurides at almost any temperature above ambient. Subtle or in extreme cases gross effects can occur rapidly.

Alternate patented and/or proprietary lead telluride compositions are available from 3M Company. One is an n-type material which is more heavily doped with iodine which is applicable to somewhat higher hot junction temperatures. A sodium doped p-type lead telluride containing a significant tin concentration along with some manganese is similarly applicable at higher hot junction temperatures.

Other alternative materials both n-type and p-type are available. Among these are iodine or sodium-doped stoichiometric lead telluride,

also iodine-doped n-type lead telluride-germanium telluride alloys, and sodium doped p-type lead telluride-lead selenide alloys. Materials discussed in this paragraph are just becoming available for use.

Within the last few years a new p-type material has become available. This material is a pseudo-binary alloy containing germanium, tellurium, silver and antimony. It has a mixed face-centered-cubic and rhombohedral structure with a liquidus of 686°C. The thermoelectric properties arise from its defect structure. This material, known by the acronym TAGS cannot be doped by common thermoelectric dopants, even at extreme relative concentrations.

Undoped stoichiometric tin telluride is used in conjunction with TAGS as a thermal barrier. In order to take full advantage of the somewhat higher temperature capability of n elements of lead telluride, a compatible p-type material must be provided between the hot junction and the TAGS element. SnTe serves this purpose. It is not a particularly good thermoelectric material when compared with TAGS or the lead tellurides, but it does provide a thermal barrier and compatible physical properties.

A safe radioisotopic heat source of much higher temperature capability will enable the thermoelectric conversion industry to make use of the n and p-type silicon germanium alloys. These alloys possess extreme stability in both air and vacuum even at their very high operating temperatures, as high as 1000°C. The basic alloy is generally composed of about 70 atomic percent silicon and 30 atomic percent germanium, but

may be varied somewhat. This is the basic composition for both p and n type SiGe alloys and was chosen because it is the alloy of lowest thermal conductivity. The alloy possesses about 10^{14} charge carriers per cubic centimeter at room temperature, and therefore dopants must be added to obtain peak figures of merit. Groups III-A and V-A elements, which closely resemble silicon and germanium, Group IV-A elements, in both size and electronic structure, are used as dopants. The elements of Group III-A possess one fewer valence electron than silicon and germanium, whereas the elements of Group V-A possess one more valence electron. The difference in the number of valence electrons of the dopant elements cause their electrical activity in SiGe alloys. Doping with Group III-A elements (electron-acceptors) yield p-type alloys, whereas Group V-A dopants (electron donors) yield n-type alloys. Because of favorable solid solubilities in the range of service temperature, boron is the commonly used p-type dopant and phosphorus is the commonly used n-type dopant. The dopant concentrations are again quite low but are somewhat higher than the concentrations of PbTe dopants.

Of importance equal to the thermoelectric materials themselves is the technology of contacting. The requirement for material compatibility is obvious. Generally, the best electrical and thermal conductors are not useable because of incompatibility for various reasons. Iron is suitable for contacting all but one of the lead telluride formulations. The lead tellurides are always bonded to the cold end contact and may or may not be bonded to the hot end contact. Generally, the thermoelectric elements and contacts are statically loaded longitudinally to the elements to provide or maintain good electrical and thermal contact. Refractory metals, for example tungsten, are commonly used as contacting materials for Si-Ge. Si-Ge thermoelectrics are generally bonded. The materials and processes for bonding are classified, therefore will not be discussed.

CHAPTER III

Thermoelectric Design Theory

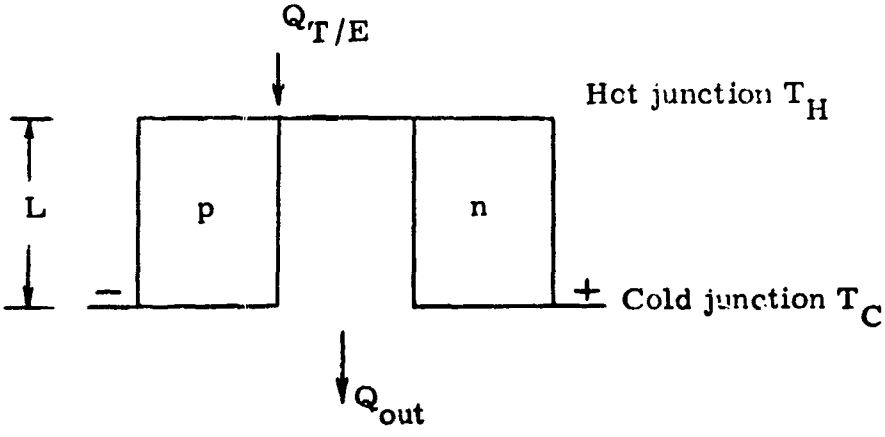
The design of thermoelectric conversion devices entails the combination of suitable materials to create efficient thermal and electrical transport characteristics. Although the treatment in Chapter I only indicated the existence of voltage polarity and the use of n and p materials, it will be shown below that the proper geometric pairing of n and p "legs" is essential to efficient conversion.

The basic design process is iterative solution of Eqs. I-2 through I-5 with length, area, current, output voltage and boundary conditions (temperature and/or heat flux) as parameters. In addition, thermal and electrical contact resistance at material interfaces are considered. The figures presented in Chapter V typify iteration results of such analyses. In practice, sophisticated computer programs, such as that described in Ref. 5, are used to select design points consistent with the establishment of ground rules such as element length (a structural/electrical constraint), output voltage (a power conditioning constraint), and boundary condition (heat source and heat sink constraints). However in order to provide a quantitative "feel" of the important design quantities, an approximate manual procedure is given below. It is important to note however, that the use of this simplified approach to the "sizing" of thermoelectric elements and calculation of efficiency is not recommended since this manual enables more precise evaluation by means of the parametric results of Chapter V.

Constant temperature boundary conditions are used at the hot and cold junctions because the analytical results are simple. This is a set of valid boundary conditions for an RTG which has a thermal control

mechanism which maintains constant junction temperatures. However, most RTG's are closer to a constant heat flux device rather than a constant temperature device. For a typical RTG, the hot junction temperature increases as the external load resistance is increased. The increasing hot junction temperature causes a shift in the optimum load resistance to higher load resistance than the constant temperature device as will be discussed later.

The accompanying sketch shows n and p element legs forming the basic thermoelectric couple. For the purpose of simplified treatment, no contact resistances will be used and thermoelectric properties will be assumed constant, independent of temperature. Also, the areas of each element will be constant throughout the elements which are of equal length.



Since the Seebeck coefficient is independent of temperature (by assumption), Thomson heating is absent and Eq. I-5 becomes for each element,

$$K A \frac{d^2T}{dX^2} + \frac{I^2\rho}{A} = 0 \qquad \text{(Eq. III-1)}$$

The solution of this simple linear differential equation is:

$$T(X) = T_H - \frac{(T_H - T_C)}{L} X + \frac{I^2 \rho}{2KA^2} X(L-X) \qquad \text{(Eq. III-2)}$$

for the boundary conditions:

$$T = T_H \text{ at } X = 0$$

$$T = T_C \text{ at } X = L$$

Thus the heat flux into each element given by Eq. I-4 is:

$$Q_{T/E} = \frac{KA(T_H - T_C)}{L} - \frac{I^2 \rho L}{2A} + I\alpha T_H \qquad \text{(Eq. III-3)}$$

By defining an overall conductance and resistance of the couple as:

$$K = \left(\frac{AK_N}{L}\right)_n + \left(\frac{AK_P}{L}\right)_p \qquad \text{(Eq. III-4)}$$

$$R = \left(\frac{\rho L}{A}\right)_n + \left(\frac{\rho L}{A}\right)_p \qquad \text{(Eq. III-5)}$$

and $\alpha_T = \left|\alpha_n\right| + \left|\alpha_p\right|$

the heat input becomes:

$$Q_{T/E} = I\alpha_T T_H + K(T_H - T_C) - \frac{I^2 R}{2} \qquad \text{(Eq. III-6)}$$

From Eq. I-2 the output power is:

$$P = I^2 R_L = I\alpha_T (T_H - T_C) - I^2 R \qquad \text{(Eq. III-7)}$$

where R_L is the load resistance.

Hence the efficiency is:

$$\eta = \frac{P}{Q_{T/E}} = \frac{\alpha_T \Delta T - IR}{\alpha_T T_H + \frac{K\Delta T}{I} - \frac{IR}{2}} \qquad \text{(Eq. III-8)}$$

Now the current is defined in Eq. III-7 as:

$$I = \frac{\alpha_T \Delta T}{R + R_L} \qquad \text{(Eq. III-9)}$$

and by insertion into Eq. III-8 with $m = R_L/R$:

$$\eta = \frac{\Delta T}{T_H} \; \frac{m}{1 + m - \frac{\Delta T}{2T_H} + \frac{(1+m)^2 RK}{\alpha_T^2 T_H}} \qquad \text{(Eq. III-10)}$$

Note that this is (Eq. I-6) with $Z = \alpha^2/RK$.

Since maximum thermoelectric efficiency is normally a design goal, the parameters which yield maximum efficiency are of interest. This is most easily done by the following steps. First, maximize with respect to m with all other variables constant. This will indicate the load resistance (or m) which yields maximum thermoelectric efficiency. The partial differential of thermoelectric efficiency with respect to m is given below:

(Eq. III-11)

$$\frac{\partial \eta}{\partial m} = \frac{\Delta T}{T_H} \left\{ \frac{1 + m - \frac{\Delta T}{2T_H} + \frac{(1+m)^2 RK}{\alpha_T^2 T_H} - m\left[1 + \frac{2(1+m)RK}{\alpha_T^2 T_H}\right]}{\text{Denominator}} \right\}$$

Setting the numerator equal to zero for a maximum η and solving for optimum m yields:

$$m_{opt} = \left[1 + \frac{\alpha_T^2 T_H}{RK} - \frac{\alpha_T^2 \Delta T}{2\,RK}\right]^{1/2} \qquad \text{(Eq. III-12)}$$

This expression is then substituted into Eq. III-10 to obtain thermoelectric efficiency. For practical materials, the optimum m for maximum efficiency is approximately 1.2 for the assumed constant hot and cold junction temperatures. This compares to the peak power output at m = 1 (matched load and internal resistance).

As discussed earlier, most RTG's are nearer constant heat flux devices which result in higher m's for peak efficiency and hence peak power. Typical values of optimum m for constant heat flux devices are 1.5 → 1.6. In a practical RTG the parasitic heat losses increase (hence heat flux to the thermoelectric materials decreases) as the load resistance is increased. Therefore typical constant thermal inventory RTG's predictably have lower value of optimum m (1.4 → 1.5) than theoretical constant heat flux devices.

Further maximizing of the thermoelectric efficiency (Eq. III-10) for constant hot and cold junction temperature can be accomplished by minimizing the denominator of that expression. For constant temperatures, the only variable in the denominator is the RK product and hence this term must be minimized. R and K are defined in (Eq. III-4) and (Eq. III-5) as functions of material properties and the shape factor (L/A) of each element. If the shape factor ratio is defined as:

$$S = \frac{(L/A)_n}{(L/A)_p} \qquad \text{(Eq. III-13)}$$

The RK product becomes:

$$RK = K_n\rho_n + \frac{K_n\rho_p}{S} + K_p\rho_n S + K_p\rho_p \qquad \text{(Eq. III-14)}$$

Minimizing RK with respect to S, one obtains:

$$S_{opt} = \sqrt{\frac{K_n \rho_p}{K_p \rho_n}} = \left. \frac{(L/A)_n}{(L/A)_p} \right|_{opt} \qquad \text{(Eq. III-15)}$$

Now when the length of both elements was assumed the same, the area ratio of n and p elements for maximum couple efficiency is:

$$\left. \frac{A_p}{A_n} \right|_{opt} = \sqrt{\frac{K_n \rho_p}{K_p \rho_p}} \qquad \text{(Eq. III-16)}$$

To complete the design, the number of couples and the diameter of the couples are obtained from output voltage and power requirements. The voltage output per couple is obtained by multiplying the load resistance times the current expressed in Eq. III-9. Substituting m into that equation yields the following expression for the voltage per couple:

$$V_{couple} = IR_L = \frac{m \alpha_T \Delta T}{1 + m} \qquad \text{(Eq. III-17)}$$

The number of couples in a straight series electrical circuit can be determined by dividing the specified RTG voltage by Eq. III-17. The total number of couples in the RTG is then obtained by multiplying the number of parallel circuits times the number of series couples. The RTG power output is obtained by multiplying the power produced per couple times the number of couples in the RTG as shown in Eq. III-17.

$$P_{RTG} = N I V_{couple} = \frac{N I m \alpha_T \Delta T}{1 + m} \qquad \text{(Eq. III-18)}$$

where: P_{RTG} = specified RTG power watts(e)

N = number of couples in RTG.

The simultaneous solution of Eqs. III-18, III-9, III-12 and III-14 yields the internal resistance which will satisfy the power and voltage requirements. By substituting the optimum shape factor from Eq. III-15 and the internal resistance into Eq. III-5, the shape factors for each element are obtained. Selection of an element length leads directly to element cross sections which completes the thermoelectric design.

Similar approximations with averaged properties have been devised for elements of varying area or segmented by layering of materials with different properties. However, as stated above, modern computational techniques obviate the necessity for such approximations and inexpensive, accurate results may be readily obtained through the use of large digital computers.

CHAPTER IV

Thermoelectric Material Property Data

As established earlier in this manual the material properties which are significant to thermoelectric design are the Seebeck coefficient (α), the electrical resistivity (ρ), and the thermal conductivity (κ). Also of interest for an indication of performance is the figure of merit (z) of the material. The significance and definition of this performance parameter was discussed in Chapter I. Table IV-1 lists the most common thermoelectric materials which are of importance to RTG designers. Also included in Table IV-1 is the Isotopes identification code and the manufacturer of each material. As shown in Table IV-1, several sets of property data exist for a number of the materials. Multiple sets of property data are presented where available because an RTG designer may encounter thermoelectric studies utilizing any one or all of the sets of property data. In reviewing the literature or previous programs, each set of data may prove useful. Tables IV-3 through IV-16 present English units of Seebeck coefficient, electrical resistivity, thermal conductivity, and figure of merit as a function of temperature for the materials listed in Table IV-1. Tables IV-17 through IV-31 present the same data in metric units.

Figure IV-1 and IV-2 present the figure of merit of each set of material property data as a function of temperature.

TABLE IV-1

List of Important Thermoelectric Materials

Element	Isotopes' Identification	Manufacturer	Type Element	Table Number for Property Data	Remarks
2N PbTe	TEDN-00-30	3M	N	IV-2 & IV-17	Data supplied by 3M in 1964. This data correlated the Phase II SNAP 19 generator performance.
	TEDN-00-34	3M	N	IV-3 & IV-18	Isotopes based data supplied by 3M in 1965 for α and ρ. k is the same as TEDN-00-30 data.
	TEDN-00-35	3M	N	IV-4 & IV-19	Isotopes based data supplied by 3M in 1965 for α. ρ and k are the same as TEDN-00-30 data. This data correlated the SNAP 29 and the 2N TAGS/SnTe SNAP 19 generators.
3N PbTe	TEDN-00-51	3M	N	IV-5 & IV-20	Data supplied by 3M in 1965.
	TEDN-00-52	3M	N	IV-6 & IV-21	Data obtained from Sandia personnel and forwarded to Isotopes personnel in 1968.
2P PbTe	TEDP-00-40	3M	P	IV-7 & IV-22	Data supplied by 3M in 1964. This data correlated the Phase II SNAP 19 generator performance.
	TEDP-00-44	3M	P	IV-8 & IV-23	Isotopes based data supplied by 3M in 1965 for α and ρ. k is the same as TEDP-00-40 data.
3P PbSnTe	TEDP-00-59	3M	P	IV-9 & IV-24	α data supplied by 3M in 1966; ρ and k data supplied by 3M in 1964.

TABLE IV-1 (Continued)

Element	Isotopes' Identification	Manufacturer	Type Element	Table Number for Property Data	Remarks
3P PbSnTe (Cont.)	TEDP-00-60	3M	P	IV-10 & IV-25	α and ρ data is equal to the TEDP-00-59 data. k data was measured on SNAP 11 elements (1966) and correlated SNAP 19 S/N 20.
	TEDP-00-63	3M	P	IV-11 & IV-26	Data obtained from Sandia personnel and forwarded to Isotopes personnel in 1968.
TAGS-85	TEDP-00-10A	Isotopes	P	IV-12 & IV-27	Average Isotopes research data. This data correlated the 2N-TAGS/SnTe SNAP 19 generator.
SnTe	TEDP-00-27	Isotopes	P	IV-13 & IV-28	Isotopes measured in 1966. This data used in correlating the 2N-TAGS/SnTe SNAP 19 generator.
$SiGe_n$	TEDN-00-23	RCA	N	IV-14 & IV-29	Data supplied by RCA in 1965.
	TEDN-00-23B	RCA	N	IV-15 & IV-30	Same as TEDN-00-23 data, but α and ρ are increased to correspond to expected change after 5 years.
$SiGe_p$	TEDP-00-24	RCA	P	IV-16 & IV-31	Data supplied by RCA in 1965.

Table IV-2

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-30

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2N.
COLD PRESSED AND SINTERED.
PROPERTY DATA MEASURED BY 3M, SEPTEMBER 1964.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-FT	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
50.	-.80116E-04	0.18160E-03	0.16439E 01	0.87982E-03
100.	-.85750E-04	0.22500E-03	0.15100E 01	0.88561E-03
150.	-.91878E-04	0.27113E-03	0.13854E 01	0.91962E-03
200.	-.98500E-04	0.32000E-03	0.12700E 01	0.97691E-03
250.	-.10469E-03	0.38063E-03	0.11669E 01	0.10097E-02
300.	-.11075E-03	0.45000E-03	0.10750E 01	0.10375E-02
350.	-.11669E-03	0.53562E-03	0.99250E 00	0.10481E-02
400.	-.12250E-03	0.63500E-03	0.92000E 00	0.10511E-02
450.	-.12809E-03	0.74625E-03	0.85937E 00	0.10469E-02
500.	-.13350E-03	0.87000E-03	0.81000E 00	0.10349E-02
550.	-.13816E-03	0.10044E-02	0.76813E 00	0.10124E-02
600.	-.14225E-03	0.11500E-02	0.73500E 00	0.97961E-03
650.	-.14527E-03	0.13031E-02	0.71062E 00	0.93259E-03
700.	-.14740E-03	0.14650E-02	0.69501E 00	0.87319E-03
750.	-.14830E-03	0.16200E-02	0.69001E 00	0.80511E-03
800.	-.14790E-03	0.17700E-02	0.70000E 00	0.72244E-03
850.	-.14605E-03	0.19067E-02	0.73000E 00	0.62711E-03
900.	-.14275E-03	0.20300E-02	0.77999E 00	0.52662E-03
950.	-.13850E-03	0.21200E-02	0.83501E 00	0.44342E-03
1000.	-.13325E-03	0.21700E-02	0.90000E 00	0.37202E-03

NOTE: The data is presented in abbreviated exponential form,

i.e., 1.0E- 03 = 1.0×10^{-3}

Table IV-3

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-34

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2N. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT AND RESISTIVITY MEASURED BY 3M, OCTOBER 1965. THERMAL CONDUCTIVITY MEASURED BY 3M, SEPTEMBER 1964.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
50.	-.80809E-04	0.19828E-03	0.16439E 01	0.81982E-03
100.	-.85500E-04	0.24000E-03	0.15100E 01	0.82543E-03
150.	-.90430E-04	0.29391E-03	0.13854E 01	0.82184E-03
200.	-.95600E-04	0.36000E-03	0.12700E 01	0.81799E-03
250.	-.10123E-03	0.43500E-03	0.11669E 01	0.82614E-03
300.	-.10725E-03	0.52000E-03	0.10750E 01	0.84201E-03
350.	-.11319E-03	0.62062E-03	0.99250E 00	0.85109E-03
400.	-.11920E-03	0.73500E-03	0.92000E 00	0.85983E-03
450.	-.12519E-03	0.86875E-03	0.85937E 00	0.85906E-03
500.	-.13120E-03	0.10200E-02	0.81000E 00	0.85255E-03
550.	-.13645E-03	0.11888E-02	0.76813E 00	0.83437E-03
600.	-.14120E-03	0.13750E-02	0.73501E 00	0.80726E-03
650.	-.14450E-03	0.15500E-02	0.71500E 00	0.77096E-03
700.	-.14700E-03	0.17250E-02	0.69501E 00	0.73756E-03
750.	-.14800E-03	0.18900E-02	0.69001E 00	0.68730E-03
800.	-.14800E-03	0.20400E-02	0.70000E 00	0.62767E-03
850.	-.14625E-03	0.21700E-02	0.73500E 00	0.54876E-03
900.	-.14390E-03	0.22599E-02	0.77998E 00	0.48068E-03
950.	-.13975E-03	0.23250E-02	0.83501E 00	0.41165E-03
1000.	-.13425E-03	0.23600E-02	0.90000E 00	0.34722E-03

Table IV-4

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-35

N TYPE MATERIAL MANUFACTURED BY 3M. 2N PROPERTY DATA RECOMMENDED BY ISOTOPES, AUGUST 1969. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT MEASURED BY 3M, OCTOBER 1965. RESISTIVITY AND THERMAL CONDUCTIVITY MEASURED BY 3M, SEPT. 1964.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
50.	-.80809E-04	0.18160E-03	0.16439E 01	0.89513E-03
100.	-.85500E-04	0.22500E-03	0.15100E 01	0.88046E-03
150.	-.90430E-04	0.27113E-03	0.13854E 01	0.89086E-03
200.	-.95600E-04	0.32000E-03	0.12700E 01	0.92023E-03
250.	-.10123E-03	0.38063E-03	0.11669E 01	0.94416E-03
300.	-.10725E-03	0.45000E-03	0.10750E 01	0.97299E-03
350.	-.11319E-03	0.53562E-03	0.99250E 00	0.98615E-03
400.	-.11920E-03	0.63500E-03	0.92000E 00	0.99524E-03
450.	-.12519E-03	0.74625E-03	0.85937E 00	0.10001E-02
500.	-.13120E-03	0.87000E-03	0.81000E 00	0.99954E-03
550.	-.13645E-03	0.10044E-02	0.76813E 00	0.98754E-03
600.	-.14120E-03	0.11500E-02	0.73500E 00	0.96520E-03
650.	-.14462E-03	0.13031E-02	0.71062E 00	0.92426E-03
700.	-.14700E-03	0.14650E-02	0.69501E 00	0.86845E-03
750.	-.14800E-03	0.16200E-02	0.69001E 00	0.80185E-03
800.	-.14800E-03	0.17700E-02	0.70000E 00	0.72341E-03
850.	-.14663E-03	0.19068E-02	0.73000E 00	0.63212E-03
900.	-.14390E-03	0.20300E-02	0.77999E 00	0.53514E-03
950.	-.13975E-03	0.21200E-02	0.83501E 00	0.45146E-03
1000.	-.13425E-03	0.21700E-02	0.90000E 00	0.37763E-03

Table IV-5

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTF

ISOTOPES IDENTIFICATION TEDN-00-51

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3N.
PROPERTY DATA MEASURED 24 SEPTEMBER 1965.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
100.	-.57500E-04	0.13000E-03	0.18550E 01	0.56103E-03
150.	-.62250E-04	0.15750E-03	0.17185E 01	0.58585E-03
200.	-.67000E-04	0.19000E-03	0.15950E 01	0.60614E-03
250.	-.71750E-04	0.22750E-03	0.14845E 01	0.62376E-03
300.	-.76500E-04	0.27000E-03	0.13870E 01	0.63947E-03
350.	-.81531E-04	0.31750E-03	0.12980E 01	0.66003E-03
400.	-.86750E-04	0.37000E-03	0.12190E 01	0.68276E-03
450.	-.92062E-04	0.43125E-03	0.11504E 01	0.69909E-03
500.	-.97500E-04	0.50000E-03	0.10920E 01	0.71245E-03
550.	-.10334E-03	0.57813E-03	0.10394E 01	0.72729E-03
600.	-.10950E-03	0.66501E-03	0.99401E 00	0.74226E-03
650.	-.11450E-03	0.76000E-03	0.95200E 00	0.74147E-03
700.	-.11800E-03	0.86001E-03	0.91301E 00	0.72565E-03
750.	-.12100E-03	0.97501E-03	0.88801E 00	0.69197E-03
800.	-.12350E-03	0.10850E-02	0.86700E 00	0.66347E-03
850.	-.12480E-03	0.12100E-02	0.85100E 00	0.61894E-03
900.	-.12500E-03	0.13400E-02	0.84898E 00	0.56201E-03
950.	-.12420E-03	0.14750E-02	0.85801E 00	0.49877E-03
1000.	-.12249E-03	0.15749E-02	0.87194E 00	0.44711E-03
1050.	-.11976E-03	0.16633E-02	0.89598E 00	0.39384E-03
1100.	-.11600E-03	0.17400E-02	0.93000E 00	0.34027E-03
1150.	-.11069E-03	0.18037E-02	0.96537E 00	0.28791E-03
1200.	-.10400E-03	0.18550E-02	0.10050E 01	0.23741E-03

Table IV-6

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-52

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3N.
PROPERTY DATA SUPPLIED BY SANDIA, 29 JULY 1968,
AS MEASURED BY 3M FOR THE SNAP-23 PROGRAM.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
100.	-.54370E-04	0.13370E-03	0.16000E 01	0.56546E-03
150.	-.60466E-04	0.15758E-03	0.14720E 01	0.64498E-03
200.	-.65970E-04	0.18610E-03	0.13600E 01	0.70363E-03
250.	-.71256E-04	0.21931E-03	0.12681E 01	0.74706E-03
300.	-.76200E-04	0.25720E-03	0.11950E 01	0.77305E-03
350.	-.81150E-04	0.29972E-03	0.11331E 01	0.79344E-03
400.	-.85990E-04	0.34690E-03	0.10850E 01	0.80389E-03
450.	-.90877E-04	0.39959E-03	0.10431E 01	0.81078E-03
500.	-.95760E-04	0.45750E-03	0.10100E 01	0.81207E-03
550.	-.10063E-03	0.52300E-03	0.98187E 00	0.80686E-03
600.	-.10548E-03	0.59530E-03	0.96000E 00	0.79665E-03
650.	-.11016E-03	0.67781E-03	0.94437E 00	0.77576E-03
700.	-.11472E-03	0.76940E-03	0.93500E 00	0.74860E-03
750.	-.11887E-03	0.87278E-03	0.93188E 00	0.71093E-03
800.	-.12270E-03	0.98690E-03	0.93500E 00	0.66764E-03
850.	-.12580E-03	0.11111E-02	0.94700E 00	0.61550E-03
900.	-.12832E-03	0.12454E-02	0.96699E 00	0.55940E-03
950.	-.12973E-03	0.13837E-02	0.99987E 00	0.49777E-03
1000.	-.13021E-03	0.15277E-02	0.10440E 01	0.43500E-03
1050.	-.12917E-03	0.16666E-02	0.11054E 01	0.37082E-03
1100.	-.12680E-03	0.18014E-02	0.11820E 01	0.30899E-03
1150.	-.12245E-03	0.19210E-02	0.12829E 01	0.24895E-03
1200.	-.11633E-03	0.20292E-02	0.14050E 01	0.19423E-03

Table IV-7

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDP-00-40

P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2P.
NA DOPED - COLD PRESSED AND SINTERED.
PROPERTY DATA MEASURED BY 3M, SEPTEMBER 1964.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
50.	0.27000E-04	0.16000E-03	0.23100E 01	0.80711E-04
100.	0.37000E-04	0.19000E-03	0.21000E 01	0.14040E-03
150.	0.47500E-04	0.22833E-03	0.18967E 01	0.21319E-03
200.	0.58500E-04	0.27500E-03	0.17000E 01	0.29955E-03
250.	0.69250E-04	0.32875E-03	0.15150E 01	0.39400E-03
300.	0.80000E-04	0.39000E-03	0.13400E 01	0.50113E-03
350.	0.90000E-04	0.47187E-03	0.11750E 01	0.59780E-03
400.	0.99500E-04	0.57000E-03	0.10200E 01	0.69680E-03
450.	0.10887E-03	0.67875E-03	0.90125E 00	0.79294E-03
500.	0.11800E-03	0.80000E-03	0.81000E 00	0.87928E-03
550.	0.12669E-03	0.93750E-03	0.74063E 00	0.94587E-03
600.	0.13500E-03	0.10900E-02	0.69501E 00	0.98445E-03
650.	0.14200E-03	0.12400E-02	0.66200E 00	0.10052E-02
700.	0.14850E-03	0.13900E-02	0.64401E 00	0.10081E-02
750.	0.15462E-03	0.15584E-02	0.64013E 00	0.98073E-03
800.	0.15900E-03	0.17350E-02	0.65200E 00	0.91450E-03
850.	0.16180E-03	0.18800E-02	0.68300E 00	0.83428E-03
900.	0.16300E-03	0.19899E-02	0.72498E 00	0.75356E-03
950.	0.16290E-03	0.20700E-02	0.77501E 00	0.67687E-03
1000.	0.16100E-03	0.21250E-02	0.83500E 00	0.59778E-03

Table IV-8

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDP-00-44

P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2P. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT AND RESISTIVITY MEASURED BY 3M, OCTOBER 1965. THERMAL CONDUCTIVITY MEASURED BY 3M, SEPTEMBER 1964.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
50.	0.27000E-04	0.17500E-03	0.23100E 01	0.73793E-04
100.	0.37000E-04	0.20000E-03	0.21000E 01	0.13338E-03
150.	0.47667E-04	0.23667E-03	0.18967E 01	0.20713E-03
200.	0.59000E-04	0.28500E-03	0.17000E 01	0.29400E-03
250.	0.70188E-04	0.34812E-03	0.15150E 01	0.38222E-03
300.	0.81500E-04	0.42500E-03	0.13400E 01	0.47726E-03
350.	0.93125E-04	0.52687E-03	0.11750E 01	0.57322E-03
400.	0.10500E-03	0.65000E-03	0.10200E 01	0.68046E-03
450.	0.11750E-03	0.78875E-03	0.90125E 00	0.79474E-03
500.	0.13050E-03	0.94500E-03	0.81000E 00	0.91042E-03
550.	0.14119E-03	0.11300E-02	0.74063E 00	0.97465E-03
600.	0.15050E-03	0.13400E-02	0.69501E 00	0.99522E-03
650.	0.15750E-03	0.15600E-02	0.66200E 00	0.98291E-03
700.	0.16350E-03	0.17700E-02	0.64401E 00	0.95965E-03
750.	0.16645E-03	0.20017E-02	0.64013E 00	0.88481E-03
800.	0.16750E-03	0.22300E-02	0.65200E 00	0.78961E-03
850.	0.16700E-03	0.24600E-02	0.68300E 00	0.67922E-03
900.	0.16560E-03	0.26499E-02	0.72498E 00	0.58408E-03
950.	0.16300E-03	0.28000E-02	0.77501E 00	0.50101E-03
1000.	0.15900E-03	0.29200E-02	0.83500E 00	0.42429E-03

Table IV-9

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-59

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P.
SEEBECK COEFFICIENT MEASURED BY 3M, JANUARY 1955.
RESISTIVITY AND THERMAL CONDUCTIVITY MEASURED BY 3M, DECEMBER 1953.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
150.	0.43300E-04	0.46800E-03	0.12500E 01	0.13115E-03
200.	0.51800E-04	0.51800E-03	0.11520E 01	0.18400E-03
250.	0.57767E-04	0.56800E-03	0.10670E 01	0.22531E-03
300.	0.61200E-04	0.61800E-03	0.99499E 00	0.24925E-03
350.	0.66350E-04	0.67062E-03	0.92475E 00	0.29048E-03
400.	0.71800E-04	0.72500E-03	0.86000E 00	0.33834E-03
450.	0.77550E-04	0.78337E-03	0.80112E 00	0.39213E-03
500.	0.83600E-04	0.84500E-03	0.74800E 00	0.45247E-03
550.	0.90025E-04	0.91063E-03	0.70175E 00	0.51897E-03
600.	0.96301E-04	0.98001E-03	0.66201E 00	0.59102E-03
650.	0.10260E-03	0.10600E-02	0.63000E 00	0.64504E-03
700.	0.10800E-03	0.11450E-02	0.61001E 00	0.68336E-03
750.	0.11280E-03	0.12300E-02	0.59801E 00	0.70736E-03
800.	0.11760E-03	0.13100E-02	0.59300E 00	0.72849E-03
850.	0.12120E-03	0.13900E-02	0.60300E 00	0.71715E-03
900.	0.12400E-03	0.14700E-02	0.62999E 00	0.67939E-03
950.	0.12580E-03	0.15460E-02	0.66893E 00	0.62612E-03
1000.	0.12660E-03	0.16180E-02	0.72000E 00	0.56298E-03
1050.	0.12614E-03	0.16659E-02	0.78813E 00	0.49594E-03
1100.	0.12500E-03	0.16900E-02	0.87500E 00	0.43238E-03

Table IV-10

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-60

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P. SEEBECK COEFFICIENT MEASURED BY 3M, JANUARY 1966, RESISTIVITY MEASURED BY 3M, DEC. 1963. THERMAL CONDUCTIVITY MEASURED ON SNAP 11 ELEMENTS BY MARTIN JULY 1966

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
150.	0.43300E-04	0.46800E-03	0.10450E 01	0.15687E-03
200.	0.51800E-04	0.51800E-03	0.10120E 01	0.20945E-03
250.	0.57767E-04	0.56800E-03	0.97966E 00	0.24539E-03
300.	0.61200E-04	0.61800E-03	0.94799E 00	0.26160E-03
350.	0.66350E-04	0.67062E-03	0.91825E 00	0.29253E-03
400.	0.71800E-04	0.72500E-03	0.89000E 00	0.32693E-03
450.	0.77550E-04	0.78337E-03	0.86325E 00	0.36391E-03
500.	0.83600E-04	0.84500E-03	0.83800E 00	0.40388E-03
550.	0.90025E-04	0.91063E-03	0.81425E 00	0.44726E-03
600.	0.96801E-04	0.98001E-03	0.79201E 00	0.49401E-03
650.	0.10260E-03	0.10600E-02	0.77800E 00	0.52233E-03
700.	0.10800E-03	0.11450E-02	0.77001E 00	0.54136E-03
750.	0.11280E-03	0.12300E-02	0.77101E 00	0.54903E-03
800.	0.11760E-03	0.13100E-02	0.78000E 00	0.55384E-03
850.	0.12120E-03	0.13900E-02	0.79500E 00	0.54395E-03
900.	0.12400E-03	0.14700E-02	0.81799E 00	0.52325E-03
950.	0.12580E-03	0.15460E-02	0.84799E 00	0.49396E-03
1000.	0.12660E-03	0.16180E-02	0.88500E 00	0.45802E-03
1050.	0.12614E-03	0.16650E-02	0.92531E 00	0.42241E-03
1100.	0.12500E-03	0.16900E-02	0.97500E 00	0.38803E-03

Table IV-11

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-63

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P.
PROPERTY DATA SUPPLIED BY SANDIA, JULY 1968,
AS MEASURED BY 3M, DECEMBER 1967.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
100.	0.26100E-04	0.37120E-03	0.91400E 00	0.82160E-04
150.	0.34849E-04	0.42218E-03	0.88200E 00	0.13346E-03
200.	0.42410E-04	0.46780E-03	0.85800E 00	0.18337E-03
250.	0.49834E-04	0.51336E-03	0.84163E 00	0.23520E-03
300.	0.56770E-04	0.55710E-03	0.83300E 00	0.28418E-03
350.	0.64010E-04	0.60662E-03	0.82612E 00	0.33455E-03
400.	0.71290E-04	0.65940E-03	0.82300E 00	0.38322E-03
450.	0.78801E-04	0.72161E-03	0.81950E 00	0.42968E-03
500.	0.86480E-04	0.79120E-03	0.81700E 00	0.47343E-03
550.	0.94075E-04	0.87199E-03	0.81588E 00	0.50904E-03
600.	0.10167E-03	0.96270E-03	0.81600E 00	0.53844E-03
650.	0.10876E-03	0.10642E-02	0.81812E 00	0.55591E-03
700.	0.11551E-03	0.11763E-02	0.82200E 00	0.56466E-03
750.	0.12132E-03	0.12959E-02	0.82950E 00	0.56028E-03
800.	0.12639E-03	0.14241E-02	0.84000E 00	0.54644E-03
850.	0.13021E-03	0.15530E-02	0.86025E 00	0.51929E-03
900.	0.13294E-03	0.16852E-02	0.88799E 00	0.48326E-03
950.	0.13432E-03	0.18089E-02	0.92662E 00	0.44043E-03
1000.	0.13443E-03	0.19281E-02	0.97499E 00	0.39337E-03
1050.	0.13344E-03	0.20313E-02	0.10403E 01	0.34484E-03
1100.	0.13130E-03	0.21223E-02	0.11200E 01	0.29678E-03
1150.	0.12875E-03	0.21967E-02	0.12206E 01	0.25299E-03
1200.	0.12555E-03	0.22559E-02	0.13400E 01	0.21338E-03

Table IV-12

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL TAGS

ISOTOPES IDENTIFICATION TEDP-00-10A

TAGS P TYPE MATERIAL MANUFACTURED BY ISOTOPES.
PROPERTY DATA MEASURED BY MARTIN, 1966.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
200.	0.62200E-04	0.31200E-03	0.87799E 00	0.57792E-03
250.	0.68637E-04	0.32600E-03	0.88199E 00	0.67046E-03
300.	0.74500E-04	0.34000E-03	0.88599E 00	0.75394E-03
350.	0.79787E-04	0.35400E-03	0.89000E 00	0.82682E-03
400.	0.84500E-04	0.36800E-03	0.89400E 00	0.88810E-03
450.	0.89012E-04	0.38275E-03	0.89800E 00	0.94329E-03
500.	0.93200E-04	0.39800E-03	0.90200E 00	0.99010E-03
550.	0.97025E-04	0.41469E-03	0.90600E 00	0.10253E-02
600.	0.10050E-03	0.43250E-03	0.91000E 00	0.10501E-02
650.	0.10351E-03	0.44600E-03	0.91587E 00	0.10734E-02
700.	0.10610E-03	0.45700E-03	0.92301E 00	0.10921E-02
750.	0.10830E-03	0.46701E-03	0.93301E 00	0.11015E-02
800.	0.10990E-03	0.47500E-03	0.94800E 00	0.10976E-02
850.	0.11020E-03	0.48200E-03	0.97000E 00	0.10629E-02
900.	0.10980E-03	0.48649E-03	0.10060E 01	0.10080E-02
950.	0.10900E-03	0.49050E-03	0.10430E 01	0.95031E-03

Table IV-13

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SNTE

ISOTOPES IDENTIFICATION TEDP-00-27

P TYPE MATERIAL, CAST SNTE MANUFACTURED BY ISOTOPES.
PROPERTY DATA MEASURED BY MARTIN, DECEMBER 1966.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
200.	0.13900E-04	0.98399E-04	0.43640E 01	0.18411E-04
250.	0.15162E-04	0.10825E-03	0.42648E 01	0.20377E-04
300.	0.16700E-04	0.11810E-03	0.41500E 01	0.23285E-04
350.	0.18512E-04	0.12795E-03	0.40194E 01	0.27269E-04
400.	0.20600E-04	0.13780E-03	0.38730E 01	0.32537E-04
450.	0.22850E-04	0.14911E-03	0.37255E 01	0.38460E-04
500.	0.25300E-04	0.16140E-03	0.35720E 01	0.45432E-04
550.	0.28288E-04	0.17470E-03	0.33915E 01	0.55264E-04
600.	0.31700E-04	0.18900E-03	0.31910E 01	0.68181E-04
650.	0.35200E-04	0.20722E-03	0.29784E 01	0.82148E-04
700.	0.38900E-04	0.22840E-03	0.27510E 01	0.98548E-04
750.	0.42913E-04	0.25103E-03	0.25250E 01	0.11888E-03
800.	0.47200E-04	0.27560E-03	0.22950E 01	0.14413E-03
850.	0.51912E-04	0.29920E-03	0.20970E 01	0.17576E-03
900.	0.57000E-04	0.32280E-03	0.19190E 01	0.21462E-03
950.	0.61637E-04	0.34865E-03	0.17831E 01	0.25007E-03
1000.	0.66099E-04	0.37600E-03	0.16820E 01	0.28270E-03
1050.	0.70989E-04	0.40407E-03	0.15984E 01	0.31928E-03
1100.	0.76100E-04	0.43310E-03	0.15380E 01	0.35576E-03
1150.	0.81175E-04	0.46345E-03	0.14682E 01	0.39626E-03
1200.	0.86300E-04	0.49500E-03	0.14000E 01	0.43977E-03

Table IV-14

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23

N TYPE MATERIAL MANUFACTURED BY RCA
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
0.	-.87500E-04	0.64000E-03	0.30300E 01	0.16156E-03
50.	-.94492E-04	0.65469E-03	0.29759E 01	0.18753E-03
100.	-.10141E-03	0.67875E-03	0.29212E 01	0.21222E-03
150.	-.10824E-03	0.71219E-03	0.28659E 01	0.23489E-03
200.	-.11500E-03	0.75500E-03	0.28100E 01	0.25508E-03
250.	-.12168E-03	0.80719E-03	0.27534E 01	0.27260E-03
300.	-.12828E-03	0.86875E-03	0.26962E 01	0.28748E-03
350.	-.13480E-03	0.93969E-03	0.26384E 01	0.29993E-03
400.	-.14125E-03	0.10200E-02	0.25800E 01	0.31024E-03
450.	-.14750E-03	0.11089E-02	0.25303E 01	0.31729E-03
500.	-.15362E-03	0.12069E-02	0.24837E 01	0.32217E-03
550.	-.15962E-03	0.13139E-02	0.24403E 01	0.32518E-03
600.	-.16550E-03	0.14300E-02	0.24000E 01	0.32658E-03
650.	-.17130E-03	0.15554E-02	0.23550E 01	0.32781E-03
700.	-.17700E-03	0.16900E-02	0.23100E 01	0.32839E-03
750.	-.18250E-03	0.18400E-02	0.22750E 01	0.32558E-03
800.	-.18800E-03	0.20300E-02	0.22400E 01	0.31806E-03
850.	-.19200E-03	0.21400E-02	0.22200E 01	0.31752E-03
900.	-.19400E-03	0.21650E-02	0.22000E 01	0.32334E-03
950.	-.19441E-03	0.21533E-02	0.21704E 01	0.33092E-03
1000.	-.19299E-03	0.21098E-02	0.21598E 01	0.33444E-03
1050.	-.19115E-03	0.20449E-02	0.21446E 01	0.34094E-03
1100.	-.18900E-03	0.19600E-02	0.21300E 01	0.35013E-03
1150.	-.18681E-03	0.18437E-02	0.21244E 01	0.36460E-03
1200.	-.18450E-03	0.17000E-02	0.21250E 01	0.38559E-03
1250.	-.18188E-03	0.15850E-02	0.21244E 01	0.40200E-03
1300.	-.17899E-03	0.14700E-02	0.21249E 01	0.41689E-03
1350.	-.17624E-03	0.13830E-02	0.21380E 01	0.42983E-03
1400.	-.17352E-03	0.12951E-02	0.21602E 01	0.44036E-03
1450.	-.17058E-03	0.12138E-02	0.21908E 01	0.44772E-03
1500.	-.16750E-03	0.11400E-02	0.22300E 01	0.45160E-03

Table IV-14 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23

N TYPE MATERIAL MANUFACTURED BY RCA
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
1550.	-.16431E-03	0.10719E-02	0.22838E 01	0.45132E-03
1600.	-.16100E-03	0.10100E-02	0.23500E 01	0.44689E-03
1650.	-.15762E-03	0.94875E-03	0.24175E 01	0.44327E-03
1700.	-.15417E-03	0.89000E-03	0.24900E 01	0.43886E-03
1750.	-.15062E-03	0.83375E-03	0.25675E 01	0.43369E-03
1800.	-.14700E-03	0.78000E-03	0.26500E 01	0.42779E-03

Table IV-15

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-238

N TYPE MATERIAL MANUFACTURED BY RCA. PROPERTY DATA SAME AS TEDN-00-23 DATA EXCEPT SEEBECK COEFFICIENT INCREASED 4.2 PERCENT AND RESISTIVITY INCREASED 17.6 PERCENT FOR FIVE YEAR LIFE EFFECT, JUNE 1966.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
0.	-.91175E-04	0.75264E-03	0.30300E 01	0.14916E-03
50.	-.98461E-04	0.76991E-03	0.29759E 01	0.17314E-03
100.	-.10567E-03	0.79821E-03	0.29212E 01	0.19594E-03
150.	-.11279E-03	0.83753E-03	0.28659E 01	0.21687E-03
200.	-.11983E-03	0.88788E-03	0.28100E 01	0.23551E-03
250.	-.12679E-03	0.94926E-03	0.27534E 01	0.25168E-03
300.	-.13367E-03	0.10217E-02	0.26962E 01	0.26542E-03
350.	-.14047E-03	0.11051E-02	0.26384E 01	0.27691E-03
400.	-.14718E-03	0.11995E-02	0.25800E 01	0.28643E-03
450.	-.15370E-03	0.13041E-02	0.25303E 01	0.29294E-03
500.	-.16008E-03	0.14193E-02	0.24837E 01	0.29745E-03
550.	-.16633E-03	0.15452E-02	0.24403E 01	0.30023E-03
600.	-.17245E-03	0.16817E-02	0.24000E 01	0.30152E-03
650.	-.17850E-03	0.18292E-02	0.23550E 01	0.30266E-03
700.	-.18444E-03	0.19875E-02	0.23100E 01	0.30319E-03
750.	-.19017E-03	0.21639E-02	0.22750E 01	0.30060E-03
800.	-.19590E-03	0.23873E-02	0.22400E 01	0.29365E-03
850.	-.20006E-03	0.25166E-02	0.22200E 01	0.29316E-03
900.	-.20214E-03	0.25460E-02	0.22000E 01	0.29853E-03
950.	-.20257E-03	0.25322E-02	0.21704E 01	0.30553E-03
1000.	-.20109E-03	0.24812E-02	0.21598E 01	0.30877E-03
1050.	-.19918E-03	0.24048E-02	0.21446E 01	0.31478E-03
1100.	-.19694E-03	0.23050E-02	0.21300E 01	0.32326E-03
1150.	-.19466E-03	0.21682E-02	0.21244E 01	0.33662E-03
1200.	-.19225E-03	0.19992E-02	0.21250E 01	0.35600E-03
1250.	-.18952E-03	0.18640E-02	0.21244E 01	0.37115E-03
1300.	-.18651E-03	0.17404E-02	0.21249E 01	0.38490E-03
1350.	-.18364E-03	0.16264E-02	0.21380E 01	0.39685E-03
1400.	-.18080E-03	0.15231E-02	0.21602E 01	0.40657E-03
1450.	-.17774E-03	0.14275E-02	0.21908E 01	0.41336E-03

Table IV-15 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23B

N TYPE MATERIAL MANUFACTURED BY RCA. PROPERTY DATA SAME AS TEDN-00-23 DATA EXCEPT SEEBECK COEFFICIENT INCREASED 4.2 PERCENT AND RESISTIVITY INCREASED 17.6 PERCENT FOR FIVE YEAR LIFE EFFECT, JUNE 1966.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
1500.	-.17453E-03	0.13406E-02	0.22300E 01	0.41695E-03
1550.	-.17121E-03	0.12605E-02	0.22838E 01	0.41669E-03
1600.	-.16776E-03	0.11878E-02	0.23500E 01	0.41260E-03
1650.	-.16425E-03	0.11157E-02	0.24175E 01	0.40926E-03
1700.	-.16064E-03	0.10466E-02	0.24900E 01	0.40519E-03
1750.	-.15695E-03	0.98049E-03	0.25675E 01	0.40042E-03
1800.	-.15317E-03	0.91728E-03	0.26500E 01	0.39496E-03

Table IV-16

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDP-00-24

P TYPE MATERIAL MANUFACTURED BY RCA.
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
0.	0.61250E-04	0.36500E-03	0.34000E 01	0.12370E-03
50.	0.64758E-04	0.37656E-03	0.33600E 01	0.13563E-03
100.	0.68219E-04	0.38875E-03	0.33200E 01	0.14755E-03
150.	0.71633E-04	0.40156E-03	0.32800E 01	0.15942E-03
200.	0.75000E-04	0.41500E-03	0.32400E 01	0.17118E-03
250.	0.78320E-04	0.42906E-03	0.32000E 01	0.18282E-03
300.	0.81594E-04	0.44375E-03	0.31600E 01	0.19428E-03
350.	0.84820E-04	0.45906E-03	0.31200E 01	0.20555E-03
400.	0.88000E-04	0.47500E-03	0.30800E 01	0.21660E-03
450.	0.91250E-04	0.49234E-03	0.30431E 01	0.22741E-03
500.	0.94500E-04	0.51062E-03	0.30075E 01	0.23795E-03
550.	0.97750E-04	0.52984E-03	0.29731E 01	0.24820E-03
600.	0.10100E-03	0.55000E-03	0.29400E 01	0.25815E-03
650.	0.10394E-03	0.56953E-03	0.29066E 01	0.26704E-03
700.	0.10675E-03	0.58937E-03	0.28737E 01	0.27532E-03
750.	0.10944E-03	0.60953E-03	0.28416E 01	0.28295E-03
800.	0.11200E-03	0.63000E-03	0.28100E 01	0.28995E-03
850.	0.11459E-03	0.65078E-03	0.27806E 01	0.29695E-03
900.	0.11712E-03	0.67187E-03	0.27525E 01	0.30354E-03
950.	0.11959E-03	0.69328E-03	0.27256E 01	0.30973E-03
1000.	0.12200E-03	0.71500E-03	0.27000E 01	0.31549E-03
1050.	0.12438E-03	0.73703E-03	0.26725E 01	0.32141E-03
1100.	0.12672E-03	0.75938E-03	0.26450E 01	0.32714E-03
1150.	0.12901E-03	0.78203E-03	0.26175E 01	0.33270E-03
1200.	0.13125E-03	0.80500E-03	0.25900E 01	0.33810E-03
1250.	0.13362E-03	0.82960E-03	0.25646E 01	0.34337E-03
1300.	0.13599E-03	0.85496E-03	0.25399E 01	0.34851E-03
1350.	0.13818E-03	0.87806E-03	0.25279E 01	0.35198E-03
1400.	0.14026E-03	0.90006E-03	0.25252E 01	0.35419E-03
1450.	0.14253E-03	0.92519E-03	0.25205E 01	0.35647E-03
1500.	0.14475E-03	0.95000E-03	0.25250E 01	0.35743E-03

Table IV-16 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDP-00-24

P TYPE MATERIAL MANUFACTURED BY RCA.
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

ENGLISH UNITS

TEMPERATURE DEG F	SEEBECK COEFFICIENT VOLT/DEG F	ELECTRICAL RESISTIVITY OHM-IN	THERMAL CONDUCTIVITY BTU/ FT-HR-DEG F	FIGURE OF MERIT 1/DEG F
1550.	0.14692E-03	0.97504E-03	0.25418E 01	0.35641E-03
1600.	0.14900E-03	0.10000E-02	0.25700E 01	0.35349E-03
1650.	0.15103E-03	0.10260E-02	0.26149E 01	0.34760E-03
1700.	0.15300E-03	0.10550E-02	0.26750E 01	0.33942E-03

Table IV-17

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-30

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2N.
COLD PRESSED AND SINTERED.
PROPERTY DATA MEASURED BY 3M, SEPTEMBER 1964.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	-.14077E-03	0.42328E-03	0.29313E-01	0.15972E-02
25.	-.14957E-03	0.51993E-03	0.27170E-01	0.15837E-02
50.	-.15909E-03	0.62220E-03	0.25156E-01	0.16171E-02
75.	-.16933E-03	0.73010E-03	0.23272E-01	0.16876E-02
100.	-.17999E-03	0.84773E-03	0.21526E-01	0.17754E-02
125.	-.18998E-03	0.99012E-03	0.19954E-01	0.18268E-02
150.	-.19978E-03	0.11510E-02	0.18538E-01	0.18705E-02
175.	-.20940E-03	0.13465E-02	0.17252E-01	0.18877E-02
200.	-.21884E-03	0.15702E-02	0.16106E-01	0.18938E-02
225.	-.22798E-03	0.18189E-02	0.15122E-01	0.18896E-02
250.	-.23684E-03	0.20930E-02	0.14299E-01	0.18742E-02
275.	-.24495E-03	0.23905E-02	0.13604E-01	0.18450E-02
300.	-.25204E-03	0.27103E-02	0.13018E-01	0.18005E-02
325.	-.25809E-03	0.30508E-02	0.12556E-01	0.17389E-02
350.	-.26257E-03	0.34067E-02	0.12216E-01	0.16566E-02
375.	-.26566E-03	0.37764E-02	0.12001E-01	0.15572E-02
400.	-.26693E-03	0.41299E-02	0.11939E-01	0.14451E-02
425.	-.26633E-03	0.44733E-02	0.12093E-01	0.13112E-02
450.	-.26360E-03	0.47897E-02	0.12524E-01	0.11584E-02
475.	-.25874E-03	0.50780E-02	0.13237E-01	0.99604E-03
500.	-.25228E-03	0.53103E-02	0.14084E-01	0.85102E-03
525.	-.24442E-03	0.54660E-02	0.15032E-01	0.72709E-03

Table IV-18

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-34

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2N. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT AND RESISTIVITY MEASURED BY 3M, OCTOBER 1965. THERMAL CONDUCTIVITY MEASURED BY 3M, SEPTEMBER 1964.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	-.14252E-03	0.47305E-03	0.29313E-01	0.14649E-02
25.	-.14996E-03	0.55701E-03	0.27170E-01	0.14860E-02
50.	-.15775E-03	0.66603E-03	0.25156E-01	0.14853E-02
75.	-.16589E-03	0.80013E-03	0.23272E-01	0.14779E-02
100.	-.17445E-03	0.95780E-03	0.21526E-01	0.14760E-02
125.	-.18369E-03	0.11336E-02	0.19954E-01	0.14917E-02
150.	-.19348E-03	0.13304E-02	0.18538E-01	0.15178E-02
175.	-.20309E-03	0.15601E-02	0.17252E-01	0.15325E-02
200.	-.21282E-03	0.18181E-02	0.16106E-01	0.15468E-02
225.	-.22254E-03	0.21140E-02	0.15122E-01	0.15492E-02
250.	-.23227E-03	0.24474E-02	0.14299E-01	0.15416E-02
275.	-.24137E-03	0.28167E-02	0.13604E-01	0.15205E-02
300.	-.24948E-03	0.32221E-02	0.13018E-01	0.14838E-02
325.	-.25641E-03	0.36441E-02	0.12576E-01	0.14346E-02
350.	-.26130E-03	0.40435E-02	0.12287E-01	0.13743E-02
375.	-.26500E-03	0.44415E-02	0.11996E-01	0.13181E-02
400.	-.26641E-03	0.48162E-02	0.11939E-01	0.12344E-02
425.	-.26645E-03	0.51598E-02	0.12093E-01	0.11378E-02
450.	-.26396E-03	0.54623E-02	0.12590E-01	0.10132E-02
475.	-.26023E-03	0.56909E-02	0.13276E-01	0.89633E-03
500.	-.25461E-03	0.58534E-02	0.14084E-01	0.78638E-03
525.	-.24651E-03	0.59630E-02	0.15032E-01	0.67791E-03

Table IV-19

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-35

N TYPE MATERIAL MANUFACTURED BY 3M. 2N PROPERTY DATA RECOMMENDED BY ISOTOPES, AUGUST 1969. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT MEASURED BY 3M, OCTOBER 1965. RESISTIVITY AND THERMAL CONDUCTIVITY MEASURED BY 3M, SEPT. 1964.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	-.14252E-03	0.42326E-03	0.29313E-01	0.16371E-02
25.	-.14996E-03	0.51993E-03	0.27170E-01	0.15920E-02
50.	-.15775E-03	0.62220E-03	0.25156E-01	0.15899E-02
75.	-.16589E-03	0.73010E-03	0.23272E-01	0.16197E-02
100.	-.17445E-03	0.84773E-03	0.21526E-01	0.16677E-02
125.	-.18369E-03	0.99012E-03	0.19954E-01	0.17079E-02
150.	-.19348E-03	0.11510E-02	0.18538E-01	0.17543E-02
175.	-.20309E-03	0.13465E-02	0.17252E-01	0.17756E-02
200.	-.21282E-03	0.15702E-02	0.16106E-01	0.17910E-02
225.	-.22254E-03	0.18189E-02	0.15122E-01	0.18005E-02
250.	-.23227E-03	0.20930E-02	0.14299E-01	0.18026E-02
275.	-.24137E-03	0.23905E-02	0.13604E-01	0.17915E-02
300.	-.24948E-03	0.27103E-02	0.13018E-01	0.17640E-02
325.	-.25647E-03	0.30508E-02	0.12556E-01	0.17172E-02
350.	-.26153E-03	0.34067E-02	0.12216E-01	0.16435E-02
375.	-.26498E-03	0.37764E-02	0.12001E-01	0.15493E-02
400.	-.26641E-03	0.41299E-02	0.11939E-01	0.14395E-02
425.	-.26645E-03	0.44733E-02	0.12093E-01	0.13124E-02
450.	-.26450E-03	0.47897E-02	0.12524E-01	0.11663E-02
475.	-.26053E-03	0.50780E-02	0.13237E-01	0.10099E-02
500.	-.25453E-03	0.53103E-02	0.14084E-01	0.86623E-03
525.	-.24651E-03	0.54660E-02	0.15032E-01	0.73955E-03

Table IV-20

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-51

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3N.
PROPERTY DATA MEASURED 24 SEPTEMBER 1965.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
50.	-.10726E-03	0.35937E-03	0.31027E-01	0.10319E-02
75.	-.11496E-03	0.42669E-03	0.28980E-01	0.10687E-02
100.	-.12265E-03	0.50430E-03	0.27116E-01	0.11001E-02
125.	-.13035E-03	0.59220E-03	0.25434E-01	0.11280E-02
150.	-.13806E-03	0.69038E-03	0.23932E-01	0.11536E-02
175.	-.14620E-03	0.79885E-03	0.22544E-01	0.11869E-02
200.	-.15462E-03	0.91761E-03	0.21297E-01	0.12234E-02
225.	-.16320E-03	0.10531E-02	0.20194E-01	0.12525E-02
250.	-.17195E-03	0.12049E-02	0.19236E-01	0.12756E-02
275.	-.18111E-03	0.13744E-02	0.18385E-01	0.12981E-02
300.	-.19082E-03	0.15628E-02	0.17621E-01	0.13223E-02
325.	-.20030E-03	0.17688E-02	0.16941E-01	0.13388E-02
350.	-.20785E-03	0.19901E-02	0.16303E-01	0.13315E-02
375.	-.21320E-03	0.22229E-02	0.15720E-01	0.13008E-02
400.	-.21798E-03	0.24877E-02	0.15346E-01	0.12446E-02
425.	-.22205E-03	0.27395E-02	0.15020E-01	0.11984E-02
450.	-.22441E-03	0.30200E-02	0.14762E-01	0.11296E-02
475.	-.22510E-03	0.33166E-02	0.14675E-01	0.10411E-02
500.	-.22429E-03	0.36216E-02	0.14766E-01	0.94066E-03
525.	-.22211E-03	0.38947E-02	0.14964E-01	0.84645E-03
550.	-.21856E-03	0.41028E-02	0.15248E-01	0.76359E-03
575.	-.21348E-03	0.42943E-02	0.15682E-01	0.67673E-03
600.	-.20673E-03	0.44614E 02	0.16230E-01	0.59023E-03
625.	-.19770E-03	0.46017E-02	0.16794E-01	0.50578E-03

Table IV-21

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDN-00-52

N TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3N.
PROPERTY DATA SUPPLIED BY SANDIA, 29 JULY 1968,
AS MEASURED BY 3M FOR THE SNAP-23 PROGRAM.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
25.	-.92461E-04	0.31565E-03	0.28793E-01	0.94062E-03
50.	-.10283E-03	0.36483E-03	0.26673E-01	0.10865E-02
75.	-.11233E-03	0.42356E-03	0.24777E-01	0.12023E-02
100.	-.12109E-03	0.49186E-03	0.23118E-01	0.12894E-02
125.	-.12954E-03	0.56981E-03	0.21743E-01	0.13545E-02
150.	-.13752E-03	0.65738E-03	0.20627E-01	0.13947E-02
175.	-.14554E-03	0.75449E-03	0.19662E-01	0.14279E-02
200.	-.15340E-03	0.86116E-03	0.18889E-01	0.14467E-02
225.	-.16129E-03	0.97888E-03	0.18221E-01	0.14586E-02
250.	-.16921E-03	0.11076E-02	0.17663E-01	0.14635E-02
275.	-.17710E-03	0.12497E-02	0.17198E-01	0.14593E-02
300.	-.18497E-03	0.14071E-02	0.16807E-01	0.14468E-02
325.	-.19275E-03	0.15807E-02	0.16505E-01	0.14241E-02
350.	-.20028E-03	0.17754E-02	0.16290E-01	0.13869E-02
375.	-.20757E-03	0.19893E-02	0.16162E-01	0.13401E-02
400.	-.21425E-03	0.22278E-02	0.16123E-01	0.12780E-02
425.	-.22046E-03	0.24885E-02	0.16170E-01	0.12078E-02
450.	-.22563E-03	0.27700E-02	0.16342E-01	0.11246E-02
475.	-.22990E-03	0.30725E-02	0.16627E-01	0.10346E-02
500.	-.23279E-03	0.33866E-02	0.17072E-01	0.93735E-03
525.	-.23419E-03	0.37103E-02	0.17687E-01	0.83575E-03
550.	-.23385E-03	0.40351E-02	0.18497E-01	0.73266E-03
575.	-.23132E-03	0.43484E-02	0.19545E-01	0.62957E-03
600.	-.22665E-03	0.46512E-02	0.20835E-01	0.53010E-03
625.	-.21906E-03	0.49197E-02	0.22469E-01	0.43411E-03

Table IV-22

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDP-00-40

P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2P.
NA DOPED - COLD PRESSED AND SINTERED.
PROPERTY DATA MEASURED BY 3M, SEPTEMBER 1964.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
25.	0.58208E-04	0.44492E-03	0.37989E-01	0.20046E-03
50.	0.74805E-04	0.52283E-03	0.34770E-01	0.30782E-03
75.	0.92131E-04	0.61789E-03	0.31645E-01	0.43411E-03
100.	0.10994E-03	0.72953E-03	0.28628E-01	0.57878E-03
125.	0.12736E-03	0.85566E-03	0.25777E-01	0.73541E-03
150.	0.14474E-03	0.99812E-03	0.23066E-01	0.90993E-03
175.	0.16095E-03	0.11849E-02	0.20495E-01	0.10666E-02
200.	0.17642E-03	0.14051E-02	0.18064E-01	0.12262E-02
225.	0.19163E-03	0.16491E-02	0.16081E-01	0.13847E-02
250.	0.20654E-03	0.19175E-02	0.14527E-01	0.15314E-02
275.	0.22092E-03	0.22158E-02	0.13314E-01	0.16544E-02
300.	0.23470E-03	0.25470E-02	0.12415E-01	0.17420E-02
325.	0.24749E-03	0.28972E-02	0.11798E-01	0.17918E-02
350.	0.25848E-03	0.32409E-02	0.11354E-01	0.18156E-02
375.	0.26890E-03	0.35887E-02	0.11117E-01	0.18124E-02
400.	0.27867E-03	0.39740E-02	0.11076E-01	0.17643E-02
425.	0.28574E-03	0.43747E-02	0.11255E-01	0.16582E-02
450.	0.29066E-03	0.47265E-02	0.11711E-01	0.15263E-02
475.	0.29312E-03	0.49907E-02	0.12336E-01	0.13956E-02
500.	0.29356E-03	0.51935E-02	0.13081E-01	0.12685E-02
525.	0.29178E-03	0.53412E-02	0.13947E-01	0.11428E-02

Table IV-23

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL PBTE

ISOTOPES IDENTIFICATION TEDP-00-44

P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 2P. COLD PRESSED AND SINTERED. SEEBECK COEFFICIENT AND RESISTIVITY MEASURED BY 3M, OCTOBER 1965. THERMAL CONDUCTIVITY MEASURED BY 3M, SEPTEMBER 1964.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
25.	0.58171E-04	0.47511E-03	0.37989E-01	0.18748E-03
50.	0.74900E-04	0.54533E-03	0.34770E-01	0.29587E-03
75.	0.92602E-04	0.63955E-03	0.31645E-01	0.42370E-03
100.	0.11101E-03	0.75919E-03	0.28628E-01	0.56703E-03
125.	0.12917E-03	0.90947E-03	0.25777E-01	0.71177E-03
150.	0.14753E-03	0.10888E-02	0.23066E-01	0.86662E-03
175.	0.16636E-03	0.13212E-02	0.20495E-01	0.10220E-02
200.	0.18555E-03	0.15973E-02	0.18064E-01	0.11932E-02
225.	0.20556E-03	0.19075E-02	0.16081E-01	0.13776E-02
250.	0.22637E-03	0.22523E-02	0.14527E-01	0.15662E-02
275.	0.24559E-03	0.26461E-02	0.13314E-01	0.17120E-02
300.	0.26181E-03	0.30970E-02	0.12415E-01	0.17827E-02
325.	0.27559E-03	0.35893E-02	0.11798E-01	0.17934E-02
350.	0.28625E-03	0.40926E-02	0.11354E-01	0.17632E-02
375.	0.29533E-03	0.45745E-02	0.11117E-01	0.17150E-02
400.	0.29972E-03	0.51085E-02	0.11076E-01	0.15877E-02
425.	0.30139E-03	0.56318E-02	0.11255E-01	0.14331E-02
450.	0.30097E-03	0.61524E-02	0.11711E-01	0.12572E-02
475.	0.29890E-03	0.66155E-02	0.12336E-01	0.10947E-02
500.	0.29534E-03	0.69866E-02	0.13081E-01	0.95439E-03
525.	0.28983E-03	0.72861E-02	0.13947E-01	0.82659E-03

Table IV-24

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-59

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P.
SEEBECK COEFFICIENT MEASURED BY 3M, JANUARY 1956.
RESISTIVITY AND THERMAL CONDUCTIVITY MEASURED BY 3M, DECEMBER 1963.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
75.	0.83653E-04	0.12319E-02	0.21025E-01	0.27019E-03
100.	0.96234E-04	0.13462E-02	0.19557E-01	0.35175E-03
125.	0.10512E-03	0.14605E-02	0.18272E-01	0.41407E-03
150.	0.11052E-03	0.15750E-02	0.17164E-01	0.45185E-03
175.	0.11886E-03	0.16952E-02	0.16069E-01	0.51860E-03
200.	0.12763E-03	0.18191E-02	0.15052E-01	0.59496E-03
225.	0.13685E-03	0.19504E-02	0.14116E-01	0.68021E-03
250.	0.14650E-03	0.20890E-02	0.13261E-01	0.77475E-03
275.	0.15664E-03	0.22351E-02	0.12495E-01	0.87862E-03
300.	0.16733E-03	0.23893E-02	0.11824E-01	0.99107E-03
325.	0.17790E-03	0.25559E-02	0.11251E-01	0.11005E-02
350.	0.18707E-03	0.27430E-02	0.10797E-01	0.11816E-02
375.	0.19567E-03	0.29384E-02	0.10516E-01	0.12390E-02
400.	0.20337E-03	0.31323E-02	0.10339E-01	0.12771E-02
425.	0.21115E-03	0.33155E-02	0.10261E-01	0.13106E-02
450.	0.21727E-03	0.34981E-02	0.10387E-01	0.12991E-02
475.	0.22204E-03	0.36811E-02	0.10750E-01	0.12458E-02
500.	0.22548E-03	0.38585E-02	0.11308E-01	0.11653E-02
525.	0.22744E-03	0.40269E-02	0.12025E-01	0.10683E-02
550.	0.22766E-03	0.41704E-02	0.12935E-01	0.96080E-03
575.	0.22649E-03	0.42588E-02	0.14109E-01	0.85369E-03
600.	0.22745E-03	0.43394E-02	0.15304E-01	0.77905E-03

Table IV-25

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-60

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P. SEEBECK COEFFICIENT MEASURED BY 3M, JANUARY 1966, RESISTIVITY MEASURED BY 3M, DEC. 1963. THERMAL CONDUCTIVITY MEASURED ON SNAP 11 ELEMENTS BY MARTIN JULY 1966

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
75.	0.83653E-04	0.12319E-02	0.17888E-01	0.31763E-03
100.	0.96234E-04	0.13462E-02	0.17373E-01	0.39597E-03
125.	0.10512E-03	0.14605E-02	0.16872E-01	0.44844E-03
150.	0.11052E-03	0.15750E-02	0.16380E-01	0.47347E-03
175.	0.11886E-03	0.16952E-02	0.15917E-01	0.52357E-03
200.	0.12763E-03	0.18191E-02	0.15474E-01	0.57871E-03
225.	0.13685E-03	0.19504E-02	0.15053E-01	0.63785E-03
250.	0.14650E-03	0.20890E-02	0.14653E-01	0.70115E-03
275.	0.15664E-03	0.22351E-02	0.14273E-01	0.76917E-03
300.	0.16733E-03	0.23893E-02	0.13915E-01	0.84219E-03
325.	0.17790E-03	0.25559E-02	0.13608E-01	0.90988E-03
350.	0.18707E-03	0.27430E-02	0.13417E-01	0.95092E-03
375.	0.19567E-03	0.29384E-02	0.13314E-01	0.97860E-03
400.	0.20337E-03	0.31323E-02	0.13342E-01	0.98969E-03
425.	0.21116E-03	0.33155E-02	0.13482E-01	0.99755E-03
450.	0.21727E-03	0.34981E-02	0.13706E-01	0.98460E-03
475.	0.22204E-03	0.36811E-02	0.14036E-01	0.95418E-03
500.	0.22548E-03	0.38585E-02	0.14471E-01	0.91058E-03
525.	0.22744E-03	0.40269E-02	0.15002E-01	0.85630E-03
550.	0.22765E-03	0.41704E-02	0.15597E-01	0.79677E-03
575.	0.22649E-03	0.42588E-02	0.16282E-01	0.73977E-03
600.	0.22745E-03	0.43394E-02	0.17053E-01	0.69915E-03

Table IV-26

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL 3P

ISOTOPES IDENTIFICATION TEDP-00-63

PBSNTE, P TYPE MATERIAL MANUFACTURED BY 3M, MFR. CODE NO. 3P.
PROPERTY DATA SUPPLIED BY SANDIA, JULY 1968,
AS MEASURED BY 3M, DECEMBER 1967.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
25.	0.39018E-04	0.87871E-03	0.16114E-01	0.10751E-03
50.	0.54173E-04	0.10015E-02	0.15552E-01	0.18841E-03
75.	0.67596E-04	0.11133E-02	0.15103E-01	0.27176E-03
100.	0.79625E-04	0.12164E-02	0.14764E-01	0.35303E-03
125.	0.91502E-04	0.13198E-02	0.14532E-01	0.43655E-03
150.	0.10271E-03	0.14199E-02	0.14406E-01	0.51570E-03
175.	0.11443E-03	0.15330E-02	0.14298E-01	0.59742E-03
200.	0.12622E-03	0.16529E-02	0.14243E-01	0.67673E-03
225.	0.13830E-03	0.17900E-02	0.14192E-01	0.75288E-03
250.	0.15065E-03	0.19438E-02	0.14149E-01	0.82525E-03
275.	0.16304E-03	0.21173E-02	0.14121E-01	0.88909E-03
300.	0.17535E-03	0.23131E-02	0.14114E-01	0.94183E-03
325.	0.18741E-03	0.25300E-02	0.14127E-01	0.98275E-03
350.	0.19874E-03	0.27691E-02	0.14168E-01	0.10068E-02
375.	0.20946E-03	0.30290E-02	0.14236E-01	0.10174E-02
400.	0.21877E-03	0.33043E-02	0.14358E-01	0.10088E-02
425.	0.22699E-03	0.35971E-02	0.14520E-01	0.98649E-03
450.	0.23340E-03	0.38916E-02	0.14818E-01	0.94467E-03
475.	0.23820E-03	0.41923E-02	0.15226E-01	0.88889E-03
500.	0.24114E-03	0.44828E-02	0.15771E-01	0.82246E-03
525.	0.24216E-03	0.47595E-02	0.16463E-01	0.74843E-03
550.	0.24145E-03	0.50165E-02	0.17334E-01	0.67041E-03
575.	0.23912E-03	0.52415E-02	0.18438E-01	0.59162E-03
600.	0.23535E-03	0.54396E-02	0.19766E-01	0.51518E-03
625.	0.23102E-03	0.56030E-02	0.21388E-01	0.44537E-03

Table IV-27

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL TAGS

ISOTOPES IDENTIFICATION TEDP-00-10A

TAGS P TYPE MATERIAL MANUFACTURED BY ISOTOPES.
PROPERTY DATA MEASURED BY MARTIN, 1966.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
95.	0.11268E-03	0.79461E-03	0.15194E-01	0.10517E-02
120.	0.12310E-03	0.82662E-03	0.15257E-01	0.12017E-02
145.	0.13269E-03	0.85862E-03	0.15319E-01	0.13385E-02
170.	0.14143E-03	0.89062E-03	0.15381E-01	0.14601E-02
195.	0.14933E-03	0.92263E-03	0.15444E-01	0.15651E-02
220.	0.15672E-03	0.95554E-03	0.15506E-01	0.16577E-02
245.	0.16376E-03	0.98984E-03	0.15568E-01	0.17403E-02
270.	0.17031E-03	0.10258E-02	0.15630E-01	0.18090E-02
295.	0.17633E-03	0.10648E-02	0.15693E-01	0.18608E-02
320.	0.18182E-03	0.11045E-02	0.15759E-01	0.18994E-02
345.	0.18663E-03	0.11347E-02	0.15853E-01	0.19362E-02
370.	0.19081E-03	0.11598E-02	0.15964E-01	0.19665E-02
395.	0.19442E-03	0.11828E-02	0.16115E-01	0.19832E-02
420.	0.19722E-03	0.12021E-02	0.16331E-01	0.19814E-02
445.	0.19844E-03	0.12185E-02	0.16639E-01	0.19422E-02
470.	0.19811E-03	0.12314E-02	0.17100E-01	0.18637E-02
495.	0.19708E-03	0.12406E-02	0.17698E-01	0.17690E-02

Table IV-28

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SNTE

ISOTOPES IDENTIFICATION TEDP-00-27

P TYPE MATERIAL, CAST SNTE MANUFACTURED BY ISOTOPES.
PROPERTY DATA MEASURED BY MARTIN, DECEMBER 1966.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
100.	0.25520E-04	0.25594E-03	0.75115E-01	0.33877E-04
125.	0.27650E-04	0.27846E-03	0.73525E-01	0.37342E-04
150.	0.30181E-04	0.30087E-03	0.71714E-01	0.42202E-04
175.	0.33113E-04	0.32349E-03	0.69683E-01	0.48641E-04
200.	0.36446E-04	0.34601E-03	0.67430E-01	0.56931E-04
225.	0.40042E-04	0.37104E-03	0.65128E-01	0.66352E-04
250.	0.43911E-04	0.39843E-03	0.62767E-01	0.77100E-04
275.	0.48348E-04	0.42787E-03	0.60155E-01	0.90817E-04
300.	0.53525E-04	0.45940E-03	0.57192E-01	0.10904E-03
325.	0.59162E-04	0.49496E-03	0.53986E-01	0.13099E-03
350.	0.64927E-04	0.53859E-03	0.50609E-01	0.15465E-03
375.	0.71000E-04	0.58787E-03	0.47051E-01	0.18225E-03
400.	0.77542E-04	0.64001E-03	0.43528E-01	0.21584E-03
425.	0.84483E-04	0.69614E-03	0.39947E-01	0.25666E-03
450.	0.92040E-04	0.75038E-03	0.36805E-01	0.30674E-03
475.	0.10015E-03	0.80432E-03	0.33968E-01	0.36714E-03
500.	0.10798E-03	0.86149E-03	0.31627E-01	0.42793E-03
525.	0.11532E-03	0.92261E-03	0.29830E-01	0.48324E-03
550.	0.12280E-03	0.98610E-03	0.28414E-01	0.53821E-03
575.	0.13086E-03	0.10511E-02	0.27253E-01	0.69779E-03
600.	0.13917E-03	0.11183E-02	0.26317E-01	0.65805E-03
625.	0.14740E-03	0.11882E-02	0.25236E-01	0.72461E-03

Table IV-29

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23

N TYPE MATERIAL MANUFACTURED BY RCA
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	-.16557E-03	0.16467E-02	0.51825E-01	0.32123E-03
25.	-.17682E-03	0.16930E-02	0.50977E-01	0.36229E-03
50.	-.18796E-03	0.17585E-02	0.50121E-01	0.40086E-03
75.	-.19899E-03	0.18433E-02	0.49256E-01	0.43612E-03
100.	-.20990E-03	0.19473E-02	0.48382E-01	0.46762E-03
125.	-.22070E-03	0.20707E-02	0.47499E-01	0.49520E-03
150.	-.23138E-03	0.22134E-02	0.46608E-01	0.51896E-03
175.	-.24195E-03	0.23753E-02	0.45708E-01	0.53917E-03
200.	-.25240E-03	0.25566E-02	0.44799E-01	0.55624E-03
225.	-.26260E-03	0.27567E-02	0.43995E-01	0.56878E-03
250.	-.27258E-03	0.29732E-02	0.43255E-01	0.57773E-03
275.	-.28238E-03	0.32094E-02	0.42559E-01	0.58380E-03
300.	-.29201E-03	0.34642E-02	0.41906E-01	0.58735E-03
325.	-.30147E-03	0.37379E-02	0.41258E-01	0.58933E-03
350.	-.31083E-03	0.40307E-02	0.40557E-01	0.59099E-03
375.	-.32000E-03	0.43438E-02	0.39873E-01	0.59121E-03
400.	-.32887E-03	0.46906E-02	0.39332E-01	0.58623E-03
425.	-.33780E-03	0.51243E-02	0.38790E-01	0.57407E-03
450.	-.34463E-03	0.54045E-02	0.38446E-01	0.57160E-03
475.	-.34862E-03	0.55035E-02	0.38154E-01	0.57881E-03
500.	-.35007E-03	0.54892E-02	0.37672E-01	0.59262E-03
525.	-.34886E-03	0.54204E-02	0.37510E-01	0.59857E-03
550.	-.34598E-03	0.52925E-02	0.37249E-01	0.60720E-03
575.	-.34278E-03	0.51258E-02	0.37013E-01	0.61933E-03
600.	-.33928E-03	0.49139E-02	0.36818E-01	0.63624E-03
625.	-.33570E-03	0.46363E-02	0.36749E-01	0.66142E-03
650.	-.33192E-03	0.43058E-02	0.36764E-01	0.69597E-03
675.	-.32768E-03	0.40428E-02	0.36754E-01	0.72260E-03
700.	-.32306E-03	0.38002E-02	0.36762E-01	0.74708E-03
725.	-.31853E-03	0.35749E-02	0.36918E-01	0.76879E-03
750.	-.31408E-03	0.33673E-02	0.37217E-01	0.78716E-03

Table IV-29 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23

N TYPE MATERIAL MANUFACTURED BY RCA
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
775.	-.30947E-03	0.31754E-02	0.37637E-01	0.80133E-03
800.	-.30461E-03	0.29981E-02	0.38181E-01	0.81058E-03
825.	-.29957E-03	0.28350E-02	0.38873E-01	0.81434E-03
850.	-.29435E-03	0.26834E-02	0.39766E-01	0.81195E-03
875.	-.28896E-03	0.25432E-02	0.40816E-01	0.80437E-03
900.	-.28348E-03	0.24037E-02	0.41874E-01	0.79838E-03
925.	-.27788E-03	0.22694E-02	0.43002E-01	0.79125E-03
950.	-.27216E-03	0.21402E-02	0.44200E-01	0.78300E-03
975.	-.26631E-03	0.20161E-02	0.45469E-01	0.77368E-03

Table IV-30

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23B

N TYPE MATERIAL MANUFACTURED BY RCA. PROPERTY DATA SAME AS TEDN-00-23 DATA EXCEPT SEEBECK COEFFICIENT INCREASED 4.2 PERCENT AND RESISTIVITY INCREASED 17.6 PERCENT FOR FIVE YEAR LIFE EFFECT, JUNE 1966.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	-.17253E-03	0.19366E-02	0.51825E-01	0.29658E-03
25.	-.18425E-03	0.19909E-02	0.50977E-01	0.33449E-03
50.	-.19586E-03	0.20679E-02	0.50121E-01	0.37010E-03
75.	-.20735E-03	0.21673E-02	0.49256E-01	0.40266E-03
100.	-.21871E-03	0.22901E-02	0.48382E-01	0.43174E-03
125.	-.22996E-03	0.24352E-02	0.47499E-01	0.45720E-03
150.	-.24110E-03	0.26029E-02	0.46608E-01	0.47914E-03
175.	-.25211E-03	0.27934E-02	0.45708E-01	0.49780E-03
200.	-.26301E-03	0.30065E-02	0.44799E-01	0.51356E-03
225.	-.27363E-03	0.32407E-02	0.43995E-01	0.52514E-03
250.	-.28403E-03	0.34965E-02	0.43255E-01	0.53341E-03
275.	-.29425E-03	0.37743E-02	0.42559E-01	0.53901E-03
300.	-.30427E-03	0.40739E-02	0.41906E-01	0.54228E-03
325.	-.31413E-03	0.43958E-02	0.41258E-01	0.54411E-03
350.	-.32388E-03	0.47401E-02	0.40557E-01	0.54564E-03
375.	-.33344E-03	0.51083E-02	0.39873E-01	0.54585E-03
400.	-.34268E-03	0.55161E-02	0.39332E-01	0.54125E-03
425.	-.35199E-03	0.60262E-02	0.38790E-01	0.53002E-03
450.	-.35910E-03	0.63557E-02	0.38446E-01	0.52774E-03
475.	-.36326E-03	0.64721E-02	0.38154E-01	0.53439E-03
500.	-.36477E-03	0.64553E-02	0.37672E-01	0.54715E-03
525.	-.36351E-03	0.63743E-02	0.37510E-01	0.55264E-03
550.	-.36051E-03	0.62239E-02	0.37249E-01	0.56061E-03
575.	-.35718E-03	0.60279E-02	0.37013E-01	0.57181E-03
600.	-.35353E-03	0.57788E-02	0.36818E-01	0.58742E-03
625.	-.34980E-03	0.54522E-02	0.36749E-01	0.61067E-03
650.	-.34586E-03	0.50637E-02	0.36764E-01	0.64256E-03
675.	-.34144E-03	0.47543E-02	0.36754E-01	0.66716E-03
700.	-.33663E-03	0.44690E-02	0.36762E-01	0.68975E-03
725.	-.33191E-03	0.42041E-02	0.36918E-01	0.70980E-03

Table IV-30 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDN-00-23B

N TYPE MATERIAL MANUFACTURED BY RCA. PROPERTY DATA SAME AS TEDN-00-23 DATA EXCEPT SEEBECK COEFFICIENT INCREASED 4.2 PERCENT AND RESISTIVITY INCREASED 17.6 PERCENT FOR FIVE YEAR LIFE EFFECT, JUNE 1966.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
750.	-.32727E-03	0.39600E-02	0.37217E-01	0.72677E-03
775.	-.32247E-03	0.37343E-02	0.37637E-01	0.73984E-03
800.	-.31741E-03	0.35258E-02	0.38181E-01	0.74839E-03
825.	-.31216E-03	0.33339E-02	0.38873E-01	0.75186E-03
850.	-.30671E-03	0.31556E-02	0.39766E-01	0.74965E-03
875.	-.30110E-03	0.29909E-02	0.40816E-01	0.74265E-03
900.	-.29538E-03	0.28268E-02	0.41874E-01	0.73712E-03
925.	-.28955E-03	0.26688E-02	0.43002E-01	0.73054E-03
950.	-.28359E-03	0.25168E-02	0.44200E-01	0.72292E-03
975.	-.27750E-03	0.23709E-02	0.45469E-01	0.71431E-03

Table IV-31

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDP-00-24

P TYPE MATERIAL MANUFACTURED BY RCA.
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
0.	0.11430E-03	0.94571E-03	0.58381E-01	0.23663E-03
25.	0.11994E-03	0.97299E-03	0.57758E-01	0.25598E-03
50.	0.12551E-03	0.10015E-02	0.57135E-01	0.27528E-03
75.	0.13101E-03	0.10314E-02	0.56512E-01	0.29447E-03
100.	0.13644E-03	0.10625E-02	0.55889E-01	0.31349E-03
125.	0.14181E-03	0.10949E-02	0.55266E-01	0.33231E-03
150.	0.14710E-03	0.11286E-02	0.54644E-01	0.35087E-03
175.	0.15233E-03	0.11636E-02	0.54021E-01	0.36914E-03
200.	0.15749E-03	0.11999E-02	0.53398E-01	0.38711E-03
225.	0.16273E-03	0.12380E-02	0.52813E-01	0.40473E-03
250.	0.16799E-03	0.12800E-02	0.52252E-01	0.42196E-03
275.	0.17326E-03	0.13231E-02	0.51709E-01	0.43878E-03
300.	0.17852E-03	0.13680E-02	0.51183E-01	0.45516E-03
325.	0.18362E-03	0.14138E-02	0.50667E-01	0.47070E-03
350.	0.18832E-03	0.14588E-02	0.50149E-01	0.48484E-03
375.	0.19284E-03	0.15041E-02	0.49640E-01	0.49806E-03
400.	0.19718E-03	0.15503E-02	0.49140E-01	0.51035E-03
425.	0.20133E-03	0.15971E-02	0.48648E-01	0.52171E-03
450.	0.20553E-03	0.16445E-02	0.48188E-01	0.53307E-03
475.	0.20965E-03	0.16926E-02	0.47746E-01	0.54390E-03
500.	0.21368E-03	0.17413E-02	0.47321E-01	0.55414E-03
525.	0.21762E-03	0.17906E-02	0.46914E-01	0.56376E-03
550.	0.22150E-03	0.18406E-02	0.46503E-01	0.57318E-03
575.	0.22533E-03	0.18913E-02	0.46075E-01	0.58265E-03
600.	0.22909E-03	0.19425E-02	0.45647E-01	0.59187E-03
625.	0.23278E-03	0.19945E-02	0.45219E-01	0.60084E-03
650.	0.23642E-03	0.20471E-02	0.44792E-01	0.60956E-03
675.	0.24025E-03	0.21033E-02	0.44396E-01	0.61812E-03
700.	0.24411E-03	0.21612E-02	0.44012E-01	0.62648E-03
725.	0.24773E-03	0.22154E-02	0.43778E-01	0.63278E-03
750.	0.25114E-03	0.22664E-02	0.43687E-01	0.63701E-03

Table IV-31 (Cont.)

THERMOELECTRIC PROPERTY DATA FILE

MATERIAL SIGE

ISOTOPES IDENTIFICATION TEDP-00-24

P TYPE MATERIAL MANUFACTURED BY RCA.
PROPERTY DATA MEASURED BY RCA, NOVEMBER 1965.

METRIC UNITS

TEMPERATURE DEG C	SEEBECK COEFFICIENT VOLT/DEG C	ELECTRICAL RESISTIVITY OHM-CM	THERMAL CONDUCTIVITY W/CM-DEG C	FIGURE OF MERIT 1/DEG C
775.	0.25461E-03	0.23197E-02	0.43634E-01	0.64048E-03
800.	0.25828E-03	0.23774E-02	0.43615E-01	0.64334E-03
825.	0.26190E-03	0.24346E-02	0.43761E-01	0.64378E-03
850.	0.26536E-03	0.24917E-02	0.44072E-01	0.64122E-03
875.	0.26872E-03	0.25494E-02	0.44557E-01	0.63569E-03
900.	0.27200E-03	0.26110E-02	0.45278E-01	0.62579E-03
925.	0.27519E-03	0.26753E-02	0.46210E-01	0.61256E-03

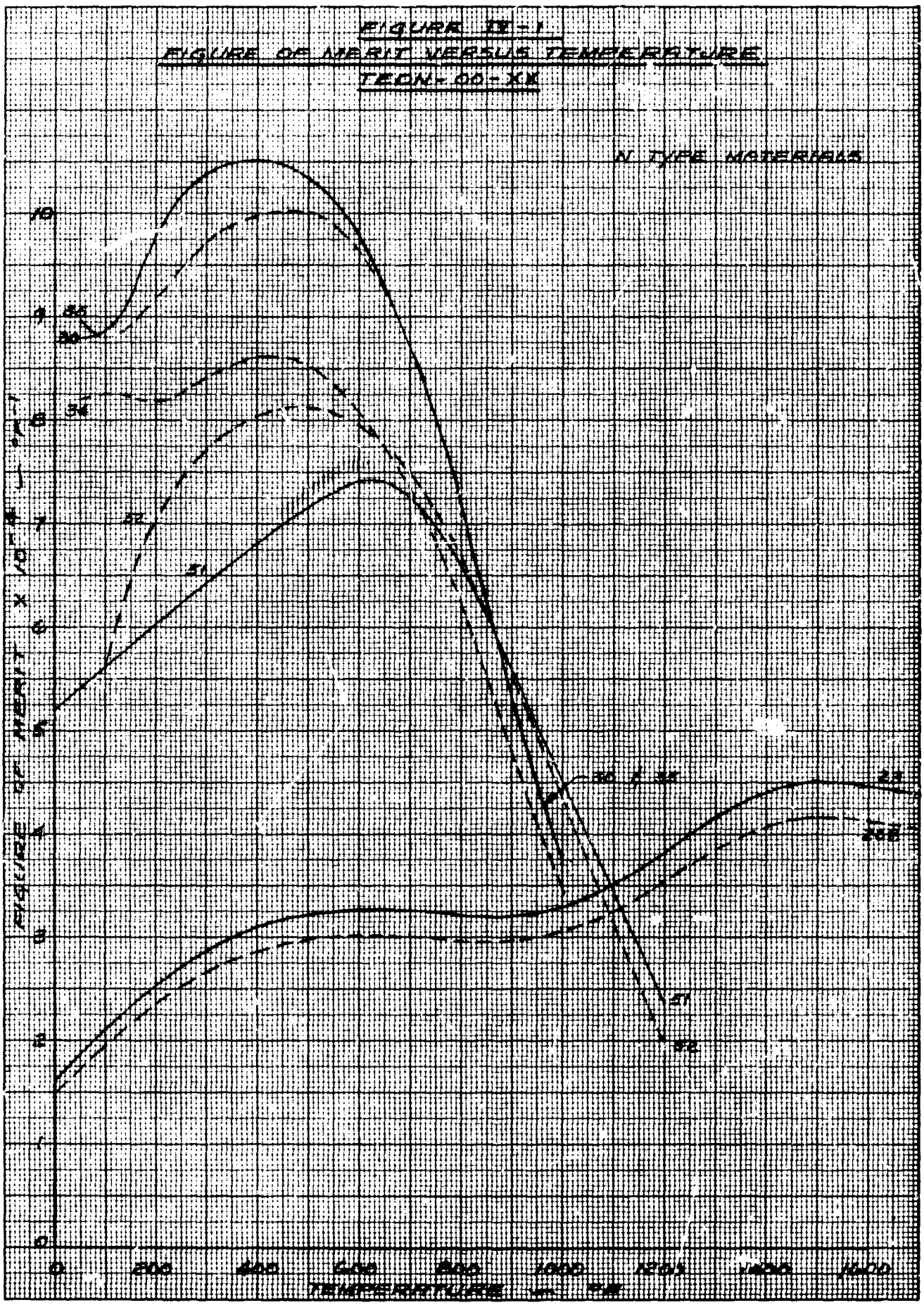


FIGURE IV-1
FIGURE OF MERIT VERSUS TEMPERATURE
TECN-00-XX
N TYPE MATERIALS
FIGURE OF MERIT X 10^-4
TEMPERATURE - °K
0
200
400
600
800
1000
1200
1400
1600
1800
2
3
4
5
6
7
8
9
10
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35

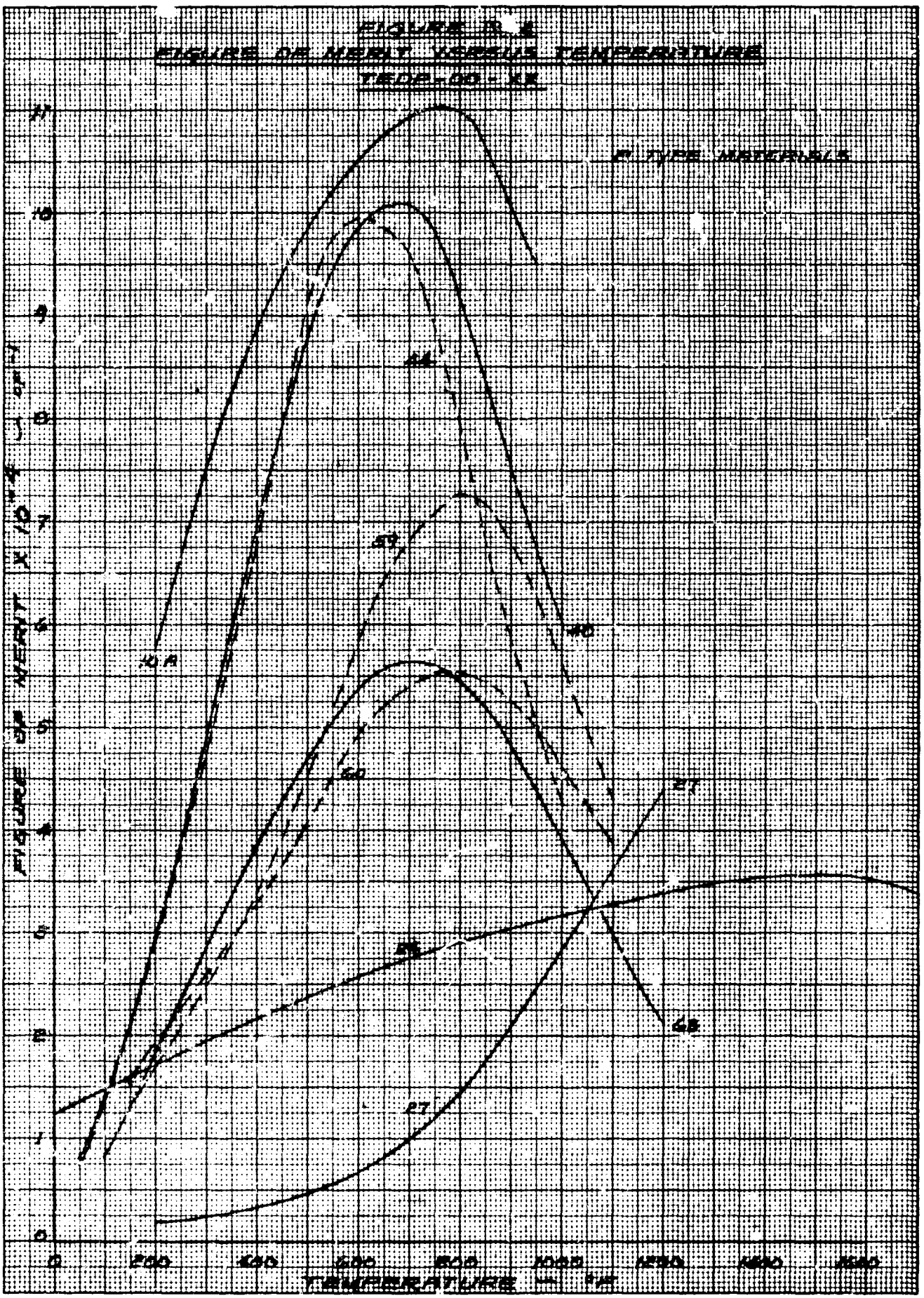


FIGURE B-3
FIGURE OF MERIT VERSUS TEMPERATURE
TEDP-00-XX
P TYPE MATERIALS
FIGURE OF MERIT X 10**4
TEMPERATURE — °F
0
200
400
600
800
1000
1200
1400
1600
1
2
3
4
5
6
7
8
9
10
11
10A
44
39
40
60
27
25
45
27

CHAPTER V

Thermoelectric Computations

A series of parametric studies were performed utilizing the Isotopes thermoelectric code (referenced in Chapter III and Ref. 5) in conjunction with five combinations of the thermoelectric property data presented in Chapter IV. Table V-1 summarizes the independent variables used in the parametric studies for five material combinations. The five material combinations were selected to represent the material combinations of greatest interest for power production at present. The early Isotopes SNAP 19's were built with 2N and 2P thermoelectric materials while the Isotopes Nimbus B SNAP 19 radioisotope fueled generator (RTG) contained 2N and 3P thermoelectric materials. Isotopes SNAP 11 RTG's were built with 2N and 3P thermoelectrics as were early modules of the SNAP 29 program. Later SNAP 29 modules plus the Pioneer SNAP 19's contain the 2N-TAGS/SnTe material combinations. RCA has built and tested hardware with SiGe since the SNAP 10A program. 3N and 3P are employed by G.E. in the SNAP 27 RTG.

The range in hot junction temperatures was selected to encompass the highest and lowest practical operating temperatures. The efficiency of the thermoelectric device increases as the hot junction temperature increases. However along with the increased efficiencies, the material degradation normally increases. Therefore the maximum hot junction temperature is obtained through trade-offs involving degradation, efficiency, heat source temperature, and life. The minimum hot junction was selected to include normal end of life temperatures (i.e., temperatures drop as the fuel decays) of RTG's presently being designed. In the case of the SiGe calculations, the maximum hot junction was selected to be consistent with planned and existing heat sources.

TABLE V-1

Summary of Independent Variables in Thermoelectric Calculations

Materials	Property Data Used	Hot Junction Temperature (°F)	Cold Junction Temperature (°F)	Total Contact Resistivity Divided by Element Length ($\mu\Omega$-cm^2/in)
2N/2P	TEDN-00-34 TEDP-00-44	850, 950, 1050	200, 300, 400, 500	0, 3000, 6000, 12000
2N/3P	TEDN-00-34 TEDP-00-60	900, 1000, 1100	200, 300, 400, 500	0, 1500, 3000, 6000, 12000
2N/TAGS*	TEDN-00-35 TEDP-10A-27	850, 950, 1050	200, 300, 400, 500	0, 1500, 3000, 6000, 12000
SiGe/SiGe	TEDN-00-23B TEDP-00-24	1200, 1400, 1600, 1800	500, 700, 900, 1100	0, 2000, 4000, 8000
3N/3P	TEDN-00-52 TEDP-00-60	900, 1000, 1100	200, 300, 400, 500	0, 1500, 3000, 6000, 12000

$^*\frac{L_{SnTe}}{L} = .2$

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REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR.

The range of cold junction temperature was selected to encompass practical space RTG operating temperatures. Lower cold junction temperatures are not practical for space RTG's because of large radiator requirements. However in the design of terrestrial RTG's, the cold junction may be less than the range given because of enhanced heat transfer to the environment and less emphasis on weight (hence larger heat rejection subsystems). For the PbTe and TAGS materials, the highest cold junction was selected to indicate the temperature at which the performance begins to decrease very rapidly resulting in decreased specific powers. The upper limit of the SiGe cold junction was selected as an upper limit of the cold junction temperature of a SiGe stage in a cascaded system.

The contact resistivity divided by the element length ($C_{T/L}$) was selected to enable consideration of true contact effects as well as material property degradation. Thus, the beginning of life performance and normal end of life performance can be predicted for practical element lengths from 0.10 in → 1 inch. The contact resistivity will typically increase with time as the thermoelectric device degrades. Beginning of life values of C_T for each material combination are obtained by comparing hardware performance with analytical predictions. The $C_{T/L}$, hence C_T, which correlates the measured power output is used for beginning of life performance predictions. It is apparent that the contact resistivity calculated from experimental performance is dependent on the material property data employed. Therefore, applicable material property data must be specified at the same time that a design value of contact resistivity is specified. Table V-2 indicates typical beginning of life contact resistivities for

TABLE V-2

Typical Beginning of Life Contact Resistivities

Material Combination	Property Data Identification	Beginning of Life ($\mu\Omega$-cm^2) Total Contact Resistivity	Source
2N/2P	TEDN-00-34 TEDP-00-44	1500 → 3000	SNAP 19 Nimbus II
2N/3P	TEDN-00-34 TEDP-00-60	-750 → 0 0 → 750	SNAP 29 SNAP 19
2N/TAGS-SnTe	TEDN-00-35 TEDP-10A-27	0 → 100	SNAP 29 SNAP 19 Pioneer
3N/3P*	TEDN-00-52 TEDP-00-60	-400 → 0	SNAP 27 Electrically Heated Generators
GeSi	TEDN-00-23B** TEDP-00-24	~0	RCA Supplied for Multi-Hundred Watt Proposal

*This combination of property data predicts the electrical power at $C_T = -400\ \mu\Omega/cm^2$ but predicts an efficiency lower than SNAP 27.

** TEDN-00-23B data is used for 5 year life.

each of the five material combinations. Also indicated in Table V-2 is the applicable property data and the source of the data.

The negative contact resistivity reported for the 2N and 3P thermoelectric material simply indicates that this material combination produces more power than theoretically possible when utilizing the notea property data. This negative number does not mean that a physically puzzling negative resistance exists at these bonds. The reported negative C_T implies that the material property data used is inaccurate.

The total contact resistivity consists of resistance at the hot and cold end of each element of the couple. The values of the calculated thermoelectric parameters depends on the distributon of the total contact resistance in each of the four locations. The hot junction bond and the p leg bonds have traditionally exhibited higher resistance than the cold junction and the n bonds respectively. Therefore, in all of these calculations, the distribution of the total contact resistivities was allocated as shown below. As new materials and/or bonding processes are developed, the allocation of the contact resistivity must be re-examined for accuracy in describing experimental results.

N hot junction	=	$5/18\ C_T$
P hot junction	=	$10/18\ C_T$
N cold junction	=	$1/18\ C_T$
P cold junction	=	$2/18\ C_T$

For the segmented 2N-TAGS/SnTe couple calculations, the hot SnTe segment length was set at 20% of the total element length. Both the SNAP 29 couple and the SNAP 19 couple, which were designed for a hot junction temperature of 1050°F, have SnTe segment lengths of ~20% of the total thermoelectric element length. The sole purpose of the SnTe segment is to reduce the maximum TAGS temperature to an acceptable (i.e., TAGS $\leq$ 950°F) level while allowing the N leg to operate at higher temperatures. The net result is a more efficient couple for operation.

The calculations were performed utilizing the fixed length-optimized area option of the thermoelectric code. The significant dependent variables calculated are: thermoelectric efficiency, power parameter, heat parameter, instantaneous open circuit voltage per couple, optimum efficiency load voltage per couple and the optimum shape factor ratio. The thermoelectric efficiency has been defined previously. The power parameter (PL/NA) is equal to the gross power per couple (P/N) times the element length divided by the sum of the N element plus P element cross section. The heat parameter (QL/NA) is equal to the power parameter divided by the thermoelectric efficiency but is presented for ease of calculations. The instantaneous open circuit voltage and optimum load voltage per couple are necessary to describe the voltage characteristics of the thermoelectrics. The final output is the optimum diameter ratio (D_N/D_P), where right circular cylinders of equal length are assumed. The significance of this term is that its square is the optimum shape factor ratio (equal element lengths) discussed in Chapter III. The diameter ratio is used in conjunction with the sum of the element cross sections to size each individual element.

Tables V-3 through V-7 present the results of the thermoelectric calculations conducted for this design manual.

Figures V-1 through V-10 present the calculated thermoelectric efficiency as a function of hot junction temperature, cold junction temperature and $C_{T/L}$. Note that the efficiency of each material combination is presented in two figures. The low $C_{T/L}$ are presented on the first graph and the higher $C_{T/L}$ are presented on the second figure for clarity.

TABLE V-3

SUMMARY OF THERMOELECTRIC COUPLE PERFORMANCE PARAMETERS

2N/2P TEDN-00-34/TEDP-00-44

OPTIMUM EFFICIENCY OPERATION

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\mu\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
850	200	0	8.33	1.59	19.1	.167	.0967	1.03
		3000	7.25	1.33	18.3	.167	.0941	1.00
		6000	6.41	1.14	17.8	.167	.0926	.982
		12000	5.20	.882	17.0	.167	.0904	.953
	300	0	7.33	1.10	15.0	.150	.0872	1.00
		3000	6.50	.937	14.4	.150	.0851	.984
		6000	5.84	.816	14.0	.150	.0839	.966
		12000	4.86	.648	13.3	.150	.0820	.940
	400	0	6.15	.706	11.5	.129	.0753	.988
		3000	5.54	.614	11.1	.129	.0739	.967
		6000	5.05	.542	10.7	.129	.0730	.953
		12000	4.28	.440	10.3	.129	.0714	.928
	500	0	4.80	.408	8.49	.105	.0612	.974
		3000	4.38	.360	8.20	.105	.0603	.959
		6000	4.03	.322	8.00	.105	.0596	.944
		12000	3.47	.266	7.66	.105	.0585	.923
950	200	0	8.94	1.93	21.6	.198	.114	1.01
		3000	7.92	1.65	20.8	.198	.112	.991
		6000	7.10	1.44	20.2	.198	.110	.972
		12000	5.89	1.14	19.4	.198	.107	.949
	300	0	7.99	1.39	17.4	.181	.105	.991
		3000	7.19	1.21	16.9	.181	.103	.974
		6000	6.54	1.07	16.4	.181	.101	.957
		12000	5.53	.869	15.7	.181	.0992	.936
	400	0	6.87	.957	13.9	.160	.0929	.974
		3000	6.27	.846	13.5	.160	.0913	.960
		6000	5.76	.758	13.2	.160	.0899	.948
		12000	4.96	.625	12.6	.160	.0885	.928
	500	0	5.60	.613	10.9	.136	.0788	.966
		3000	5.15	.548	10.6	.136	.0776	.952
		6000	4.77	.495	10.4	.136	.0768	.938
		12000	4.11	.472	9.90	.136	.0759	.919

TABLE V-3 (CONT'D)

2N/2P TEDN-00-34/TEDP-00-44

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\mu\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
1050	200	0	9.25	2.24	24.3	.227	.130	.997
		3000	8.30	1.95	23.5	.227	.128	.980
		6000	7.52	1.72	22.9	.227	.126	.966
		12000	6.33	1.39	22.0	.227	.123	.945
	300	0	8.36	1.66	20.1	.210	.120	.981
		3000	7.60	1.48	19.5	.210	.119	.963
		6000	6.97	1.33	19.0	.210	.117	.952
		12000	5.97	1.09	18.3	.210	.115	.933
	400	0	7.30	1.21	16.6	.190	.109	.966
		3000	6.71	1.08	16.1	.190	.107	.950
		6000	6.20	.978	15.8	.190	.106	.940
		12000	5.39	.819	15.2	.190	.104	.921
	500	0	6.09	.800	13.5	.165	.0944	.958
		3000	5.65	.750	13.3	.165	.0934	.942
		6000	5.25	.683	13.0	.165	.0927	.934
		12000	4.61	.579	12.5	.165	.0912	.915

TABLE V-4

SUMMARY OF THERMOELECTRIC COUPLE PERFORMANCE PARAMETERS

2N/3P TECN-00-34 / TEDP-00-00

OPTIMUM EFFICIENCY OPERATION

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\mu\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
900	200	0	7.32	1.38	18.9	.154	.0870	1.06
		1500	6.77	1.25	18.5	.154	.0860	1.04
		3000	6.30	1.14	18.1	.154	.0850	1.02
		6000	5.53	.972	17.6	.154	.0841	.995
		12000	4.44	.750	16.9	.154	.0822	.954
	300	0	6.45	1.00	15.6	.138	.0783	1.08
		1500	6.00	.916	15.3	.138	.0775	1.06
		3000	5.61	.843	15.0	.138	.0767	1.04
		6000	4.98	.725	14.6	.138	.0763	1.02
		12000	4.06	.569	14.0	.138	.0744	.978
	400	0	5.48	.690	12.6	.120	.0683	1.11
		1500	5.13	.634	12.4	.120	.0677	1.08
		3000	4.82	.587	12.2	.120	.0671	1.06
		6000	4.31	.510	11.8	.120	.0664	1.03
		12000	3.57	.406	11.4	.120	.0652	.996
	500	0	4.42	.436	9.85	.100	.0569	1.12
		1500	4.16	.403	9.68	.100	.0565	1.10
		3000	3.93	.375	9.53	.100	.0561	1.08
		6000	3.54	.329	9.29	.100	.0554	1.05
		12000	2.96	.265	8.94	.100	.0545	1.01
1000	200	0	7.92	1.71	21.6	.181	.102	1.06
		1500	7.38	1.56	21.2	.181	.101	1.05
		3000	6.91	1.44	20.8	.181	.0998	1.03
		6000	6.13	1.24	20.2	.181	.0985	.999
		12000	5.02	.985	19.5	.181	.0973	.959
	300	0	7.08	1.30	18.3	.165	.0934	1.09
		1500	6.64	1.19	18.0	.165	.0923	1.07
		3000	6.24	1.10	17.7	.165	.0916	1.05
		6000	5.58	.961	17.2	.165	.0903	1.02
		12000	4.62	.764	16.6	.165	.0886	.984

TABLE V-4 (CONT'D)

2N/3P TEDN-00-34/TEDP-00-60

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$4\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
1000	400	0	6.16	.943	15.3	.147	.0832	1.11
		1500	5.79	.872	15.0	.147	.0825	1.09
		3000	5.47	.811	14.8	.147	.0818	1.07
		6000	4.93	.713	14.4	.147	.0802	1.04
		12000	4.12	.573	13.9	.147	.0795	1.00
	500	0	5.14	.645	12.6	.127	.0719	1.12
		1500	4.86	.600	12.3	.127	.0713	1.10
		3000	4.61	.561	12.2	.127	.0708	1.08
		6000	4.18	.496	11.9	.127	.0700	1.05
		12000	3.53	.404	11.5	.127	.0688	1.02
1100	200	0	8.30	2.04	24.6	.206	.116	1.07
		1500	7.78	1.88	24.1	.206	.115	1.05
		3000	7.32	1.74	23.7	.206	.114	1.03
		6000	6.54	1.51	23.1	.206	.112	1.01
		12000	5.40	1.20	22.2	.206	.110	.968
	300	0	7.50	1.60	21.3	.190	.107	1.08
		1500	7.06	1.48	20.9	.190	.106	1.07
		3000	6.67	1.37	20.6	.190	.105	1.05
		6000	6.01	1.21	20.1	.190	.104	1.02
		12000	5.01	.969	19.3	.190	.102	.988
	400	0	6.62	1.21	18.3	.172	.0971	1.10
		1500	6.25	1.12	18.0	.172	.0963	1.08
		3000	5.93	1.05	17.7	.172	.0956	1.07
		6000	5.37	.927	17.3	.172	.0949	1.04
		12000	4.53	.754	16.7	.172	.0932	1.00
	500	0	5.65	.876	15.5	.152	.0857	1.11
		1500	5.35	.817	15.3	.152	.0850	1.09
		3000	5.09	.767	15.1	.152	.0845	1.08
		6000	4.64	.682	14.7	.152	.0837	1.05
		12000	3.94	.560	14.2	.152	.0823	1.01

TABLE V-5

SUMMARY OF THERMOELECTRIC COUPLE PERFORMANCE PARAMETERS

2N/SnTe-THGS TEDN-00-35/TEDP-10A-27

OPTIMUM EFFICIENCY OPERATION

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	μΩCM²/IN	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
850	200	0	9.13	1.88	20.6	.140	.0813	1.33
		1500	7.99	1.58	19.7	.140	.0796	1.24
		3000	7.13	1.37	19.1	.140	.0782	1.19
		6000	5.90	1.08	18.3	.140	.0766	1.12
		12000	4.41	.768	17.4	.140	.0746	1.04
	300	0	7.88	1.33	16.8	.123	.0720	1.39
		1500	6.95	1.13	16.2	.123	.0706	1.30
		3000	6.25	.984	15.8	.123	.0697	1.24
		6000	5.21	.790	15.2	.124	.0680	1.16
		12000	3.95	.570	14.4	.124	.0665	1.08
	400	0	6.51	.872	13.4	.105	.0613	1.44
		1500	5.78	.748	12.9	.105	.0602	1.35
		3000	5.22	.659	12.6	.105	.0594	1.28
		6000	4.46	.534	12.1	.105	.0582	1.21
		12000	3.37	.391	11.6	.105	.0567	1.12
	500	0	5.05	.513	10.2	.0840	.0494	1.48
		1500	4.51	.445	9.86	.0840	.0485	1.39
		3000	4.09	.394	9.62	.0840	.0479	1.33
		6000	3.48	.323	9.30	.0840	.0469	1.24
		12000	2.69	.240	8.89	.0840	.0458	1.15
950	200	0	9.99	2.35	23.5	.165	.0957	1.36
		1500	8.84	2.00	22.6	.165	.0937	1.28
		3000	7.96	1.75	22.0	.165	.0922	1.22
		6000	6.66	1.41	21.1	.165	.0902	1.14
		12000	5.06	1.01	20.1	.165	.0880	1.06
	300	0	8.79	1.74	19.8	.148	.0869	1.40
		1500	7.83	1.50	19.1	.148	.0847	1.32
		3000	7.09	1.32	18.6	.148	.0835	1.26
		6000	5.98	1.07	17.9	.148	.0818	1.18
		12000	4.60	.784	17.0	.148	.0798	1.10

TABLE V - 5 (CONT'D)

2N/SnTe - TAG: TEON-00-35/TEOP-10A-27

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{oc}	E_L	$\frac{D_N}{D_P}$
°F	°F	μΩCM²/IN	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
950	400	0	7.47	1.22	16.3	.130	.0760	1.46
		1500	6.69	1.06	15.8	.130	.0743	1.37
		3000	6.08	.939	15.4	.130	.0733	1.31
		6000	5.17	.770	14.9	.130	.0718	1.22
		12000	4.02	.571	14.2	.130	.0702	1.13
	500	0	6.06	.795	13.1	.109	.0637	1.50
		1500	5.46	.695	12.7	.109	.0625	1.41
		3000	4.98	.619	12.4	.109	.0619	1.34
		6000	4.26	.513	12.0	.109	.0606	1.26
		12000	3.34	.385	11.5	.109	.0592	1.16
1050	200	0	10.6	2.83	26.6	.189	.110	1.37
		1500	9.48	2.44	25.7	.189	.107	1.30
		3000	8.59	2.15	25.0	.189	.106	1.24
		6000	7.26	1.74	24.0	.189	.104	1.16
		12000	5.58	1.28	22.9	.189	.101	1.08
	300	0	9.47	2.17	22.9	.172	.100	1.43
		1500	8.50	1.88	22.2	.172	.0982	1.34
		3000	7.73	1.67	21.6	.172	.0968	1.28
		6000	6.58	1.37	20.8	.172	.0949	1.20
		12000	5.11	1.01	19.8	.173	.0928	1.11
	400	0	8.20	1.60	19.5	.154	.0892	1.47
		1500	7.39	1.40	18.9	.154	.0878	1.38
		3000	6.75	1.24	18.4	.154	.0867	1.32
		6000	5.78	1.03	17.8	.154	.0851	1.23
		12000	4.53	.772	17.0	.154	.0830	1.14
	500	0	6.84	1.11	16.3	.133	.0772	1.50
		1500	6.18	.978	15.8	.133	.0761	1.41
		3000	5.67	.877	15.5	.133	.0751	1.35
		6000	4.88	.730	15.0	.133	.0739	1.26
		12000	3.86	.553	14.3	.133	.0720	1.17

TABLE V-6

SUMMARY OF THERMOELECTRIC COUPLE PERFORMANCE PARAMETERS

SiGe/SiGe TEON-00-23B / TEUP-00-24

OPTIMUM EFFICIENCY OPERATION

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	μΩCM²/IN	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
1200	500	0	4.32	2.17	50.2	.213	.116	1.42
		2000	3.86	1.91	49.4	.213	.115	1.35
		4000	3.50	1.71	48.8	.213	.114	1.29
		8000	2.97	1.42	47.9	.213	.112	1.21
	700	0	3.14	1.11	35.2	.158	.0864	1.43
		2000	2.83	.981	34.7	.158	.0856	1.36
		4000	2.58	.884	34.2	.158	.0848	1.30
		8000	2.20	.742	33.6	.158	.0842	1.23
	900	0	1.93	.404	20.9	.0969	.0532	1.41
		2000	1.74	.359	20.6	.0969	.0527	1.34
		4000	1.60	.325	20.2	.0969	.0524	1.29
		8000	1.37	.274	20.0	.0969	.0518	1.22
	1100	0	.663	.0464	6.97	.0323	.0179	1.36
		2000	.603	.0414	6.87	.0323	.0178	1.30
		4000	.552	.0374	6.77	.0323	.0177	1.25
		8000	.465	.0307	6.61	.0323	.0175	1.19
1400	500	0	5.63	3.68	65.4	.277	.152	1.38
		2000	5.06	3.25	64.2	.277	.150	1.31
		4000	4.61	2.91	63.2	.277	.149	1.26
		8000	3.92	2.43	61.8	.277	.147	1.19
	700	0	4.47	2.34	50.2	.223	.123	1.38
		2000	4.04	1.99	49.2	.223	.121	1.32
		4000	3.70	1.79	48.5	.223	.121	1.26
		8000	3.17	1.50	47.5	.223	.119	1.20
	900	0	3.28	1.17	35.7	.161	.0895	1.35
		2000	2.98	1.04	35.0	.161	.0887	1.29
		4000	2.73	.940	34.5	.161	.0878	1.24
		8000	2.34	.790	33.7	.161	.0869	1.18
	1100	0	2.05	.443	21.6	.0968	.0541	1.28
		2000	1.86	.392	21.1	.0968	.0536	1.23
		4000	1.70	.353	20.8	.0968	.0532	1.19
		8000	1.46	.296	20.3	.0968	.0525	1.14

TABLE V - 6 (CONT'D)

SiGe/SiGe TEDN-00-23B/TEDP-00-24

T_H	T_C	$\frac{C_I}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\mu\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
1600	500	0	6.92	5.67	81.8	.341	.188	1.33
		2000	6.25	5.00	80.0	.341	.187	1.27
		4000	5.70	4.48	78.6	.341	.185	1.23
		8000	4.87	3.73	76.6	.341	.182	1.16
	700	0	5.78	3.83	66.3	.287	.159	1.32
		2000	5.24	3.40	64.9	.287	.157	1.26
		4000	4.80	3.06	63.7	.287	.156	1.22
		8000	4.13	2.56	62.1	.287	.154	1.16
	900	0	4.62	2.38	51.6	.225	.126	1.28
		2000	4.20	2.12	50.5	.225	.125	1.23
		4000	3.85	1.91	49.6	.225	.123	1.19
		8000	3.31	1.60	48.2	.225	.122	1.14
	1100	0	3.42	1.28	37.3	.161	.0907	1.22
		2000	3.11	1.13	36.4	.161	.0896	1.18
		4000	2.85	1.02	35.7	.161	.0888	1.14
		8000	2.44	.848	34.7	.161	.0874	1.10
1800	500	0	8.11	8.11	100.	.404	.225	1.27
		2000	7.34	7.16	97.6	.404	.222	1.22
		4000	6.71	6.42	95.7	.404	.220	1.19
		8000	5.75	5.34	92.4	.404	.216	1.13
	700	0	6.99	5.89	84.2	.349	.196	1.26
		2000	6.35	5.22	82.2	.349	.193	1.21
		4000	5.82	4.69	80.6	.349	.191	1.17
		8000	5.01	3.92	78.2	.349	.189	1.12
	900	0	5.86	4.00	69.3	.288	.162	1.22
		2000	5.32	3.60	67.6	.288	.160	1.18
		4000	4.89	3.24	66.3	.288	.159	1.14
		8000	4.21	2.70	64.2	.288	.156	1.10
	1100	0	4.69	2.58	54.9	.223	.127	1.16
		2000	4.26	2.26	53.4	.223	.125	1.12
		4000	3.91	2.04	52.3	.223	.124	1.10
		8000	3.35	1.70	50.6	.223	.122	1.05

TABLE V-7
SUMMARY OF THERMOELECTRIC COUPLE PERFORMANCE PARAMETERS
3N/3P TEDN-00-52/TEDP-00-60
OPTIMUM EFFICIENCY OPERATION

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{P_L}{NA}$	$\frac{Q_L}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
900	200	0	7.00	1.43	20.5	.133	.0748	.845
		1500	6.31	1.26	19.9	.133	.0736	.839
		3000	5.74	1.12	19.4	.133	.0729	.834
		6000	4.85	.912	18.8	.133	.0714	.828
		12000	3.70	.664	17.9	.133	.0708	.809
	300	0	6.23	1.07	17.2	.120	.0678	.857
		1500	5.66	.948	16.8	.120	.0669	.849
		3000	5.19	.850	16.4	.120	.0660	.844
		6000	4.44	.702	15.8	.120	.0649	.836
		12000	3.44	.520	15.1	.120	.0637	.827
	400	0	5.35	.756	14.1	.105	.0596	.865
		1500	4.90	.675	13.8	.105	.0589	.857
		3000	4.52	.609	13.5	.105	.0582	.852
		6000	3.91	.509	13.0	.105	.0574	.842
		12000	3.08	.383	12.4	.105	.0562	.831
	500	0	4.37	.490	11.2	.088	.0502	.872
		1500	4.03	.441	10.9	.088	.0497	.865
		3000	3.74	.400	10.7	.088	.0492	.859
		6000	3.27	.338	10.4	.088	.0484	.849
		12000	2.61	.258	9.89	.088	.0475	.835
1000	200	0	7.65	1.80	23.6	.158	.0893	.865
		1500	6.98	1.60	23.0	.158	.0882	.857
		3000	6.41	1.44	22.5	.158	.0871	.850
		6000	5.51	1.20	21.7	.158	.0856	.841
		12000	4.30	.893	20.8	.158	.0838	.830
	300	0	6.91	1.40	20.2	.145	.0829	.867
		1500	6.35	1.26	19.8	.145	.0813	.867
		3000	5.87	1.14	19.4	.145	.0804	.859
		6000	5.10	.955	18.7	.145	.0793	.849
		12000	4.03	.722	17.9	.145	.0776	.836

TABLE V-7 (CONT'D)
3N/3P TEDN-00-52/TEDP-00-60

T_H	T_C	$\frac{C_T}{L}$	$\eta_{T/E}$	$\frac{PL}{NA}$	$\frac{QL}{NA}$	E_{OC}	E_L	$\frac{D_N}{D_P}$
°F	°F	$\mu\Omega CM^2/IN$	%	WATTS/IN	WATTS/IN	VOLTS	VOLTS	
1000	400	0	6.07	1.04	17.2	.131	.0743	.881
		1500	5.61	.942	16.8	.131	.0733	.874
		3000	5.22	.857	16.4	.131	.0727	.866
		6000	4.57	.728	15.9	.131	.0715	.857
		12000	3.67	.557	15.2	.131	.0701	.843
	500	0	5.14	.731	14.2	.114	.0648	.890
		1500	4.78	.664	13.9	.114	.0640	.881
		3000	4.46	.609	13.6	.114	.0635	.875
		6000	3.94	.521	13.2	.114	.0626	.865
		12000	3.20	.404	12.6	.114	.0614	.851
1100	200	0	8.05	2.16	26.8	.184	.104	.883
		1500	7.42	1.94	26.2	.184	.102	.876
		3000	6.88	1.76	25.7	.184	.101	.867
		6000	5.99	1.49	24.8	.184	.0997	.855
		12000	4.76	1.13	23.8	.184	.0976	.841
	300	0	7.36	1.73	23.5	.171	.0967	.892
		1500	6.82	1.57	23.0	.171	.0957	.883
		3000	6.35	1.43	22.5	.171	.0945	.878
		6000	5.58	1.22	21.8	.171	.0931	.866
		12000	4.49	.939	20.9	.171	.0913	.850
	400	0	6.56	1.34	20.4	.156	.0884	.901
		1500	6.11	1.22	19.9	.156	.0876	.890
		3000	5.72	1.12	19.6	.156	.0867	.884
		6000	5.07	.963	19.0	.156	.0854	.872
		12000	4.13	.750	18.2	.156	.0838	.855
	500	0	5.68	.990	17.4	.139	.0789	.908
		1500	5.31	.907	17.1	.139	.0782	.898
		3000	4.99	.837	16.8	.139	.0775	.890
		6000	4.45	.725	16.3	.139	.0765	.877
		12000	3.66	.572	15.6	.139	.0751	.862

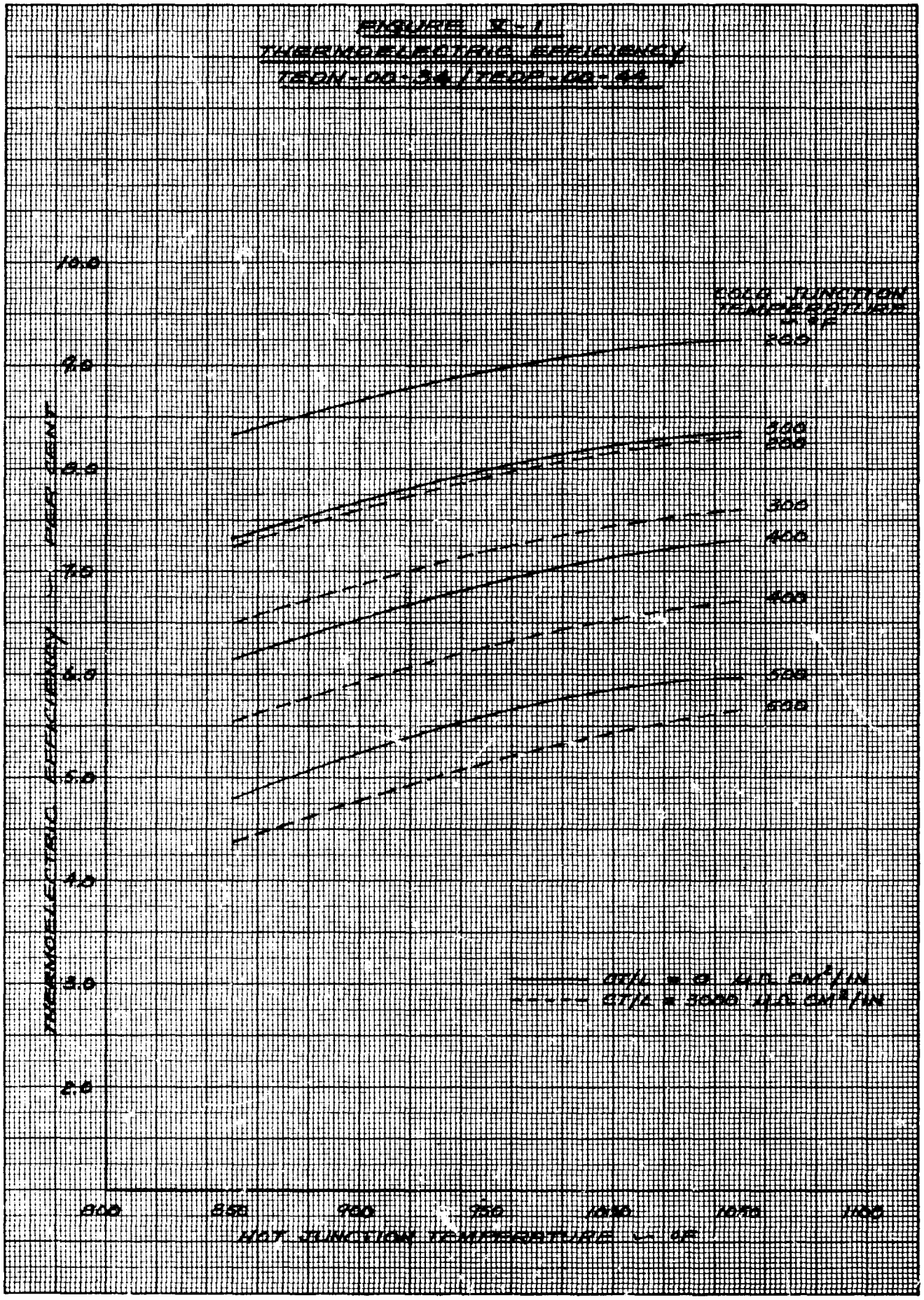
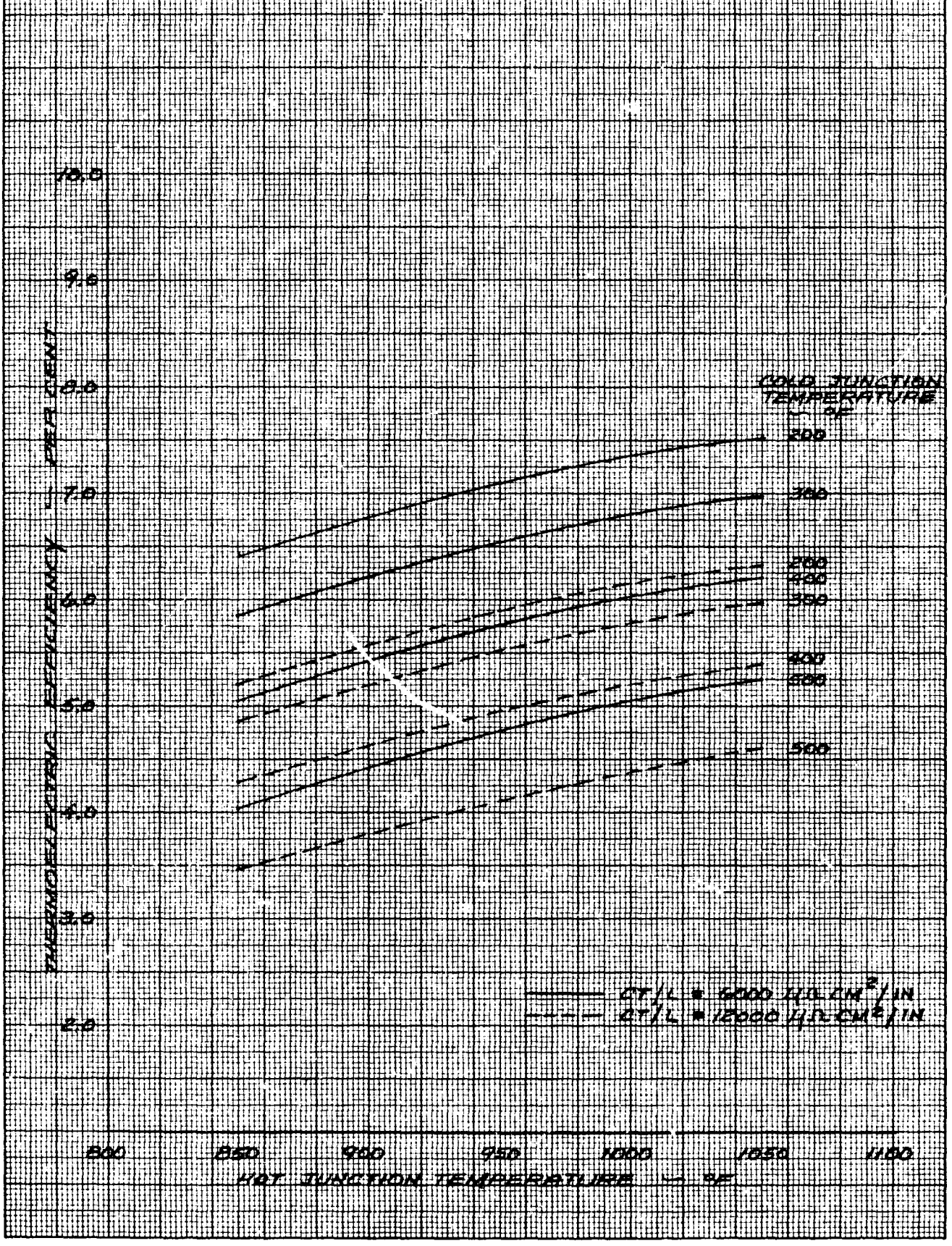


FIGURE V-1
THERMOELECTRIC EFFICIENCY
TEON-00-34/TEOP-00-44
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
THERMOELECTRIC EFFICIENCY PER CENT
COLD JUNCTION TEMPERATURE ~ °F
200
300
400
500
600
ΔT/L = 0 KB CM²/IN
ΔT/L = 3000 KB CM²/IN
800
850
900
950
1000
1050
1100
HOT JUNCTION TEMPERATURE ~ °F

FIGURE V - 2
THERMOELECTRIC EFFICIENCY
TEON-00-34/TEOP-00-44



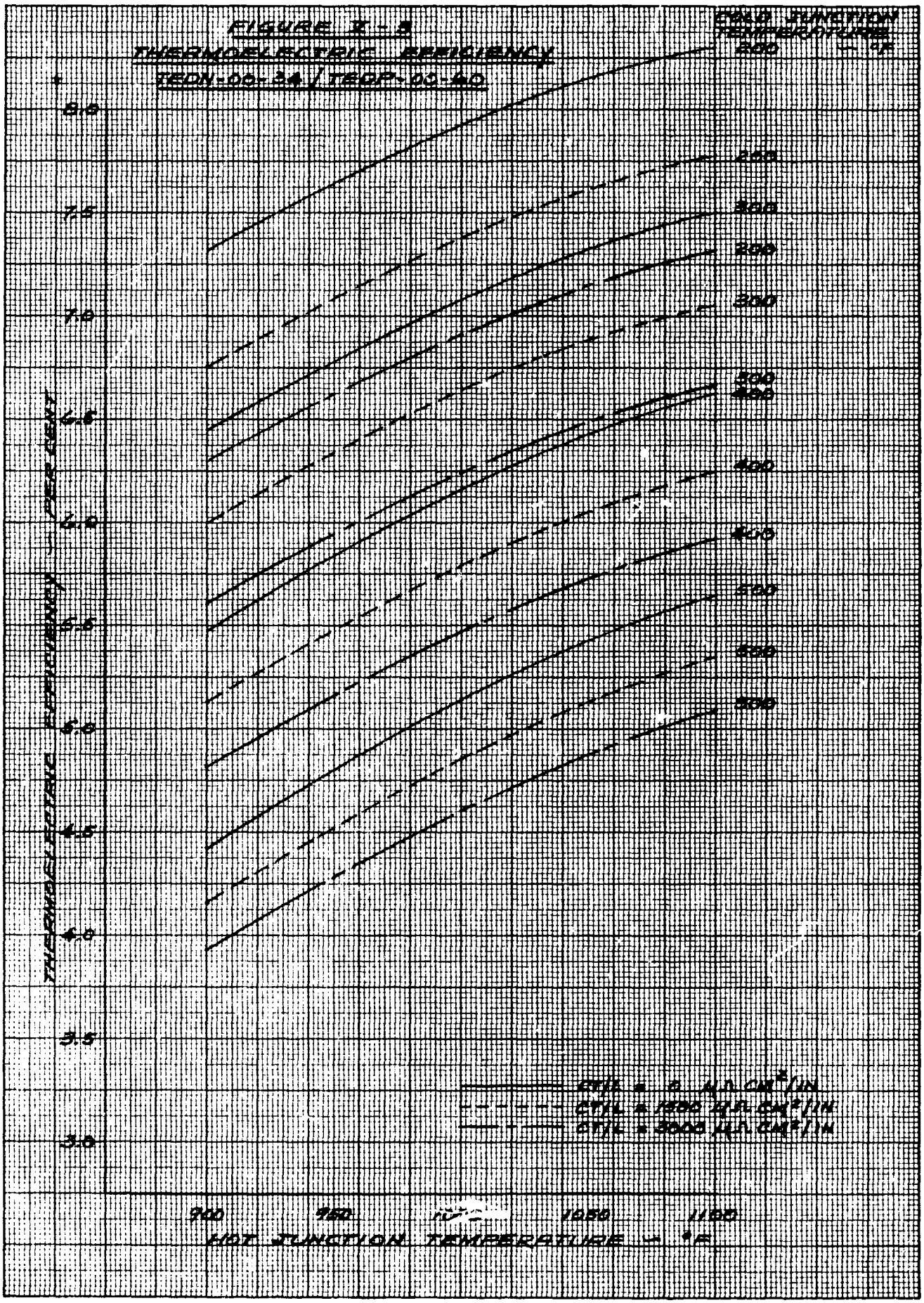


FIGURE K-3
THERMOELECTRIC EFFICIENCY
TEON-00-34 / TEOP-00-40
COLD JUNCTION TEMPERATURE
400 — °F
200
300
200
300
300
400
400
400
400
300
THERMOELECTRIC EFFICIENCY — PER CENT
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
CT/L = 0 μΩ CM²/IN
CT/L = 1200 μΩ CM²/IN
CT/L = 3000 μΩ CM²/IN
900
950
1000
1050
1100
HOT JUNCTION TEMPERATURE — °F

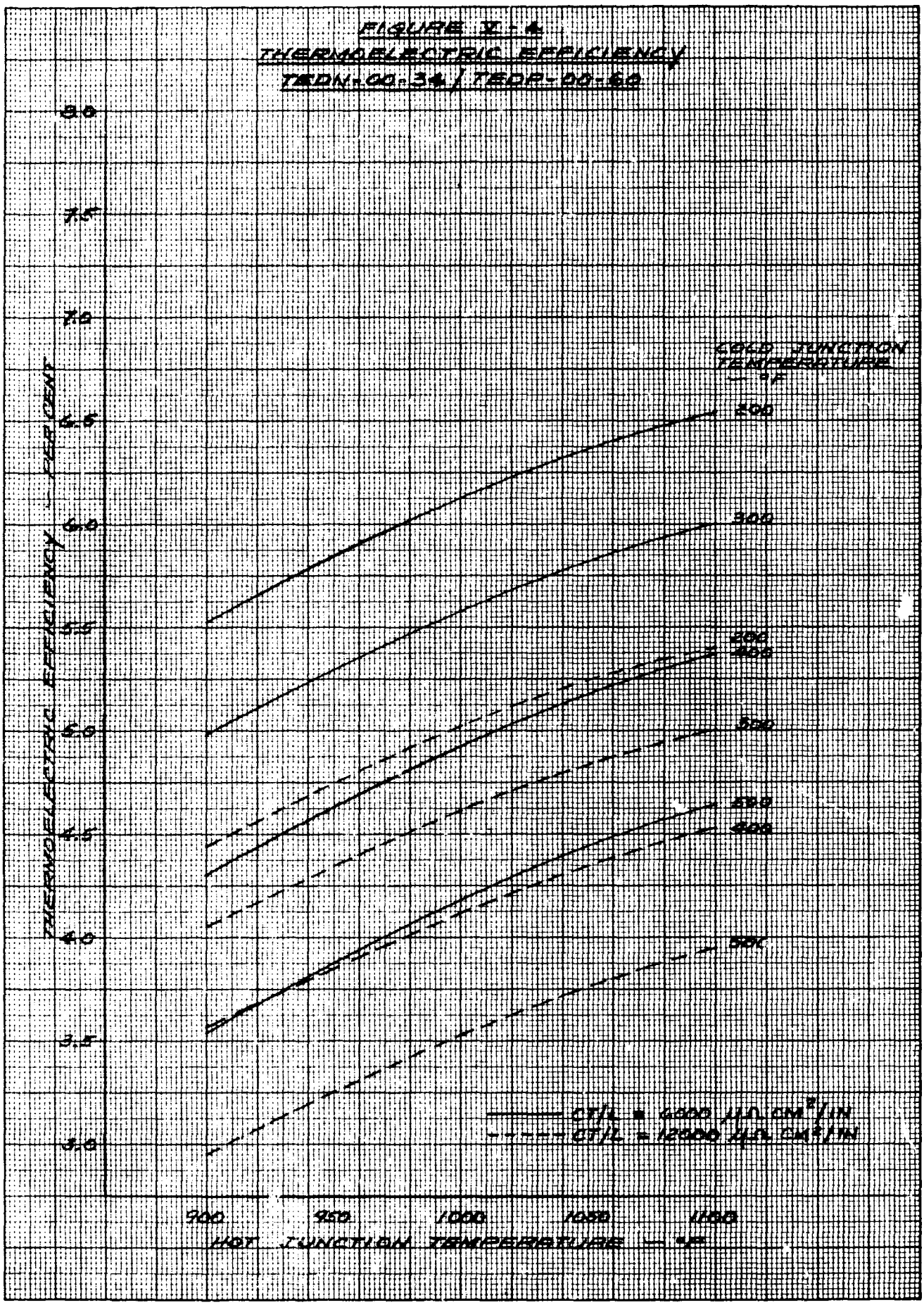


FIGURE V-4
THERMOELECTRIC EFFICIENCY
TEDN-00-34 / TEDP-00-60
THERMOELECTRIC EFFICIENCY — PER CENT
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
COLD JUNCTION TEMPERATURE — °F
500
300
200
400
500
500
400
500
900
950
1000
1050
1100
HOT JUNCTION TEMPERATURE — °F
CT/L = 6000 μΩ CM²/IN
CT/L = 12000 μΩ CM²/IN

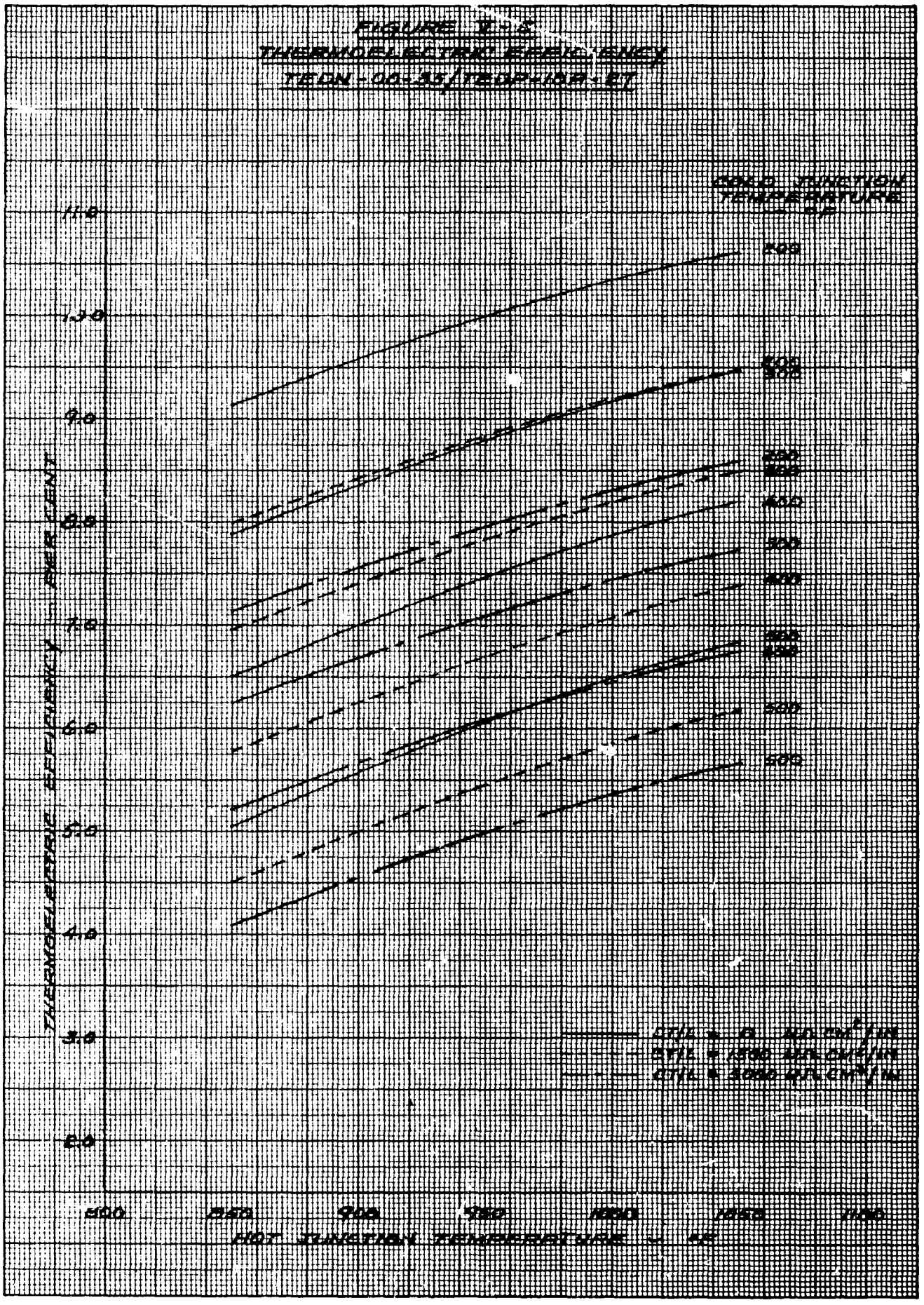


FIGURE V-6
THERMOELECTRIC EFFICIENCY
TECN-00-35/TEOP-100-ET
COLD JUNCTION TEMPERATURE
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
THERMOELECTRIC EFFICIENCY — PER CENT
HOT JUNCTION TEMPERATURE — °F
QTIL = 0, 100 CM²/IN
QTIL = 1500 MM CM²/IN
QTIL = 3000 MM CM²/IN

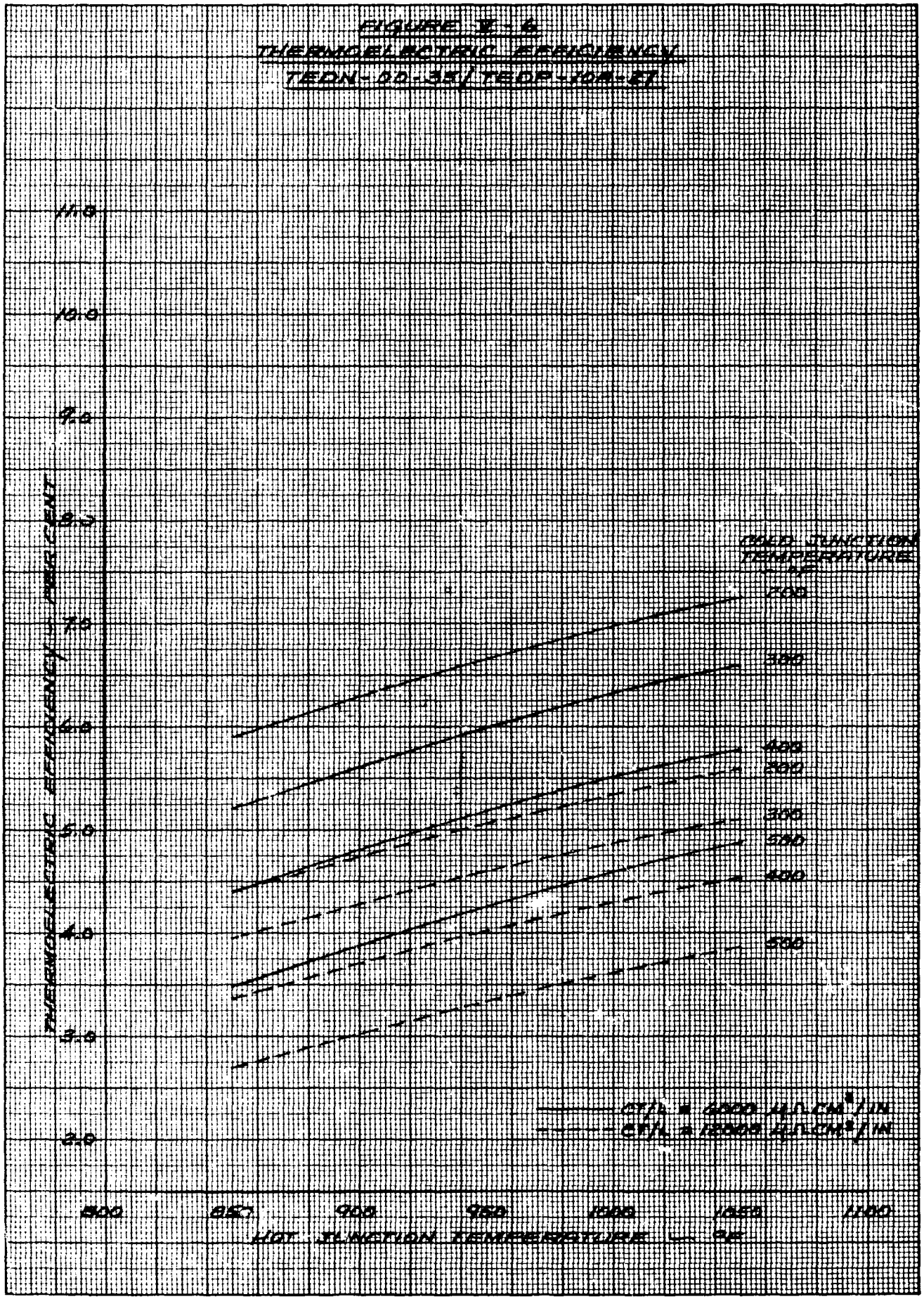


FIGURE V-6
THERMOELECTRIC EFFICIENCY
TEDN-00-35 / TEDP-104-67
THERMOELECTRIC EFFICIENCY — PER CENT
11.0
10.0
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
COLD JUNCTION TEMPERATURE — °F
200
300
400
200
300
500
400
500
σ/λ = 4000 μΩ-CM²/IN
σ/λ = 12000 μΩ-CM²/IN
800
850
900
950
1000
1050
1100
HOT JUNCTION TEMPERATURE — °F

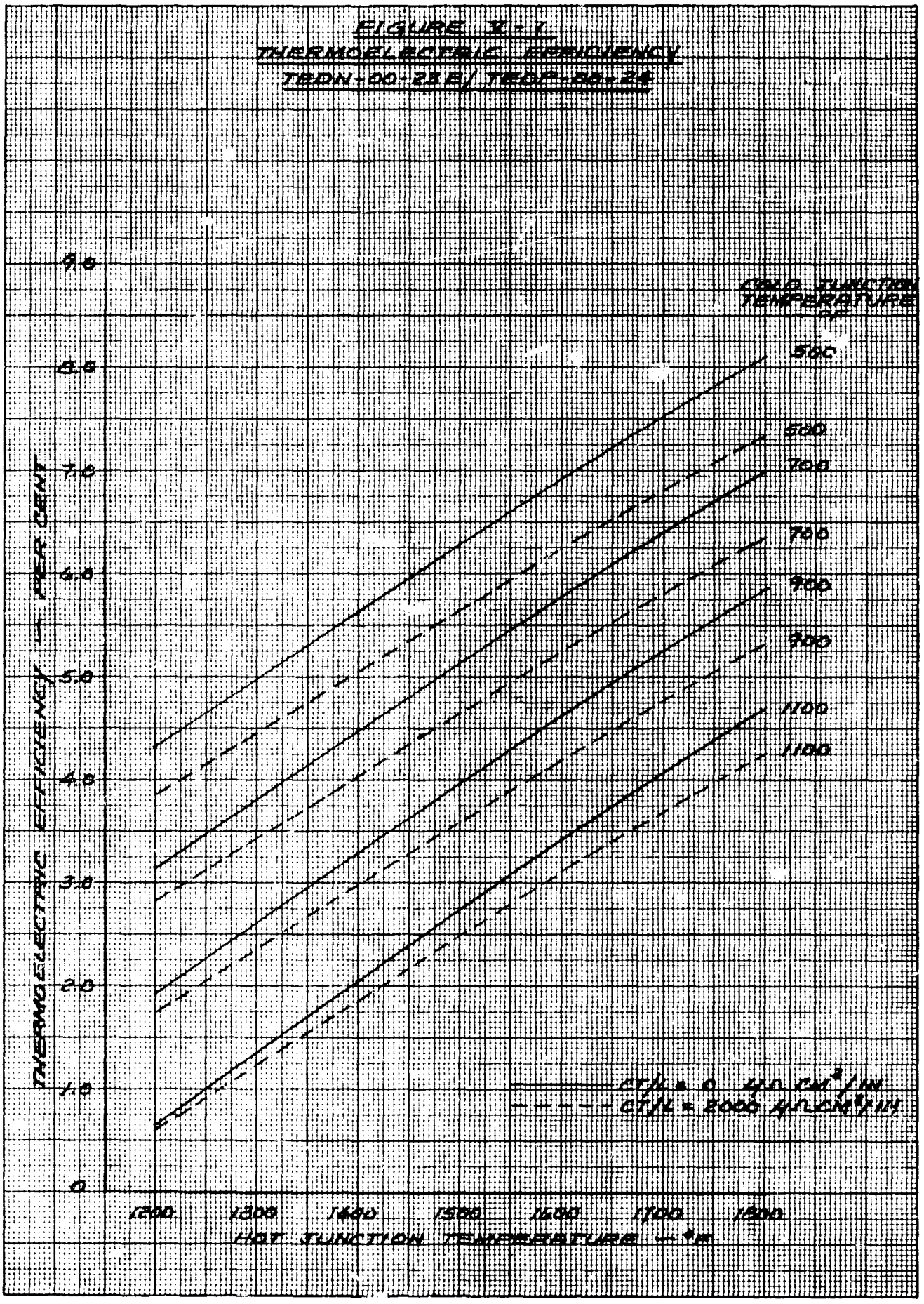


FIGURE V-1
THERMOELECTRIC EFFICIENCY
TEDN-00-23 E/ TEDF-00-24
COLD JUNCTION TEMPERATURE — °F
500
600
700
800
900
1000
1100
1200
THERMOELECTRIC EFFICIENCY — PER CENT
9.0
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1200
1300
1400
1500
1600
1700
1800
HOT JUNCTION TEMPERATURE — °F
CT/L = 0 μΩ CM²/IN
CT/L = 2000 μΩ CM²/IN

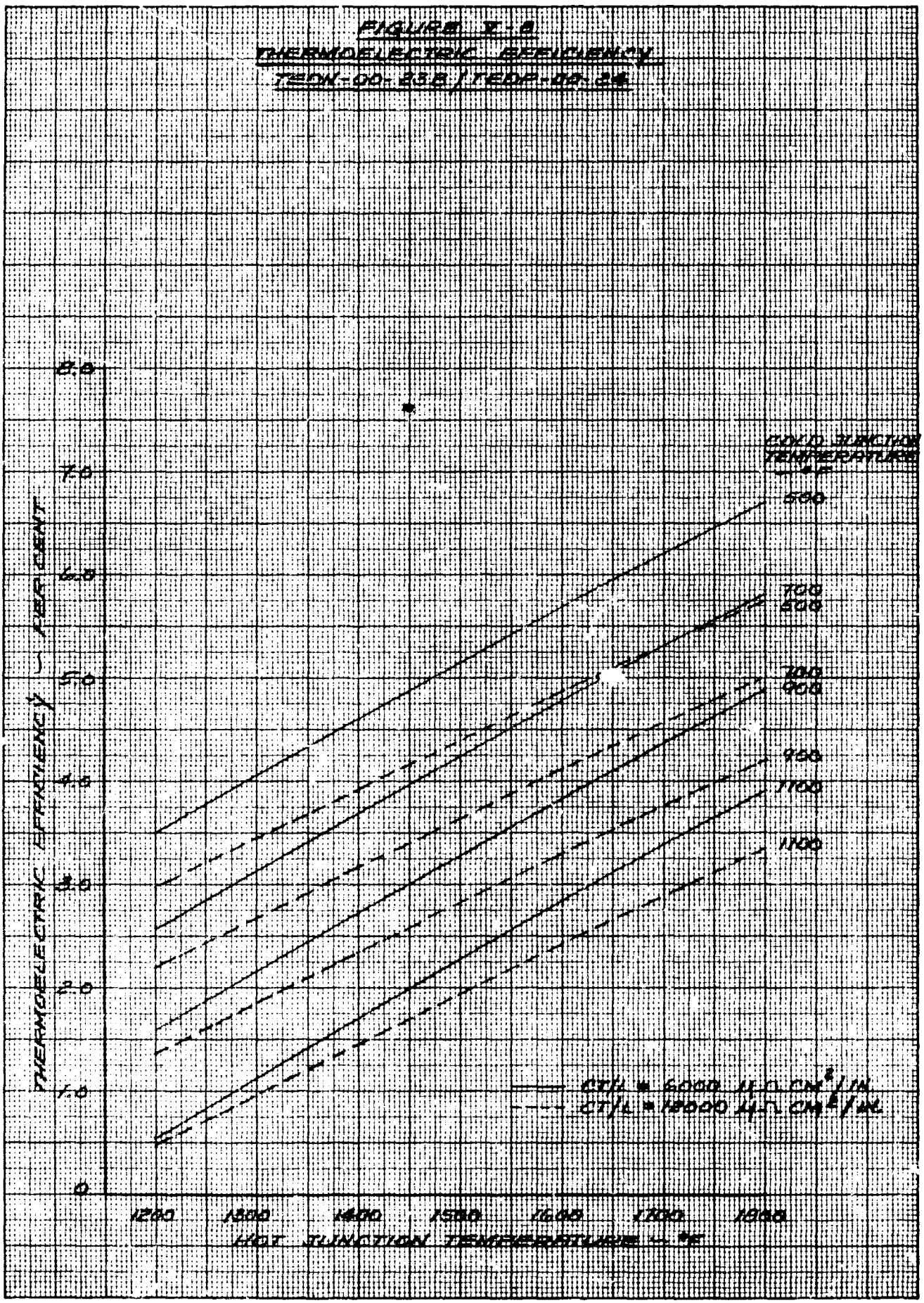


FIGURE V-8
THERMOELECTRIC EFFICIENCY
TEDW-00-23B / TEDP-00-24
THERMOELECTRIC EFFICIENCY — PERCENT
8.0
7.0
6.0
5.0
4.0
3.0
2.0
1.0
0
1200
1300
1400
1500
1600
1700
1800
HOT JUNCTION TEMPERATURE — °F
COLD JUNCTION TEMPERATURE — °F
500
700
600
700
900
950
1100
1100
CT/L = 6000 μΩ-CM²/IN.
CT/L = 12000 μΩ-CM²/IN.

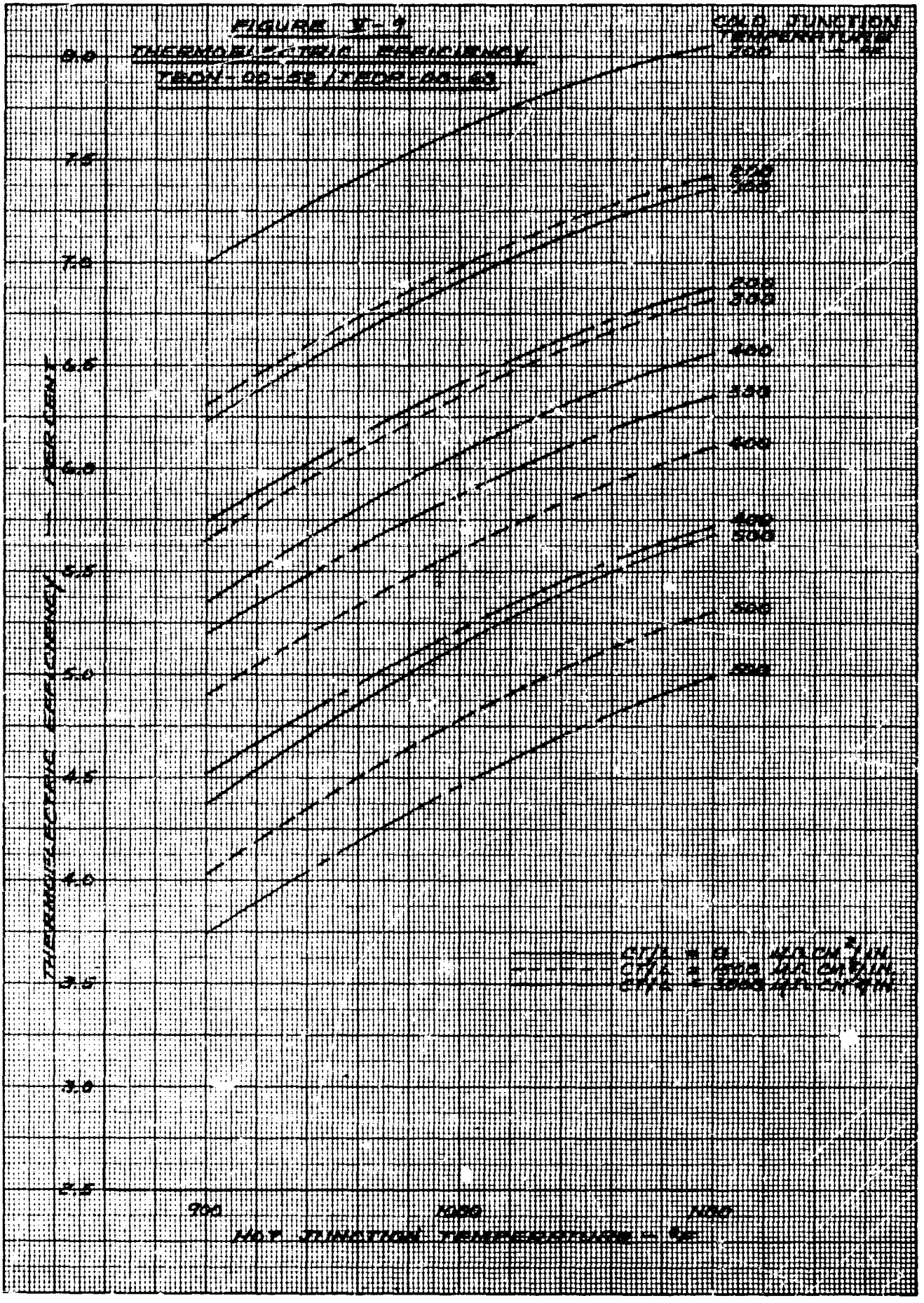


FIGURE V-9
THERMOELECTRIC EFFICIENCY
TEOY-00-42 / TEOP-00-63
COLD JUNCTION TEMPERATURE
300 — °K
THERMOELECTRIC EFFICIENCY — PER CENT
9.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
900
1000
1100
HOT JUNCTION TEMPERATURE — °K

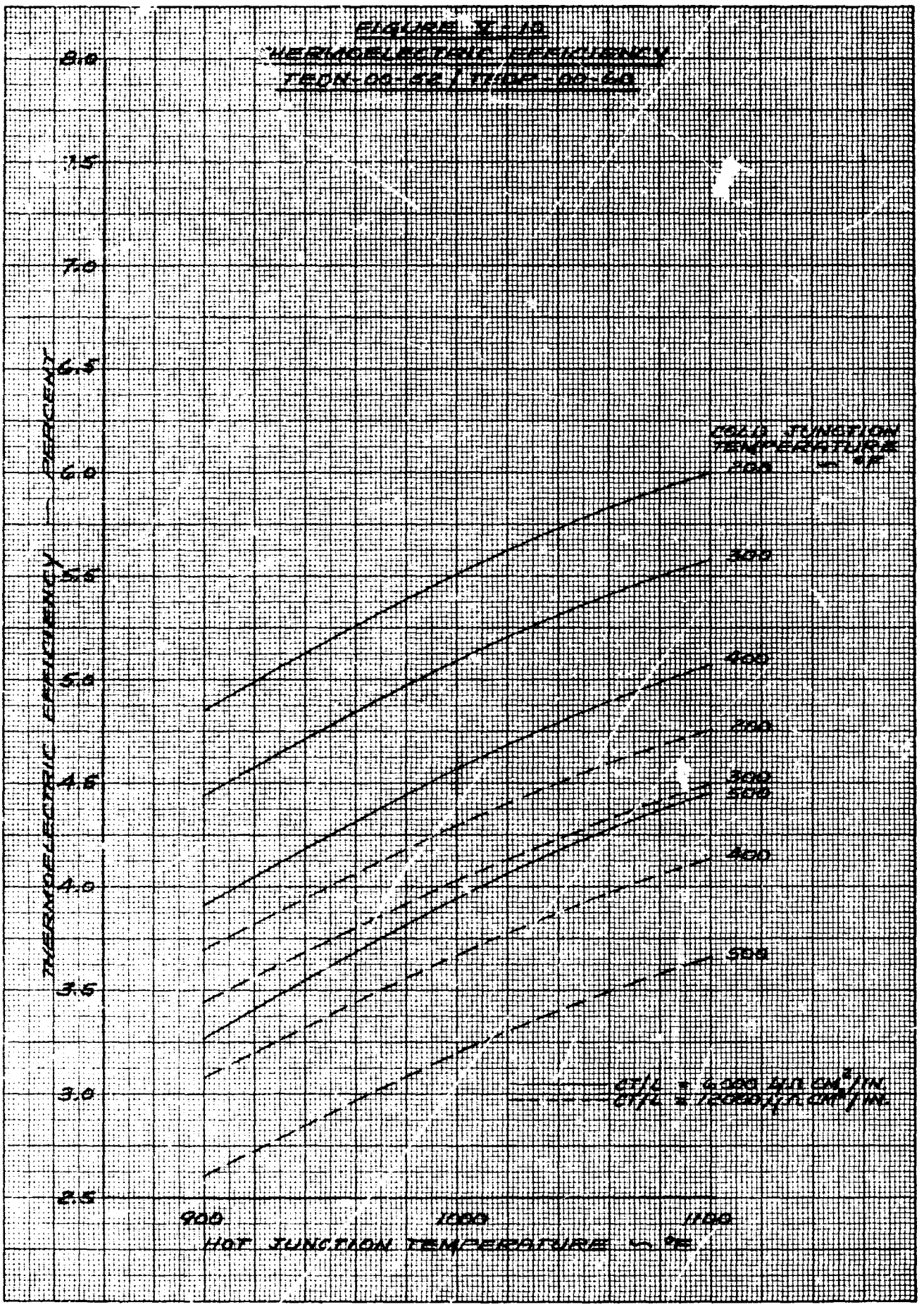


FIGURE X-18
THERMOELECTRIC EFFICIENCY
TEDN-00-52 / TEDP-00-60
THERMOELECTRIC EFFICIENCY — PERCENT
8.0
7.5
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
2.5
COLD JUNCTION TEMPERATURE ~ °F
200
300
400
200
300
500
400
500
900
1000
1100
HOT JUNCTION TEMPERATURE ~ °F

CHAPTER VI

Sample Design Solutions

This chapter presents three examples of typical uses of the thermoelectric calculation parametric results presented in Chapter V. These examples represent three of the most common requirements of conceptual thermoelectric design. Each is presented by first stating the requirement with the associated ground rules or known parameters. The second step consists of selecting independent variables which are not specified in the requirements. The rationale behind the selection of the independent variables is presented in the first example but not repeated in the next two examples where similarity exists. The third step is the presentation of a typical calculation used in completing the requirement. Finally, a summary of the resultant thermoelectric parameters is presented.

The three types of examples presented below can briefly be described as:

1. Knowing the power and voltage requirement, design an optimum efficiency RTG.
2. Having an existing heat source and knowing the thermoelectric material along with the maximum allowable operating temperature, design an RTG for maximum power at X volts.
3. Having a defined RTG, determine the performance parameters for a fixed thermal inventory and known cold junction temperature.

Design Sample No. 1

Requirement: Design the thermoelectric couples of an RTG which will produce a beginning of life power of 100 watts at 14 volts when operating at optimum efficiency load voltage.

Approach:

Material Selection

One of the first considerations in designing an RTG is to select the candidate thermoelectric material combination(s). Additional ground rules other than the ones stated above must be specified before materials selection can be made. The RTG environment (i.e., earth orbital, terrestrial, lunar surface etc.), heat source technology (i.e., existing design, existing technology, or anticipated technology) and mission life must be known. In a typical RTG design, the optimum material combination may not be evident until conceptual designs for several material combinations have been completed. The materials can then be selected for compliance with RTG ground rules (i.e., maximum efficiency or maximum specific power or design simplicity). For the purpose of this example, 2N PbTe in combination with TAGS/SnTe was chosen to indicate typical design procedure for one such material combination. The property data used for this material combination is TEDN-00-35 and TEDP-10A-27.

Parameter Selection

The design contact resistivity is based on experimental data of a system employing the material combination of interest. The contact resistivity of an operating thermoelectric device is determined through the PL/NA parameter. The PL/NA parameter is calculated by knowing the thermoelectric device design (i.e., number of couples (N), element length (L) and the cross section of the N and P elements (A), and interconnecting wiring resistance) plus the measured electrical power output. The power which appears in the PL/NA parameter is the gross electrical power generated by the thermoelectric elements. To obtain the gross power output of the operating thermoelectric device, the following calculation must be made:

$$P = P_N + I^2 R_E \qquad \text{(Eq. VI-1)}$$

where: P = Gross electrical power produced by elements (watts(e))

P_N = Measured (net) power (watts(e))

I = Measured current (amps)

R_E = Measured or calculated interconnecting conductance resistance (ohms)

After determining the PL/NA at the measured average hot and cold junction temperature, thermoelectric calculations such as those appearing in Table V-3 must be consulted to obtain the $C_{T/L}$ which correlates the experimental data. Once the C_T which predicts the experimental data is obtained, performance predictions for other temperatures and T/E designs utilize the experimentally based C_T. For 2N and TAGS/SnTe, the SNAP 19 and SNAP 29 hardware data indicates that a $C_T \approx 0$ should be used in conjunction with TEDN-00-35 and TEDP-10A-27 thermoelectric data to predict the observed performance. Therefore $C_T = 0$ will be used in this design example.

As the hot junction temperature is increased, the Carnot efficiency of the device increases (assuming a constant cold junction temperature) resulting in a thermoelectric efficiency increase. Therefore the design hot junction temperature of the thermoelectric material is usually maximized consistent with the thermoelectric material stability and heat source compatibility. Long-life systems will generally be designed at a lower hot junction temperature than short-life systems. These sample calculations will be performed for a range of hot junction temperatures to show the implications of variable hot junction temperatures on thermoelectric design. In the final selection of the sample RTG design, a hot junction temperature of 1050°F, which is consistent with a short RTG life, will be selected to size the T/E elements.

The design cold junction temperature selection is usually based on RTG environment and system considerations. The relative importance of maximum efficiency, maximum specific power, and RTG envelope will influence the design cold junction temperature. As the cold junction temperature is decreased, the Carnot efficiency increases causing a decrease in fuel inventory, fuel cost and heat which must be rejected to the environment. However, as the cold junction is lowered the heat rejection temperature must be lowered. A lower heat rejection temperature necessitates a larger heat rejection system which increases the weight of the heat rejection system. If maximum efficiency is of prime importance, major emphasis will be placed on lowering the cold junction temperature. However, if maximum specific power is desired, the increasing weight of the heat rejection system may dictate a higher cold junction temperature. An envelope constraint on the RTG heat rejection system will often limit reduction of the cold junction temperature.

A typical procedure for selecting the design cold junction temperature includes performing thermoelectric calculations over a range of cold junction temperatures. From the thermoelectric calculations of thermal energy required by the elements ($Q_{T/E}$) the heat rejection requirements are determined as shown below:

$$Q_{rej} = Q_{T/E} + Q_L - P_N \qquad \text{(Eq. VI-2)}$$

where: Q_{rej} = Heat which must be rejected to environment (watts(t))

$Q_{T/E}$ = Energy required by the elements to maintain the assumed hot and cold junction temperature (watts(t))

Q_L = Parasitic heat losses through the RTG at the assumed temperature (watts(t))

The size and weight of the heat rejection system which meets the above requirements must be determined. The weight of the heat rejection system is then added to the heat source, thermoelectric conversion assembly, plus any other weights to obtain the total RTG weight. From the RTG weight, the specific power of the RTG can be determined as a function of the cold junction temperature. Final cold junction temperature selection can be based on system design goals such as those mentioned above.

In the design example presented, the cold junction temperature has been varied from 200°F up to 500°F. The T/E parameters required as input in determining system weight are also presented (i.e., number and size of couples plus required thermal energy). System weights will not be determined in this example due to the detail required to obtain realistic values. However based on past work with an earth orbital RTG which required maximum specific power, a cold junction temperature of 400°F is typical and will be selected for this example. Typical terrestrial generators will have much lower cold junction temperatures (~200°F or lower) because of: 1) less emphasis on specific power, 2) emphasis on fuel costs, and 3) enhanced heat rejection capability.

The significant geometry factor in thermoelectric element sizing is L/A. Two approaches which can be taken to design the elements are:

1) Select element length and then solve for optimum element cross section (element diameter for cylindrical elements)

2) Select element cross section (diameter) and solve for the optimum length.

The approach taken in this sample is to assume a cylindrical element length (both elements of the same length for mechanical design simplicity) and then solve for the element diameters. The element length selection affects the weight of the T/E module and the resultant heat flux required from the heat source and which must be rejected by the heat rejection hardware. Compatibility of the heat source and heat rejection subsystem must therefore

be evaluated in selecting an element length. For the purpose of this design example, an element length of 0.5 inches will be used.

Typical Calculation

The voltage of an RTG is directly proportional to the number of couples placed in series in the electrical circuit.

$$V_S = N_S V_C \qquad \text{(Eq. VI-3)}$$

where:

V_S = Voltage of RTG (volts)

N_S = Number of couples in series

V_C = Load voltage per couple (volts)

For a given RTG voltage requirement (in our case 14 volts at maximum efficiency) the number of couples in series is obtained by utilizing the calculated voltage per couple at maximum T/E efficiency (function of hot and cold junction temperature). The total number of couples in the RTG is obtained by multiplying the above number of couples in series times the number of parallel circuits.

$$N = N_P N_S \qquad \text{(Eq. VI-4)}$$

where:

N = Number of couples in RTG

N_P = Number of parallel circuits.

Parallel circuits provide redundancy in the electrical circuit. Therefore, the number of parallel circuits selected for a given RTG design is dependent on the system reliability goal. For the purpose of this example, two parallel circuits will be considered. The top portion of Fig. VI-1 shows the number of couples required for a series parallel generator to produce 14 volts when operating at peak efficiency load voltage. It can be seen that the number of required couples increases as the hot junction temperature is decreased and the cold junction temperature is increased. At the assumed design hot junction temperature

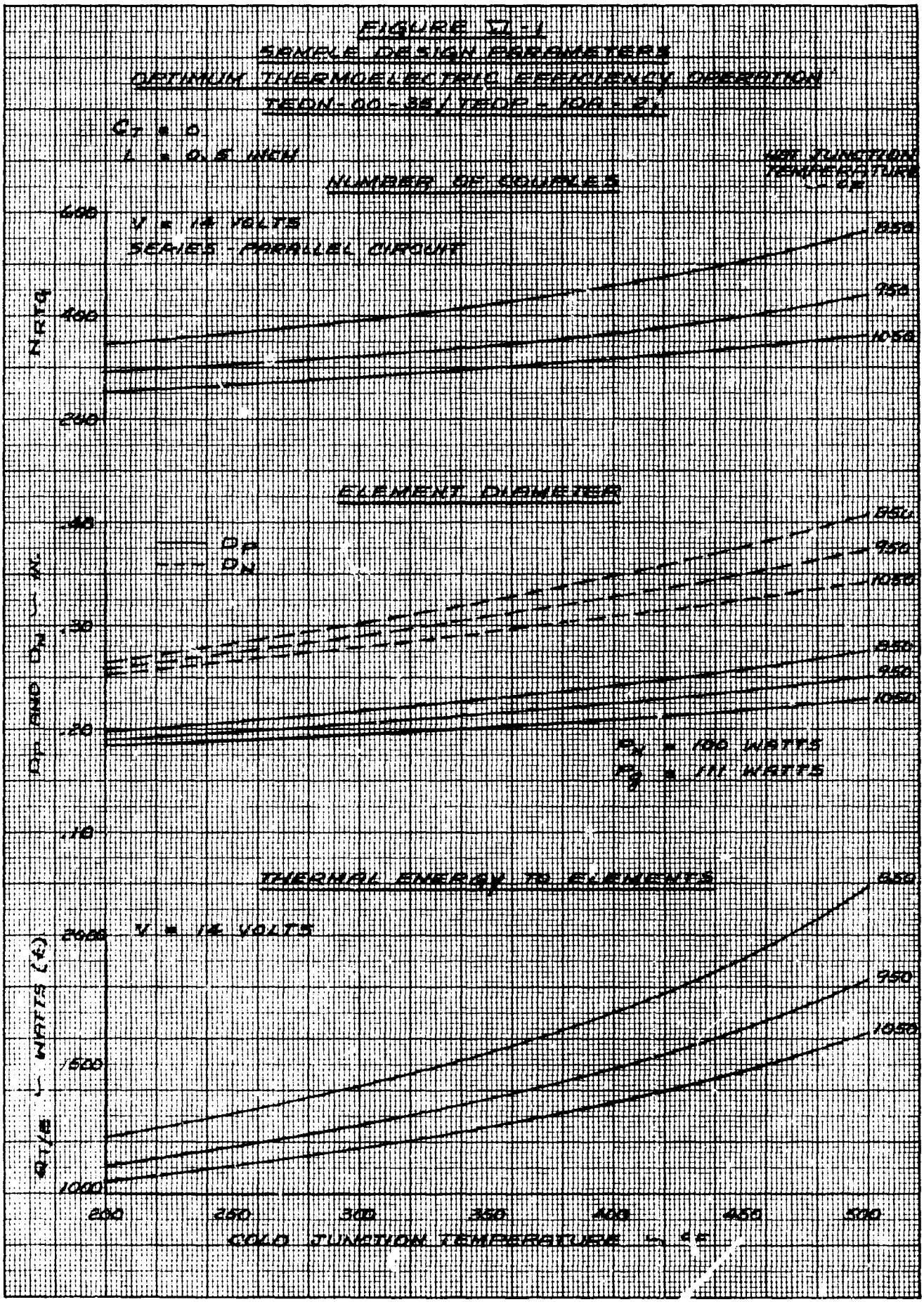


FIGURE VI-1
SAMPLE DESIGN PARAMETERS
OPTIMUM THERMOELECTRIC EFFICIENCY OPERATION
C_J = 0
L = 0.5 INCH
HOT JUNCTION TEMPERATURE ~ °F
NUMBER OF COUPLES
V = 14 VOLTS
SERIES - PARALLEL CIRCUIT
N_{RTG}
600
400
200
850
950
1050
ELEMENT DIAMETER
D_P
D_N
D_P AND D_N ~ IN.
.40
.30
.20
.10
P_N = 100 WATTS
P_P = 111 WATTS
THERMAL ENERGY TO ELEMENTS
V = 14 VOLTS
Q_T/P ~ WATTS (t)
2000
1500
1000
200
250
300
350
400
450
500
COLD JUNCTION TEMPERATURE ~ °F

(i.e., 1050°F) and cold junction temperature (i.e., 400°F), the required number of couples is seen to be 314. Therefore this RTG must have 157 pairs of thermoelectric couples in series.

The instantaneous open circuit voltage of the RTG is determined by:

$$E_O = N_S E_{OC} \qquad \text{(Eq. VI-5)}$$

where: E_O = RTG open circuit voltage

E_{OC} = Open circuit voltage per couple

N_S = 157 for the assumed T_H = 1050°F and T_C = 400°F

From Table 3, the value of E_{OC} is 0.154 volts. The resultant instantaneous open circuit voltage of the RTG is 24.2 volts.

The electrical power output of a thermoelectric device is directly proportional to the number of couples, couple cross section and inversely proportional to the element length. For constant hot junction temperature, cold junction temperature and $C_{T/L}$, the expression for power output at optimum efficiency load voltage is:

$$P = C_1 N A/L \qquad \text{(Eq. VI-6)}$$

where: C_1 = Unique constant for fixed T_H, T_C, $C_{T/L}$, and shape factor ratio

A = Cross section of the Nelement plus the P element

Solving for C_1 yields:

$$C_1 = \frac{PL}{NA} \quad (T_H, T_C, C_{T/L}) \qquad \text{(Eq. VI-7)}$$

Substitution of Eq. VI-7 into Eq. VI-6 yields the following expression for gross power output of a thermoelectric device.

$$P = \left[\frac{NA}{L}\right] \cdot \left[\frac{PL}{NA} \quad (T_H, T_C, C_{T/L})\right] \qquad \text{(E . VI-8)}$$

The value of $PL/NA\ (T_H, T_C, C_{T/L})$ as a function of the independent variables is calculated by the Isotopes thermoelectric code and is presented in tabular form in Tables V-3 through V-7 for several of the most often used material combinations. The shape factor ratio (presented in this case in terms of diameter ratio) associated with the above thermoelectric performance parameter is also presented in Tables V-3 through V-7.

The couple cross sectional area required to produce a given power can be determined by solving Eq. VI-8 for element area and substituting the known factors in the expression:

$$A = \left[\frac{PL}{N}\right] \cdot \left[\frac{1}{\frac{PL}{NA}\ (T_H, T_C, C_{T/L})}\right] \qquad \text{(Eq. VI-9)}$$

Since the power calculated by the Isotopes thermoelectric code only considers the thermoelectric elements, the net power of the RTG is obtained by subtracting the extraneous Joule heating power loss (See Eq. VI-1) from the gross power. When designing an RTG to meet a specified net power level, Joule heating power loss must be considered. For the purpose of a conceptual design, the Joule losses are usually expressed as a fraction of the gross power (or net power). Prudent design of the electrical circuit usually yields a Joule heating loss of 5→15% of the gross power.

The magnitude of this factor is affected by the weight goals of the RTG. If a terrestrial generator is being designed where weight is not critical, larger interconnecting straps will be used resulting in lower losses. However, in a space RTG where the weight and specific power are very important, the conductors might be sized to maximize the specific power resulting in lower weight connectors (i.e., higher losses). The factor which is assumed for the purposes of a conceptual design must be compared with the predicted losses when the complete electrical circuit is designed in detail. Adjustments in the gross power level or thermoelectric element sizing may be required to obtain a net electrical power which is compatible with the required net RTG power.

In this design example, a factor of 10% will be used yielding the following:

$$P = P_N + .1P \qquad \text{(Eq. VI-10)}$$

Solution of P and substitution of 100 watts as the net power design value yields a gross power requirement of 111 watts.

The addition of the extraneous resistance in the RTG changes the E-I characteristics by an effective increase in the internal resistance of the RTG. The resultant change in the E-I characteristics can change the optimum load voltage per couple. Previous Isotopes experience utilizing an option in the Isotope thermoelectric code, which generates the E - I characteristics of a fixed geometry thermoelectric design, indicates that the shift in optimum efficiency load voltage is small for reasonable values of extraneous resistance. Therefore the gross optimum load voltage is considered adequate for conceptual design purposes. This means that the number of couples determined through the gross optimum load voltage is adequate for conceptual designs which consider typical extraneous resistance (up to 20% of the elements resistance).

Substitution of the gross power requirement and the assumed element length into Eq. VI-9 yields:

$$A = \frac{55.5 \text{ watt-in.}}{N} \cdot \left[\frac{PL}{NA}(T_H, T_C, C_{T/L})\right]^{-1} \qquad \text{(Eq. VI-11)}$$

Since the number of couples required to produce 14 volts is also a function of the hot and cold junction temperature as shown in Fig. VI-1, the expression for couple cross section becomes:

$$A = \frac{55.5 \text{ watts-in.}}{\eta(T_H, T_C)} \left[\frac{PL}{NA}(T_H, T_C, C_{T/L})\right]^{-1} \qquad \text{(Eq. VI-12)}$$

In most practical cases, the elements are right circular cylinders and therefore cylinders will be assumed in this example. Since A is the sum of the cross section of the N element and the P element, solution of the P element diameter in terms of the total cross section and the diameter ratio (i.e., thermoelectric calculations output D_N/D_P) required for optimum efficiency yields:

$$D_P = \left\{ \frac{4A}{\pi \left[\left(\frac{D_N}{D_P} \right)^2 + 1 \right]} \right\}^{1/2} \qquad \text{(Eq. VI-13)}$$

The N element diameter is then calculated through Eq. VI-14.

$$D_N = \left[\frac{D_N}{D_P} \quad (T_H, T_C) \right] \cdot \left[D_P \right] \qquad \text{(Eq. VI-14)}$$

The center portion of Fig. VI-1 shows the N element and P element diameters required to produce a gross power of 111 watts at 14 volts. For a typical design point of 1050°F hot junction temperature and 400°F cold junction temperature, D_P = 0.211 inches and D_N = 0.310 inches meet the design constraints.

In order to integrate the thermoelectric couples into the RTG system, the thermal energy required to maintain the assumed temperatures (or produce the desired power) must be known. This is obtained by dividing the gross power by the thermoelectric efficiency.

$$Q_{T/E} = \frac{P}{\eta} \qquad \text{(Eq. VI-15)}$$

where: $Q_{T/E}$ = Thermal energy which must enter the thermoelectric elements (watts(t))

η = Thermoelectric efficiency

A second expression for determining the thermal energy required by the elements can be obtained by substituting Eq. VI-8 into Eq. VI-15 as shown:

$$Q_{T/E} = \frac{\frac{NA}{L} \cdot \frac{PL}{NA} \; (T_H, T_C, C_{T/L})}{\eta \; (T_H, T_C, C_{T/L})} \qquad \text{(Eq. VI-16)}$$

For convenience of calculation, a thermoelectric performance parameter is defined which combines the power and efficiency terms above. The resultant expression is:

$$Q_{T/E} = \frac{NA}{L} \cdot \frac{QL}{NA} \; (T_H, T_C, C_{T/L}) \qquad \text{(Eq. VI-17)}$$

The QL/NA parameter is included in the tabulated thermoelectric data presented in Tables V-3 through V-7.

The lower portion of Fig. VI-1 shows the thermal energy required by the thermoelectric elements to produce the 111 watts of gross power as a function of the design hot and cold junction temperatures. From this figure, the advantages of a high hot junction temperature are apparent. The tradeoffs of operating temperature versus fuel requirement are seen on this figure. For the sample design point we are considering (T_H = 1050°F, T_C = 400°F) the required thermal energy for the elements is 1350 watts(t)).

The total thermal energy which must be placed in the heat source is obtained by adding the parasitic heat losses to the above determined element requirement. Detailed heat losses can only be determined after the mechanical design of the RTG is defined since heat losses are highly configuration dependent. However, in conceptual designs where an order of magnitude of heat source fuel inventory is desired, an estimate of heat losses can be useful in designing the heat source. Typical heat loss factors for RTG's range from 5 to 30% of the total thermal inventory. If a factor of 15% is assumed for

this example, the total heat source thermal inventory would be 1590 watts(t). The system efficiency is then found by dividing the net power output by the total heat source thermal inventory:

$$\eta_S = \frac{P_N}{Q_{HS}} = \frac{100}{1590} = 6.29\% \qquad \text{(Eq. VI-18)}$$

Table VI-1 presents a summary of the thermal and electrical characteristics of the hypothetical RTG used in this design example.

TABLE VI-1

Summary of Design Sampe No. 1 RTG Thermal and Electrical Characteristics Optimize for Power and Weight

Materials	2N PbTe and TAGS/SnTe
Net Power (watts(e))	100
Gross Power (watts (e))	111
Load Voltage (volts)	14
Instantaneous Open Circuit (volts)	24.2
Optimum Efficiency Load Voltage	
Series Parallel Circuitry	
Hot Junction Temperature (°F)	1050
Cold Junction Temperature (°F)	400
Number of Couples	314
Element Length (in)	0.5
Length SnTe (in.)	0.1
Element Diameter	
N Element (in)	0.31
P Element (in)	0.211
Thermal Energy to Elements (watts(t))	1350
Assumed Thermal Losses (watts(t))	240
Heat Source Thermal Inventory (watts(t))	1590
RTG System Efficiency (%)	6.29

Design Sample No. 2

Requirement: Design a 2N PbTe and TAGS/SnTe RTG which will utilize an existing 1500 watt(t) heat source. The RTG will be operated at maximum efficiency load voltage and the design hot junction temperature shall be 1050°F. The thermoelectrics should be designed to produce maximum power at 14 volts.

Approach: The design of this RTG is approached through a heat balance on the cold junction temperature. After selecting a design cold junction temperature based on heat rejection capability, the required number of couples and the shape factor (L/A) can be determined through the thermoelectric calculation tabulation. The element cross sectional area and length are selected to be consistent with the lateral surface area of the heat source to be employed in the RTG.

To perform the heat balance on the cold junction temperature requires the knowledge of the system heat rejection capability as a function of cold junction temperature. The purpose of this design example is to show the thermoelectric calculations and the method of integrating the thermoelectric couples into the RTG system. Therefore the cold junction at which a heat balance occurs will be assumed without looking at an actual heat rejection subsystem.

Compatibility of the elements cross sectional area with the lateral surface area of the heat source is also required for a design example of this type. A conceptual design with layouts is required to establish this compatibility. In this example, a compatible element cross section will be assumed to show a typical design approach.

Material Selection: The thermoelectric material has been specified as 2N PbTe and TAGS/SnTe. As noted in the first design example, the material property data which will be used is TEDN-00-35 and TEDP-10A-27. Therefore

thermoelectric calculations are those tabulated in Table V-5.

Parameter Selection

A design contact resistivity of 0, hence $C_{T/L} = 0$, will be used in this example. The basis of this selection was given under example 1. When the materials under consideration require a C_T other than 0 to correlate the experimental performance, the parametric study must consider the variable $C_{T/L}$ as the element length is varied. However the basic approach to designing the RTG is not altered---only the number of calculations are increased.

In this example the design hot junction temperature has been specified to be 1050°F. The considerations which must be evaluated in selecting a hot junction temperature are discussed under design example 1.

The design cold junction temperature will be defined by the heat rejection capability of the RTG. The heat rejection requirement is equal to the total heat source thermal inventory minus the electrical energy generated by the thermoelectric elements.

$$Q_{rej} = Q_{HS} - P_N \qquad \text{(Eq. VI-18)}$$

where:

Q_{HS} = Heat source thermal inventory.

As can be seen from this expression, the final heat rejection requirement can not be determined until the net power is known. However, the net power is such a small portion (~5-10%) of the total thermal inventory that the uncertainties in determining the power output do not significantly influence the heat rejection requirement (or cold junction temperature). The design cold junction temperature is the temperature at which the heat rejection capability equals the heat rejection requirement.

The gross power output of a thermoelectric device is equal to the thermoelectric efficiency times the amount of heat entering the thermoelectric

elements:

$$P = \eta_{T/E}^{(T_C)} \cdot Q_{T/E} \qquad \text{(Eq. VI-19)}$$

where: (T_C)

$\eta_{T/E}$ = Thermoelectric efficiency as a function of cold junction at 1050°F hot junction temperature and $C_{T/L} = 0$.

$Q_{T/E}$ = Heat entering the thermoelectric elements.

The amount of heat entering the thermoelectric elements is obtained by subtracting the parasitic heat losses from the total heat source fuel inventory.

$$Q_{T/E} = Q_{HS} - Q_L \qquad \text{(Eq. VI-20)}$$

The heat losses in an RTG are dependent on the configuration and temperature distribution. At this stage of an RTG design neither the configuration or temperature distribution are known. Therefore the heat losses must be handled parametrically until a conceptual design is developed resulting in the heat losses being determined. As discussed in design example 1, typical RTG's will have heat losses from 5% to 30% of the total fuel inventory. Substitution of Eq. VI-20 into Eq. VI-19 yields an expression of gross power in terms of the thermoelectric efficiency and the heat losses.

Design example number 1 discussed the approach to obtaining the net power output from the gross power output. If a Joule loss of 10% of the total gross power is again assumed, the net power output of a thermoelectric device is given below:

$$P_N \quad 0.9 \left[\eta_{T/E}^{(T_C)} \right] \left[Q_{HS} - Q_L \right] \qquad \text{(Eq. VI-21)}$$

The top half of Fig. VI-2 shows the resultant net power output for cold junction temperature from 200°F to 500°F parametric in heat losses. In this example, the heat losses were varied from 5% to 20% of the total thermal inventory.

Substitution of Eq. VI-21 into Eq. VI-18 yields the following expression for the heat rejection requirements.

$$Q_{rej} = Q_{HS} \left[1 - .9 \, \eta_{T/E}^{(T_C)} \right] + .9 \, \eta_{T/E}^{(T_C)} \, Q_L \quad \text{(Eq. VI-22)}$$

The bottom half of Fig. VI-2 shows the heat rejection requirement as a function of cold junction and heat losses. This figure shows that the heat rejection requirement is not significantly influenced by the two variables. As mentioned earlier, the heat rejection capability is now required as a function of cold junction temperature in order to complete this heat balance. For the purpose of this example a heat rejection capability of 1385 watts(t) at 300°F cold junction temperature will be assumed resulting in a 300°F cold junction temperature if the heat losses are 150 watts(t). The 300°F cold junction temperature will be assumed at this time until the conceptual design is completed. An iteration on cold junction temperature may be necessary after the conceptual design is developed because of heat loss variations which alter the heat rejection requirement slightly. As mentioned before Fig. VI-2 indicates that a large error in heat loss estimate will not significantly alter the resultant cold junction temperature.

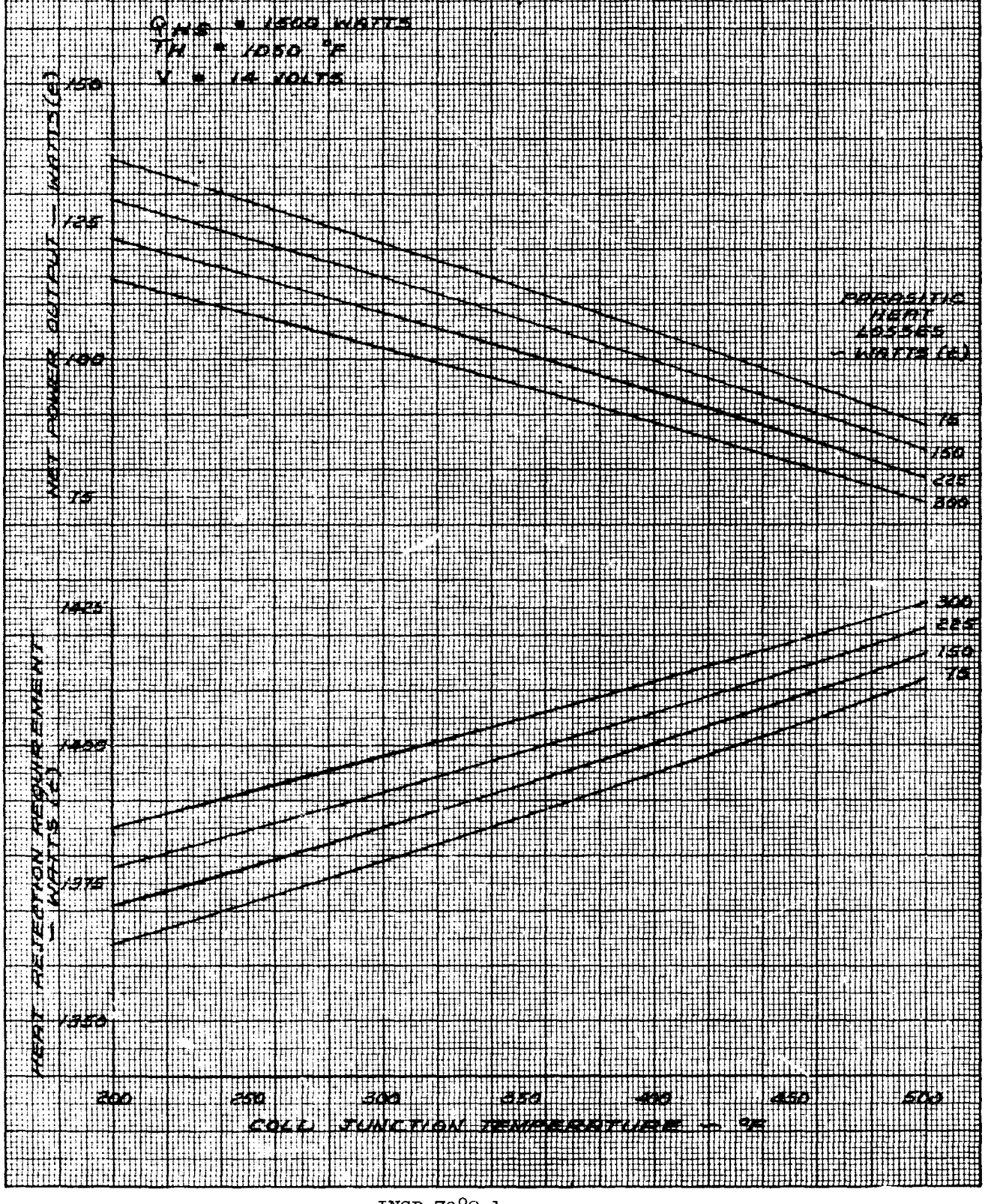
After the cold junction temperature is defined, the number of couples required to produce 14 volts at optimum load voltage is determined as in Design example No. 1. Assuming series parallel circuitry, the required number determined from Fig. VI-1 is 280 couples.

The instantaneous open circuit voltage is also determined in the same manner as discussed in Design Example No. 1. In this example the instantaneous open circuit voltage is 24.1 volts.

FIGURE VI-2

SAMPLE DESIGN PARAMETERS

NET POWER OUTPUT AND HEAT REJECTION REQUIREMENT AS A FUNCTION OF HEAT LOSSES AND COLD JUNCTION TEMPERATURE



The shape factor (A/L) of the thermoelectric elements can be determined by the following expression:

$$A/L = \frac{Q_{T/E}}{\left.\frac{QL}{NA}\right|_{\cdot N}} = \frac{Q_{HS} - Q_L}{\left.\frac{QL}{NA}\right|_{\cdot N}} \qquad \text{(Eq. VI-23)}$$

where: $\frac{QL}{NA}$ is determined at $T_H = 1050°F$, $T_C = 300°F$ and $C_{T/L} = 0$.

The elements cross section is inversely proportional to the element length as shown in Fig. VI-3 for several values of heat losses. The element diameters are determined from the cross section and the optimum diameter ratio (D_N/D_P) at these temperatures as discussed in Example No. 1. At this stage of the RTG design, a conceptual design layout of the thermoelectric element cross section which is compatible with the heat source is required. However for the purpose of this design example, an area of 0.07 in.^{2} is assumed to be compatible with the heat source area. The element diameters which are compatible with this element area ($D_N/D_P = 1.43$) are $D_N = .245$ inches and $D_P = 0.171$ inches.

Since the number and diameters of the elements are known, the heat losses of the conceptual design can be calculated as a function of element length (i.e., thermal insulation thickness). The element length at which the calculated heat losses equals the allowed heat losses represents a heat balance at the hot junction and defines the element length. The heat losses determined in this calculation must then be compared to the heat losses assumed in establishing the cold junction temperature. Any significant differences in the heat losses will necessitate an iteration on cold junction temperature. For the purpose of this example an element length of 0.330 inches and a heat loss of 150 watts(t) will be assumed representing a convergence of the iterations on RTG design. Now that a convergence on the cold junction temperature has been

attained, referral to the top half of Fig. VI-2 indicates that the net power output is 115 watts(e). The resultant system efficiency for this RTG is 7.67%. The gross power produced by the thermoelectrics elements is 128 watts(e) allowing ~13 watts(e) loss for Joule heating.

Table VI-2 presents a summary of the characteristics of the RTG designed for Design Sample 2.

TABLE VI-2

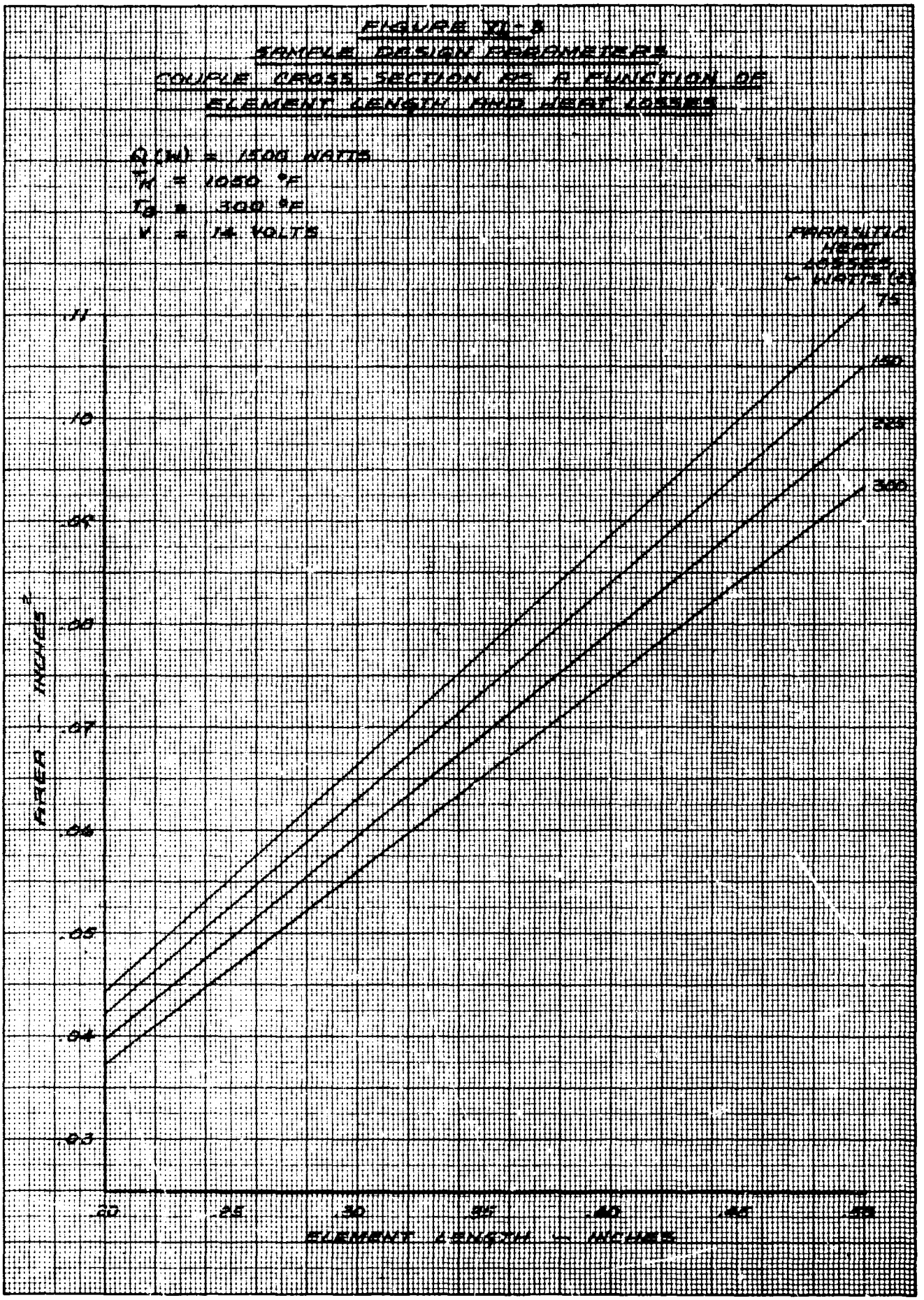
Summary of Design Sample No. 2 RTG Thermal and Electrical Characteristics
Maximum Power RTG for Fixed Thermal Inventory

Materials	2N PbTe and TAGS/SnTe
Net Power	115 watts(e)
Gross Power	128 watts(e)
Load Voltage	14 volts
Instantaneous Open Circuit Voltage	24.1 volts
Hot Junction Temperature	1050(°F)
Cold Junction Temperature	300(°F)
Number of Couples	280
Element Length	
Total	0.330 inches
SnTe	0.066 inches
Element Diamter	
N	0.245 inches
P	0.171 inches
Thermal Energy to Elements	1350 watts(t)
Heat Losses (assumed)	150 watts(t)
Heat Source Thermal Inventory	1500 watts(t)
System Efficiency	7.67%

FIGURE XI-3

SAMPLE DESIGN PARAMETERS

COUPLE CROSS-SECTION AS A FUNCTION OF ELEMENT LENGTH AND HEAT LOSSES



Design Sample No. 3

Requirements: For the RTG design described below predict the hot junction temperature, electrical power output, load voltage and instantaneous open circuit voltage for a fuel inventory of 550 watts(t). Assume that the load voltage will be set for optimum efficiency.

Material	2N PbTe-TAGS/SnTe
Number of couples	90

Series-Parallel Circuitry

$L = 0.4$ in.

$L_{SnTe} = 0.080$ in.

$D_N = 0.28$ in.

$D_P = 0.20$ in.

Cold junction temperature = 300°F

Heat Losses are expressed as $Q_L = .2\ W/°F\ (T_H - T_C)$

Extraneous wiring resistance = .05 ohms

Approach: The solution to this example is approached through a heat balance performed at the thermoelectric hot junction. The heat balance is used to determine the hot junction temperature which is consistent with fuel inventory. After determining the hot junction temperature, the load voltage, instantaneous open circuit voltage and gross power are obtained through the thermoelectric calculations presented in Table V-5. The net power output of the RTG is then obtained by subtracting the Joule heating losses from the gross power.

Parameter Selection:

The material properties recommended for these materials was previously established as TEDN-00-35 and TEDP-10A-27. Therefore the thermoelectric parameters are those presented in Table V-5.

A design contact resistivity of 0 was also established in design example No. 1 and will be used in this example. Therefore a $C_{T/L}$ of 0 will be used.

Typical Calculation:

The heat balance at the hot junction is performed by equating the heat delivered by the heat source to the heat which enters the thermoelectric elements plus the parasitic heat which bypasses the elements:

$$Q_{HS} = Q_{T/E} + Q_L \qquad \text{(Eq. VI-24)}$$

The heat which enters the thermoelectric elements was shown in Eq. VI-17 in terms of the thermoelectric design characteristics (i.e., number of elements, length of elements, and elements cross section) plus the calculated heat parameters (QL/NA). In this RTG, the heat losses have previously been determined as a function of hot and cold junction temperature as presented in the ground rules for this example. Substitution of these functions into Eq. VI-24 yields the following expression:

$$Q_{HS} = \frac{NA}{L} \cdot \frac{QL}{NA} (T_H, T_C, C_{T/L}) + .2\ W/°F \left[T_H - T_C\right] \qquad \text{(Eq. VI-25)}$$

For the 300°F cold junction temperature and substitution of the know values, Eq. VI-25 becomes:

$$550\ W = 20.9 \text{ in } \frac{QL}{NA} (T_H,\ T_C = 300°F,\ C_{T/L} = 0) + .2 W/°F \left[T_H - T_C\right] \qquad \text{(Eq. VI-26)}$$

The solution to this energy balance is obtained graphically by plotting the right side of the equation vs the hot junction temperature.

Figure IV-4 shows the results of that heat balance and indicates that the heat balance occurs at a hot junction temperature of 958°F. At this temperature the heat losses are 132 watts(t) leaving 418 watts(t) to enter the thermoelectric elements. The usefullness of this graphical solution is obvious for rapid evaluation of other thermal inventories (such as ± fueling tolerances). The gross power output is defined by multiplying the thermoelectric efficiency times the heat entering the elements as defined in Eq. VI-15 of design example No. 1. The thermoelectric efficiency is determined from Fig. V-5 of Chapter 5 to be 8.80% at a hot junction temperature of 958°F. Therefore the gross power output is 37 watts(e). The gross load voltage is obtained through Eq. VI-3 of design sample No. 1 after the load voltage per couple is determined. A cross plot of the data presented in Table V-5 indicates that a load voltage of ~.0883 volts is consistent with optimum load operation at 958°F hot junction temperature. The resultant load voltage is 3.97 volts and the gross current is 9.32 amps. The instantaneous open circuit voltage is obtained in the same manner to be 6.76 volts.

The net power output of the above example is obtained by subtracting the extraneous losses from the gross power. The actual load voltage which yields optimum load voltage can only be determined by constructing an E-I characteristic with the extraneous losses considered in the computer model. As discussed earlier the optimum load voltage changes very little with the additional extraneous losses. Therefore in development of conceptual designs the assumption that the load voltage does not change (i.e., equal to the above determined gross value) is adequate. After assuming an unchanged optimum load voltage, the resultant current is determined by considering the extraneous resistance as internal resistance in the RTG. The resultant expression for net power is:

$$P_N = V_S I \frac{R_i}{R_i + R_E} \qquad \text{(Eq. VI-27)}$$

where:

V_S = Optimum load voltage (assumed equal to the optimum gross voltage) - (Volts)

I = Gross current - (amps)

R_i = Internal resistance of the thermoelectric couples - (Ω)

R_E = Extraneous resistance - (Ω)

The internal resistance of the thermoelectric couples is obtained from Eq. VI-28.

$$R_i = \frac{E_o - V_S}{I} = \frac{6.76 - 3.97}{9.32} = .299\,\Omega \qquad \text{(Eq. VI-28)}$$

Substitutionof R_i and the given R_E into Eq. VI-27 yields a net power of 31.7 watts(e) as shown below:

$$P_N = (3.97\ V)\ (9.32\ a) \left[\frac{.299\Omega}{.299\Omega + .05\Omega}\right] = 31.7 \text{ watts(e)} \qquad \text{(Eq. VI-29)}$$

The system efficiency for this RTG is 5.76%.

A summary of the calculated RTG thermoelectric performance for a thermal inventory of 550 watts is presented below in Table VI-3.

TABLE VI-3

Summary of RTG Performance for Design Sample No. 3
Fixed Q_{HS} in a Known RTG

Material	2N PbTe and TAGS/SnTe
Gross Power	37.0 watts(e)
Extraneous Resistance	.05 ohms
Net Power	31.7 watts(e)
Load Voltage	3.97 volts
Instantaneous Open Circuit Voltage	6.76 volts
Hot Junction Temperature	958 (°F)
Cold Junction Temperature	300(°F)

TABLE VI-3 (Cont.)

Number of Couples	90
Series Parallel Circuitry	
Element Length	
Total	0.40 in.
SnTe	0.080 in.
Element Diameter	
N	0.280 in.
P	0.20 in.
Thermal Energy to Elements	418 watts(t)
Heat Losses	132 watts(t)
Heat Source Thermal Inventory	550 watts(t)
System Efficiency	5.76%

FIGURE VI-4

SAMPLE DESIGN HEAT BALANCE

TEON-00-36 / TEOP-108-27

$L = 0.4$ IN.

$L_{SHE} = 0.08$ IN.

$D_H = 0.28$ IN.

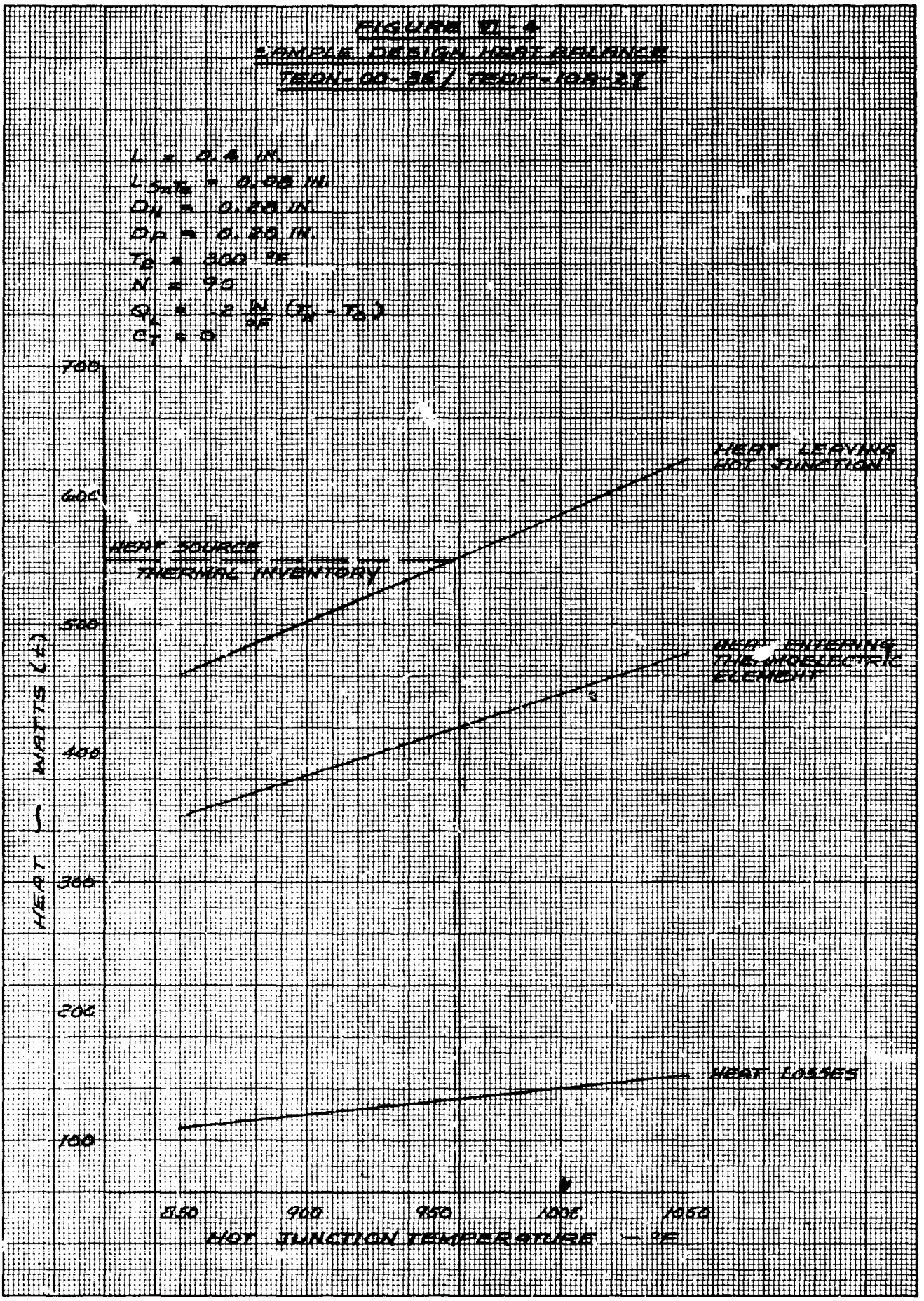
$D_P = 0.28$ IN.

$T_B = 300$ °F

$N = 90$

$Q_K = .2 \frac{N}{2F} (T_H - T_B)$

$C_T = 0$



CHAPTER VII

REFERENCES

1. Thermoelectric and Thermomagnetic Effects and Applications, T. C. Harman and J. M. Honig, McGraw-Hill, New York (1967).

2. Direct Energy Conversion, edited by G. W. Sutton, McGraw Hill, New York (1956).

3. Semiconductor Thermoelement and Thermoelectric Cooling, A. F. Ioofe, Infosearch, London (1957).

4. Thermoelectricity: Science and Engineering, R. R. Heikes and R. W. Ure, Jr., Interscience, New York (1961).

5. "Digital Computation of Thermoelement Operational Parameters, " W. C. Lyon and T. S. Bustard, Advanced Energy Conversion, Vol. 2, pp. 197-208, 1962, Pergamon Press, Great Britain.