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PRELIMINARY INVESTIGATION OF A RADIOISOTOPE FUELED THERMIONIC DIODE POWER SYSTEM FOR THE 0.5 TO 3.0 KW POWER RANGE REQUIREMENTS ASSOCIATED WITH ELECTRIC PROPULSION DEVICES

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PRELIMINARY INVESTIGATION OF A RADIOISOTOPE FUELED THERMIONIC DIODE POWER SYSTEM FOR THE 0.5 TO 3.0 KW POWER RANGE REQUIREMENTS ASSOCIATED WITH ELECTRIC PROPULSION DEVICES

By

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SUMMARY

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The use of radioisotopes as thermal sources in a thermionic diode power system has been investigated. The power system was envisioned to meet the requirements of electric propulsion devices in the 0.5 to 3.0 KW range. The diode loss and output, fuel block thermal, and system weight analyses utilized to obtain the system efficiencies and system performances (watts per pound) are presented herein. Also included are the resultant costs and electrical power availability analyses from the above information. The analyses indicate that the best isotope fuel from a technical feasibility viewpoint is plutonium primarily because the other competitive fuels are eliminated due to the heavy shielding weights associated with radiological safety requirements. The costs for plutonium compounds, however, are prohibitive in the 0.5 KW to 3.0 KW range and the present and planned availabilities are hardly equal to a requirement of 0.5 KW. Further, it is indicated that direct radioisotope heating of a propellant in the thrustor might be a more practical and feasible approach to propulsion requirements.

AUTHOR

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DEFINITION OF TERMS

A	isotope atomic mass, gm
A'	constant in equation (B-5), 120 $\frac{\text{amps}}{\text{cm}^2\text{-}^\circ\text{K}^2}$
A_{eff}	isotope effective cross sectional area of fuel block, cm^2
B	buildup factor, dimensionless
C	constant–dimensionless
D	conversion constant, 7.75×10^5 $\frac{\text{watts-dis-days}}{\text{mev}}$
D_E	emitter diameter, cm
D_F	fuel block diameter, cm
D_R	dose rate, rem/hr
$D_{R\ req.}$	required dose rate level at 1 meter, rem/hr
E_{AV}	average energy per disintegration, $\frac{\text{mev}}{\text{dis}}$
h_{cs}	cesium heat conduction coefficient, $\frac{\text{watts}}{\text{cm}^2\text{-thousands }^\circ\text{K}}$
J	diode output current density, $\frac{\text{amp}}{\text{cm}^2}$
K_1	thermal shield loss constant, $\frac{\text{watts}}{\text{cm}^2}$
K_2	thermal shield edge loss constant, $\frac{\text{watts}}{\text{cm}}$
k_F	molybdenum fuel block heat conduction coefficient $\frac{\text{watt}}{\text{cm}^2\text{-}^\circ\text{C}}$
L_F	fuel block length, cm

ℓ	shield thickness for 100 watt-thermal, cm
ℓ_s	shield thickness for present cases, cm
N_0	Avogadro number, $6.0247 \times 10^{23} \frac{\text{atoms}}{\text{gm atomic weight}}$
P_D	diode power density, $\frac{\text{watts-electrical}}{\text{cm}^2}$
P_{d_i}	isotope power density, $\frac{\text{watts-thermal}}{\text{gm}}$
P_{d_c}	isotope compound power density, $\frac{\text{watts-thermal}}{\text{cm}^3}$
P'_{d_c}	effective isotope compound power density (See Eqn. (C-1)), $\frac{\text{watts-thermal}}{\text{cm}^3}$
P_{out}	system electrical output power, watts
P_{TD}	thermionic diode output power, watts
Q_{cs}	cesium conduction loss, watts
Q_{dc-dc}	DC-DC converter loss, watts
$Q_{E-C_{rad}}$	emitter-collector radiation loss, watts
Q_{ec}	electron cooling loss, watts
Q_{ss}	structural support and lead loss, watts
Q_{ts}	thermal shield loss, watts
S	system specific power, $\frac{\text{watts}}{\text{lb}}$
T	decay time, days
$T_{1/2}$	half-life of radioisotope, days
T_{bs}	temperature of bottom shield, °K

T_C	collector temperature, °K
T_{cs}	cesium reservoir temperature, °C
T_E	emitter temperature, °K
T_s	temperature of side shield, °K
t	time, sec
V_f	fuel block volume, cm^3
V_{out}	output voltage, volts
x	distant from isotope source, cm
W_D	weight of diode, structural support and leads, lbs.
W_{dc-dc}	weight of DC-DC converter, lbs.
W_F	weight of fuel block, lbs.
ΔT_L	longitudinal temperature difference, °K
ΔT_R	radial temperature difference, °K
ϵ	experimental value of $\dfrac{1}{\dfrac{1}{\epsilon_E}+\dfrac{1}{\epsilon_C}-1}$, dimensionless
ϵ_E	emitter total emissivity evaluated at T_E, dimensionless
ϵ_C	collector total emissivity evaluated at $\sqrt{T_E - T_C}$, dimensionless
η_S	system efficiency, percent
η_{dc-dc}	converter efficiency, percent
ϕ	neutron flux rate, $\dfrac{\text{neutron}}{cm^2\text{-sec}}$
ϕ^*	equivalent emitter work function from Richardson equation at T_E and J, ev
μ	neutron attenuation coefficient, cm^{-1}

ρ_I isotope density, $\frac{gm}{cm^3}$

ρ_F molybdenum fuel block density, $\frac{gm}{cm^3}$

ρ_{Pb} lead density, $\frac{gm}{cm^3}$

σ Stephan-Boltzmann constant

for eqn (B-1) $5.679 \times 10^{-12} \frac{watts}{cm^2\text{-}^\circ K^4}$

for eqn (B-5) $8.6167 \times 10^{-5} \frac{ev}{^\circ K}$

PRELIMINARY INVESTIGATION OF A RADIOISOTOPE FUELED THERMIONIC DIODE POWER SYSTEM FOR THE 0.5 TO 3.0 KW POWER RANGE REQUIREMENTS ASSOCIATED WITH ELECTRIC PROPULSION DEVICES

INTRODUCTION

Electric propulsion devices have been proposed to provide the attitude control and station keeping functions of long term (3 years) synchronous satellites. It is generally felt that the electric power requirements for these devices fall in the range of 0.5 to 3.0 KW for the subject mission (See, e.g., Reference 1). Further analysis indicated that a radioisotope-fueled high temperature thermionic diode would offer the highest system efficiencies and best performance, watts per pound of system as the power generator in a power system. The geometry of the opposing emitter-collector surfaces of a thermionic diode can either be planar (two opposing disks) or cylindrical (two opposing cylinders). The selection of the geometry, however, is determined by the power density of the radioisotope heat source. The cylindrical diode configuration will not operate satisfactorily with isotopes of power density of less than about 12 thermal watts per cubic centimeter, and this eliminates the low and medium power density isotopes which have some of the most desirable radiological safety characteristics. Further, the most favorable operating conditions for the cylindrical diode would be met with the short life, very high power density isotopes which would not meet the mission life requirements of the present task. Thus, this investigation was performed for a thermionic diode with the planar geometry, and the results of the investigation are given in this report. Some comparisons with solar cell and nuclear thermoelectric power systems are also included.

The investigation has been performed in the following manner: first, radioisotope physical properties, cost and availability data have been updated and evaluated; second, the thermal power losses in both the fuel block and thermionic diode of the power generator have been considered

in some detail; and last, system weights have been estimated. The results of the latter two parts of the analysis were integrated with the radioisotope data to provide the performance data presented here.

SYSTEM DESCRIPTION

The system under study consists of a radioisotope fueled high temperature thermionic diode power generator connected electrically in series with a DC-DC converter, which in turn is connected electrically directly to the load. The thermionic diode power generator with the diode in the planar geometric configuration consists of a circular emitter opposite a collector of the same geometry separated by a narrow gap into which cesium vapor is injected under pressure. The operation of a cesium filled thermionic diode can be summarized as follows: first, the temperature of the emitter is raised sufficiently by the radioisotope heat source to the point where electrons are emitted from the surface of the emitter, i.e., the work function of the emitter is exceeded; and secondly, the cesium vapor in the gap reduces the space charge which builds up as more and more electrons are freed, thus allowing the electrons to be set in motion toward the collector; and hence, the thermionic diode acts as a power generator. The DC-DC converter takes the output of the thermionic diode generator (which is inherently a low voltage device) and raises its voltage to some required load value. The radioisotope heat source is joined thermally to the emitter by a heat conduction path in the form of a molybdenum cylinder. The radioisotope fuel consists of cylindrical pellets inserted into many small diameter holes drilled in the molybdenum block. This combination is called the "fuel block" in this paper. The fuel block is surrounded by thermal shields to reduce heat losses by heat radiation to space. A schematic of the above system is shown in Figure 1.

The efficiency of the system is defined by the following equation:

$$\eta_s = \frac{P_{out}}{\underbrace{Q_{ts}}_{\text{Fuel block losses}} + \underbrace{Q_{E\text{-}C_{rad}} + Q_{ss} + Q_{cs} + Q_{ec}}_{\text{Thermionic Diode Losses}} + \underbrace{Q_{dc\text{-}dc} + Q_{out}}_{\text{Thermionic Diode Output, } P_{TD}}} \qquad (1)$$

The system performance parameter, specific power (watts output to load per pound of system weight), is defined by equation (2) below.

$$S = \frac{P_{out}}{W_D + W_{dc-dc} + W_F} \tag{2}$$

For the purpose of the present analysis a specific size of power supply (50 watts-electrical output to the load) was selected. This power supply consists of one of a pair of back-to-back diode power generators of a 100 watt electrical output module. This pair of power generators was connected in series to give at least 1.0 volt DC output or greater to the DC-DC converter which was assumed to have an 80 percent conversion efficiency at this voltage. Thus, the power generator used in the analysis had an output of 62.5 watts electrical. The fuel block was designed to be 57.7 percent fuel and 42.3 percent molybdenum by volume. Further, the fuel block was covered laterally and on the side of the diode by multi-layers of thin tantalum sheet, except at the interface of the fuel block for the other half of the back-to-back diode of the 100 watt module.

ANALYSIS

The analysis is divided into several sections to expand on the quantities in equations (1) and (2), and also to introduce the summary of the radioisotope data and subsequently the method of computing the isotope cost and the electrical availability data. A summary of the cases and parameters investigated is given in Table I.

A. Summary of Radioisotope Data

Data on the physical properties, cost, and availability of radioisotopes useable as heat sources are given in Table II. In the present study, several isotopes were rejected before performing the analysis, these are: Cobalt 60–due to its extreme radiological hazards and low melting point; Cesium 137–due to hazard, low power density and low melting point; Promethium 147–low power density, low melting point and high cost; Actinium 227, Thorium 228 and Uranium 232, due to their low availability and predicted high cost. Also excluded were Polonium 210 and Curium 242 because of short half life. The power density values shown in the table for the isotopes used in the present investigation were calculated by the method indicated in Appendix A.

Although the mission time requirement of this report is three years, the analysis below was performed for mission times of one and three years essentially to illustrate the fall off in performance of the shorter half life isotopes considered in the analysis. The resulting data should be considered as bonus information however not directly applicable to the stated requirements of the present report.

B. Thermionic Diode Power Generator Losses Output

The thermionic diode power generator losses treated include those associated with the emitter-collector radiation, structural support and leads, cesium conduction and electron cooling. The power generator output has been considered to be fixed in all cases at 62.5 watts electrical before entering the DC-DC converter, whose efficiency allowed a 50 watt-electrical system power output.

The sum of all these losses and the diode power generator output for one of the cases investigated are shown in Figure (2) as a thermal power flow diagram for the system under study. Also shown are the equations which were used to calculate the losses. A more detailed analysis of the diode losses is given in Appendix B. Below is a compilation of the total diode losses for the 62.5 watts thermionic diode and the experimental diode power densities and output voltages which set the emitter sizes in this study. The approximate corresponding emitter-collector spacing is indicated.

T_E, °K	Thermoinic Diode Losses plus P_{TD}, Watts	P_D, watts/cm^2	V_{out}, volts	Emitter-Collector Spacing, Mils
1700	674.94	3	0.5	12
1790	533.89	6.9	0.5	4
1984	419.90	10	0.8	2

C. Thermal Shield Losses

The thermal shield losses are computed after the diode losses, since the diode losses and the output are used to initially size the fuel block. After the fuel block is initially sized, thermal shield losses corresponding to this size are determined. The sum of the diode losses, power generator output, and this initial thermal shield loss are then used to determine a new fuel block requirement to supply this amount of thermal

power. Further iterations could be performed, but it was found that even the loss associated with the first iteration could be compensated for, if it were considered permissible to increase the percentage of the isotope fuel in the fuel block. The details of this analysis are given in Appendix C.

D. System Weight

The system weight in this analysis includes three components namely; W_D – the diode weight including support structure and leads, W_{dc-dc} – the DC-DC converter weight; and W_F – the fuel block weight. The various items of system weight are described in more detail in Appendix D. Not included in the system weight calculated therein is the weight of radiological safety shielding, but for the fuels requiring it estimates have been made, considering only the radiation from the lateral direction of the cylindrical fuel block. The equations and methods used are given in Appendix E.

E. Cost

The cost per 50 electrical watts output deliverable to the load was determined by multiplying the thermal watts required per 50 electrical-watt module by the cost per thermal watt given in Table II. These cost data with the sources noted represent the best available information.

F. Availability

The availability in electrical-kilowatts was calculated, based on the 50 watt system analysis by multiplying the system efficiency by the corresponding isotope thermal kilowatt availability shown in Table II. The availability data with sources noted represent the best available information suitable for the engineering judgments made herein.

G. Other Power Systems

Data were obtained on solar cells and radioisotope fueled thermoelectric power systems (references 2 and 3, respectively) in order to provide a comparison with the radioisotope fueled thermionic devices treated in this paper. Actual hardware data were obtained on the solar cells for the Eccentric Orbiting Geophysical Observatory, while the data obtained on the thermoelectrics corresponds to predictions based on the most current development data.

PRESENTATION OF RESULTS

The results are presented in the following figures and tables:

	Figure
System Efficiency versus Isotope Power Density	3
Loss, Percent of Total versus Isotope Density (a) Mission time 1 year (b) Mission time 3 years	4
System Specific Power versus Isotope Power Density (a) Mission time 1 year (b) Mission time 3 years	5
Available Electric Power, KW, versus Emitter Temperature for Plutonium Compounds	6

	Table
Variation of Cost per 50 watts-electrical output (P_{out}) for the Various Isotopes Listed in Increasing Value of Power Density	III
Variation of Available Electric Power, KW, for the Various Isotopes Listed in Increasing Value of Power Density	IV

DISCUSSION OF RESULTS

The discussion follows the figures presented above. It should be pointed out that all the figures correspond to an emitter temperature of 1700°K unless otherwise noted. This emitter temperature was chosen since it is representative of state-of-the-art materials capabilities. Further, it should be noted that the remarks below are in general applicable to the three year mission time except as noted.

System Efficiencies

The system efficiencies for the various isotopes (See Figure 3) show a variation from about 5 to 7 percent with the higher power density isotopes yielding the higher efficiencies. This result is attributable to reduced thermal shielding requirements, because the higher power density

fuel required a smaller volume, hence smaller surface area fuel block. The efficiencies appear low at first glance for high temperature thermionic devices. These efficiencies include the fuel block and converter efficiencies which explains why a diode of efficiency about 10 percent (corresponding to our case for $T_E = 1700°K$) is reduced to the values given above, with the variation in the final result mainly a function of the fuel block efficiency. The percentage contribution of the various losses is shown in Figure 4 to illustrate the effect of isotope density. The previous remark is illustrated by noting that the percent loss for thermal shielding is smaller for the higher power densities.

System Performance

In Figure 5, the system performance parameter, watts per pound, is shown for the various isotopes considered for one and three year missions, respectively. The three highest power density isotopes, at first glance namely, thulium 170, cerium 144 and curium 244 appear to offer the highest performance for the 1 and 3 year missions. If, however, radiological hazards associated with these isotopes are considered (if the requirement to attenuate the dose rate to 10 mrem/hr at one meter must be fulfilled) drastic reductions in the performance occur as shown in the figure. To investigate the effect of relaxing this criterion, a level was set at 100 millirem/hr at one meter for the Thulium 170 case (1 year mission). This computation showed an increase in the shielded watts per pound value from 0.61 to 0.83. While this is a gain, it falls short of the original value of 5.1 and makes the system not competitive, even with the solar cells. The above results essentially leave the plutonium compounds as the best from a watts per pound standpoint and inherently (even though not stated previously), from a hazard viewpoint. It should be noted that the present approach shows some improvement over solar cells and radioisotope fueled (fuel is plutonium 238 for data shown in this report) thermoelectrics, but the improvement is not as large as previously anticipated.

Cost

The cost results (Table III) show that some of the more hazardous isotopes are less costly than plutonium. The smaller cost, however, may not be realizable because of other cost resulting from safety handling requirements. In general, (excepting Strontium-90) the cost would be high compared to solar cells (approx. $\$0.015 \times 10^6$ per 50 watts elec.). The cost for the plutonium compounds, even at the future price for the highest power density fuel, would be excessive for 0.5 KW-electrical (Approximately $\$5.2 \times 10^6$ compared to $\$0.15 \times 10^6$ for solar cells).

Available Electrical Power

The available electric power, Table IV, shows some rather disappointing results; namely, that for almost all the isotopes, the present and planned availability will not satisfy the minimum requirements of 0.5 KW. Further, the future availability for plutonium just barely satisfies this requirement and will never satisfy the upper limit of the requirement, 3 KW electrical. The power availability values indicate fairly clear that radioisotope fueled thermionics will never have a wide application as a basic power unit for a multitude of space missions. A comment might be made about the fact that if the hazard problem can be accepted, a way to satisfy the power availability requirement is to use either strontium or cerium for the long and short duration missions, respectively.

General

Since the plutonium offers the best useable performance and inherent lack of hazard, it is of interest to investigate methods to alleviate the problems of cost and availability. One approach to increase the availability and reduce the cost of plutonium is to increase the emitter temperature. The variation in availability with emitter temperature for the plutonium compounds is given in Figure 6. Although there is some improvement in the availability with increasing emitter temperature, the planned production just meets the minimum requirement of 0.5 KW and the future availability is still about 30 percent short of the maximum requirement. Thus, the capability of isotope fueled thermionics in general to satisfy the 0.5 to 3.0 KW requirement at a reasonable cost and at a performance level (watts per pound) far in excess of other power systems such as solar cells and isotope fueled thermoelectrics appears to be somewhat short of the goal. However, for specific missions such as one of a spacecraft traveling in a direction of reduced solar constant or one in which the spacecraft is in an orbit in the most intense region of the radiation belt, radioisotope fueled thermionics might offer a solution to the power system requirement if the power requirement is in the range of 0.5 KW. The answer to the initial problem, however, of providing a power system for the requirements of electrical propulsion devices for attitude control and station keeping does not exist in the radioisotope fueled thermionics at present, and more investigative effort into possible systems to meet this requirement should go on. An answer to the problem, however, could be provided presently if the electric thrust system could be replaced by a competitive one. Such a system is a direct radioisotopically fueled heater in the thrustor to avoid the inherent losses in

the thermal-electrical-thermal conversion of the present system. This latter method would also appear to be more compatible with the availability and cost picture for radioisotopes at present.

CONCLUSIONS

The conclusions pertinent to the various parameters considered herein are given as follows:

(a) System Efficiencies–The system efficiencies vary from 5 to 7 percent for an emitter termperature of 1700°K. These values reflect the reduction in the usual quoted thermionic efficiency by the DC-DC converter and fuel block thermal shield losses with the variance in the efficiency due to isotope power density.

(b) System Performance–The specific power data, watts/pound, show significant gains over such systems as solar cells and thermoelectrics, but this apparent advantage in reality only exists for the plutonium fuels because the others require very heavy shielding for radiological safety considerations. Thus, the plutonium fuels show the only real potential for isotope fueled thermionics.

(c) Cost–The isotopes with radiological safety hazards are less costly than plutonium, where the cost for a 0.5 KW electrical plutonium fueled unit would be $\$5.2 \times 10^6$. This appears prohibitively high except for missions where the cost might be written off against requirements unattainable by any other means.

(d) Available Electric Power–The available electric power shows even a more drastic picture when plutonium is considered the only suitable fuel. Planned availability, even when higher emitter temperatures are considered, is barely sufficient for providing 0.5 KW of electrical power. Future availability would provide at best about 2 KW and the upper bound of the task, 3 KW, could never be met.

(e) General–Other than for specific missions such as traveling away from the sun or traveling in an orbit in the radiation belts, radioisotope fueled thermionic power systems do not appear practical from a cost viewpoint or feasible from an isotope availability standpoint for any known 0.5 to 3.0 KW electrical power supply requirement. One scheme to stay within isotope availability and at reasonable cost by reducing some of the conversion losses is to use direct radioisotope heating of the propellant in the thrustor.

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Appendix A

Isotopic Compound Power Density Calculation

The power density, Pd_c, of the various isotopic compounds was calculated in the following steps:

Step 1–Isotope Power Density, P_{d_i}:

The isotope power density is given by the following equation (see reference 4):

$$P_{d_i} = \left(\frac{D\,E_{AV}}{AT_{1/2}}\right) \exp\left[-0.693\left(\frac{T}{T_{1/2}}\right)\right] \qquad \text{(A-1)}$$

The average energy, E_{AV}, for the isotopes considered in this report are given below:

Isotope	Mode of Decay	E_{AV}, Mev
Sr^{90}	β	2.237
Tm^{170}	β	0.335
Tm^{171}	β	0.030
Ce^{144}	β	0.414
Cm^{244}	α	5.880
Pu^{238}	α	5.486

It should be noted that for the β emitters an integration of the continuous emission spectra must be performed to obtain E_{AV}.

Step 2–Isotopic Purity:

The isotope power densities from the first step are multiplied by a constant factor to reflect the fact that the fuel after irradiation and

processing is not always 100 percent pure radioactive. A list of this multiplication factor is given below:

Isotope	Constant
Sr^{90}	0.24
Tm^{170}	1.00
Tm^{171}	1.00
Ce^{144}	0.80
Cm^{244}	0.80
Pu^{238}	0.80

Step 3–Isotope Compound Power Density, P_{d_c}:

The value of power density from Step 2 is multiplied again by the ratio of the radioisotope mass to the compound mass to account for chemical dilution in the compound form. A list of these constants is given below. After these multiplications, the resultant values are multiplied by the corresponding densities in Table II to yield the isotope compound power density, P_{d_c} in watts per cubic centimeter. These final power density values are also given below.

Isotope Compound	Constant	P_{d_c}, Power Density, Watts/cm^3	
		after 1 year	after 3 years
$SrTiO_3$	.484	1.14	1.07
$Tm_2^{170}O_3$	.876	12.54	2.40
$Tm_2^{171}O_3$	.877	.95	.49
CeO_2	.818	12.61	2.37
Cm_2O_3	.910	27.00	24.93
PuO_2	.881	4.52	4.48
Pu-Alloy	--	6.63	6.50

It should be noted that the Pu-Alloy data were estimated by taking 0.7 of the value for the pure metallic nondiluted radioisotope.

Appendix B

Diode Losses and Output Analysis

A discussion of the various diode losses and the output along with the equations and data utilized to determine them where applicable follows.

1. Emitter-Collector Radiation Losses

This loss is the radiation heat transfer between the emitter and collector and the governing equation corresponding to the condition of two materials of different emissivities is given from Reference 5.

$$Q_{E-C_{rad}} = \frac{\pi}{4} \epsilon \sigma D_E^2 \left[T_E^4 - T_C^4\right] \qquad \text{(B-1)}$$

where ϵ represents an experimental value of $(1/\epsilon_E + 1/\epsilon_c - 1)^{-1}$ for the particular emitter-collector materials (Rhenium-Molybdenum) operating at temperature of about 1700°K. (If materials handbook values for the emitter and collector material emissivities were used in this quantity, the resultant value would be about one-half of the experimental value.) It is noted that use of the handbook values would not correspond to actual conditions because the emissivities are quoted for rather ideal conditions such as polished surfaces, for example. The value for ϵ used in this report (0.18) was obtained from reference 6.

2. Structural Support and Lead Losses

Although these losses can be fairly accurately determined when the detail design is known, the present analysis had to resort to a rule of thumb. The rule used was to take 87 percent of the emitter-collector radiation losses, because this percentage was representative of other analyses available to the author. Thus

$$Q_{ss} = 0.87\ Q_{E-C_{rad}} \qquad \text{(B-2)}$$

3. Cesium Conduction Losses

This is the loss of heat from emitter by the mechanism of conduction through the cesium vapor. The equation for this loss is given simply by

$$Q_{cs} = h_{cs} \, (T_E - T_C) \frac{\pi D_E^2}{4} \qquad \text{(B-3)}$$

The quantity h_{cs}, the heat conduction coefficient, was obtained from reference 7, (Figure 3-10), for cesium reservoir temperature corresponding to the various emitter temperatures investigated. Below is a short list of these values:

T_E, °K	T_{cs}, °C	h_{cs}, $\left[\frac{\text{watts}}{\text{cm}^2\text{-thousands °K}}\right]$
1700	277	1
1790	302	2.5
1984	332	3.5

4. Electron Cooling Losses

This quantity represents an irreversible process in which a portion of the energy carried from the emitter to the collector by the electrons is converted to heat, that is, a portion of the energy carried by the electrons is recovered as the output and the remainder is converted to heat which then is rejected at the collector temperature to the thermodynamic heat sink. The relation for the electron cooling losses is defined to be

$$Q_{ec} = J \, \phi^* \, \pi \frac{D_E^2}{4} - P_{TD} \qquad \text{(B-4)}$$

Values of J and ϕ^* were obtained from reference (8) (page 46, Figure 15 and page 27, Figure 7, respectively) corresponding to the emitter temperature and cesium reservoir conditions stated in the previous paragraph. An estimate of ϕ^* was made utilizing the experimental current density in the Richardson equation at the emitter temperature for the ignited mode of the diode, to provide a check on the experimental value. The following version of the Richardson equation (See Ref. 7) was used:

$$\phi^* = \sigma T_E \ln \left(\frac{A' T_E^2}{J} \right) \qquad \text{(B-5)}$$

A compilation of the experimental and computed values is given below:

T_E, °K	T_E / T_{cs}	J	ϕ^* (Ref. 8), ev	ϕ^* (Calc.), ev
1700	3.09	6	2.72	2.62
1790	3.11	13.8	2.75	2.64
1984	3.28	12.5	2.85	2.98

Since the correlation between the predicted and experimental values was good, experimental values were used in the present analysis. The above four items comprise the diode losses.

5. Output and DC-DC Converter Loss

The power generator output as mentioned in the body of the report was fixed at 62.5 watts and a DC-DC converter efficiency of 80 percent was assumed with a resultant 50 watt system output and attendant 12.5 watt DC-DC converter loss.

Appendix C

Thermal Shield Loss Analysis

The thermal shield loss is directly dependent on the thermionic diode analysis, and cannot be performed until the thermionic diode losses and the power generator output are known. The method used in this analysis consists of initially determining a fuel block size and, hence, thermal shield loss first by using just the thermionic diode losses and the output. Next, this estimate is iterated to determine the fuel block size to provide the corresponding amount of thermal power. The iterated thermal shield losses are then determined. Further iterations were not performed, because it was found that the incremental difference in the thermal shield losses for the first iteration actually could have been taken care of by changing the proportional amount of isotope fuel in the fuel block. The steps to perform the thermal shield loss calculations are detailed below.

Step (1): Initial Fuel Block Size

First, the volume of the fuel block is obtained from the following equation–

$$V_F = \frac{(\text{Diode losses} + P_{TD}) \times C}{P'_{d_c}} \qquad \text{(C-1)}$$

where

(a) C = 1.577 for α emitting fuels to account for void volume required for helium buildup and is equal to 1, obviously, for β emitters.

(b) $P'_{d_c} = P_{d_c} \times (.577)$.

The fuel block diameter is then defined as–

$$D_F = \sqrt[3]{\frac{4\,V_F}{\left(\frac{L_F}{D_F}\right)\pi}} \qquad \text{(C-2)}$$

The ratio of (L_F/D_F) was 0.8 for all cases investigated with the exception of the curium 244 cases where it was 0.64 and 0.69 for the 1 and 3 year mission time, respectively. The fuel block length can be solved for directly from these ratios.

Step (2): Initial Estimate of Longitudinal Temperature Gradient

The one dimensional axial temperature difference for uniform heat generation is given by

$$\Delta T_L = \frac{(\text{Diode losses} + P_{TD}) \times L_F}{2\, k_F\, A_{eff}} \qquad \text{(C-3)}$$

where

(a) k_F (shown versus temperature in Figure 7) obtained from data in Ref. 9 evaluated at T_E.

(b) A_{eff} was assumed to be 0.328 of the cross sectional area of the fuel block.

Step (3): Initial Estimate of Radial Temperature Gradient

The one dimensional radial temperature gradient for uniform heat production in a solid cylinder is given by–

$$\Delta T_R = \frac{P_{d_c}\, D_F^2}{16\, k_F} \qquad \text{(C-4)}$$

Step (4): Initial Fuel Block Surface Temperatures

It was assumed that the side shield radiates at a temperature of

$$T_S = T_E + \Delta T_L - \Delta T_R \qquad \text{(C-5)}$$

Since the heat path is from top to bottom and radially inward to the emitter, the bottom shield was assumed to be at a temperature given by

$$T_{bs} = T_E + \Delta T_R \qquad \text{(C-6)}$$

and the edge of the bottom shield also to be at this temperature.

Step (5): Thermal Shield Loss Calculation

$$Q_{ts_{initial}} = K_1\Big|_{T_s} (\pi D_F L_F) + K_1\Big|_{T_{bs}} \pi (D_F^2 - D_E^2) + K_2\Big|_{T_{bs}} \pi D_F \qquad \text{(C-7)}$$

where K_1 and K_2 are experimental heat loss constants (see Figures 8 and 9, respectively) evaluated at the conditions indicated.

Step (6): Iteration of Thermal Shield Loss Calculation

An iteration of the above result to obtain a slightly more accurate and representative evaluation of this loss is accomplished as follows:

The initial thermal shield loss determined by equation (C-7) in Step 5 above is added to the diode losses and power generator output to determine a new volume as per Step 1 above. The fuel block size is redetermined and the above analysis Steps 2 to 5 repeated to reflect the effect of the increased size. The only difference between the initial and first iteration is that k_F is now evaluated at the calculated value of T_s and T_{bs} for the equation (C-3) and (C-4) computations, respectively, of this iteration.

Appendix D

System Weights

The diode weight used, including support and leads, was based on values obtainable on a 50 watt diode preliminary design. The weight was 5.4 pounds of which 2.3 pounds was for internal diode structure, 2.4 pounds for collector radiator casing, 0.2 pounds for leads and 0.5 pounds for structural support.

The DC-DC converter weight was estimated for the 50 watt system to be 2.4 pounds based on a state-of-art converted electrical power to converter weight ratio of 20.5 watts/pound at a 500 electrical watt power level.

The fuel block weight consists of the fuel plus the cylindrical molybdenum block into which it is inserted. The fuel block weight is defined by the following equation:

$$W_F = 2.2 \times 10^{-3} \frac{V_F}{C} \left[0.577\ \rho_I + 0.423\ \rho_F\right] \qquad \text{(D-1)}$$

The isotope densities used in the above equation are given in Table II, and the value used for molybdenum was 10.2 gm/cm^3.

Appendix E

Estimate of Shielding Weights

The shielding weight calculation consists of first determining the dose rate associated with the particular isotope, and then the determination of the shield thickness to attenuate this dose rate to some prescribed dose rate level at a specified fixed distance. An example of a dose rate determination is given below and the equations used to determine the shield thicknesses for the isotopes requiring shielding and consequent weight are also given.

(1) Dose Rate Determination

The isotope whose dose rate is to be calculated is Curium 244. Although there is slight gamma radiation resultant from the radioisotope decay process, the dose rate from Curium 244 is primarily associated with the neutrons which are yielded in the spontaneous fissioning of the isotope. Thus, the calculations below will be for the fission neutron contribution to the dose rate only.

Step A–Neutron Flux Rate

First, the number of neutrons per second per gm must be determined as follows:

The number of fissions per second per gm is defined by the following equation–

$$\frac{\text{Fissions}}{\text{sec-gm}} = \frac{0.693\ N_o}{AT_{1/2}} \qquad \text{(E-1)}$$

where $T_{1/2}$ (half life of fission neutron) equals 1.4×10^7 years (Ref. 10). The value of (E-1) is then 3.87×10^6 fissions per second per gm. The number of fission neutrons yielded in the spontaneous fission process is given in Reference 11 as 2.6 ± 0.15 neutrons per fission, and for the present calculations, a value of 2.75 was assumed for conservatism.

When this value is combined with that obtained from equation (E-1) the following result is obtained–

$$\frac{\text{Neutrons}}{\text{sec-gm}} = 1.06 \times 10^{17} \qquad \text{(E-2)}$$

In order to perform the shield calculation and set a reference value for the correspondence between the required thermal watts of isotope and the dose rate, 100 thermal watts was chosen as this reference. Thus, to convert the neutron flux in (E-2) to this reference, the following relation was used:

$$\frac{\text{Neutrons}}{\text{sec} - 100\ \text{watt}_{th}} = (\text{E}-2) \times \frac{100}{P_{d_i}\Big|_{t=0}} \qquad \text{(E-3)}$$

When the indicated operation is performed, the result is 0.373×10^9 neutrons per second per 100 watts-thermal. The final operation in determing the neutron flux rate is to consider the geometry and fix the distance at which you want to determine this rate. This equation for a point source radiating radially is–

$$\phi = \frac{(\text{E}-3)}{4\pi x^2} \qquad \text{(E-4)}$$

For this example at one meter from the source, the value is 0.297×10^4 neutrons per second per 100 watts-thermal per square centimeter.

Step B–Dose Rate

First it was assumed that the fission neutrons had an average energy of 2 Mev, because this energy level is representative of the probable energy of a fast neutron. Using this energy value, the correlation between neutron flux rate and dose rate was found in Reference 12 (p. 22) and this relation is as follows:

$$\frac{1\ \text{neutron}}{\text{sec-cm}^2} = \frac{0.12\ \text{mrem}}{\text{hr}} \qquad \text{(E-5)}$$

The dose rate for the 100 watt-thermal source at one meter is then determined by multiplying the result of equation (E-4) by the (E-5) relation to yield

$$D_R = 6.356 \frac{\text{rem}}{\text{hr}} \text{ at 1 meter} \tag{E-6}$$

(2) Determination of Lead Shield Thicknesses

The basic equation for the shield thickness to change the dose rate level D_R to some required value is given as follows–

$$\ell = -\frac{1}{\mu} \ln \left(\frac{D_{R_{req}}}{BD_R} \right) \tag{E-7}$$

In the present investigation, this level was fixed at 10 mrem at one meter. Since the dose rate calculation is somewhat long and involved, lead shield thickness values were obtained from the literature for the reference dose rate of 10 mrem per hr at 1 meter and these are as follows–

Isotope	Thermal Source Watts	ℓ, cm	Reference
Sr^{90}	10	15.24	3
Ce^{144}	10	19.05	3
Tm^{170}	0.5	5.4	13
Cm^{244}	100	6.5	Above calculation

The above values were then used in the following equation to calculate the shield thickness in a lateral direction as this equation is

$$\ell_s = \ell - \ln \left(\frac{\text{Reference thermal source}}{\text{Required thermal source}} \right) \tag{E-8}$$

Shielding was assumed to be only required in the lateral direction, since the diode structure and perhaps the spacecraft itself could provide attenuation in the axial direction. Thus, the shield weight was then calculated by the following equation–

$$W_s = \rho_{Pb} \frac{\pi}{4} (\ell_s^2 - D_F^2) L_F \qquad \text{(E-9)}$$

The above approach to the shielding was taken, because if the source were covered spherically to shield the radiation in all directions, the shield weight would be even more horrendous than determined from the assumption above.

TABLE I

Summary of Cases and Parameters Studied for Thermionic Power Supply Systems. (All Cases Evaluated for 1 and 3 Years*)

Fuel	T_E, °K		
	1700	1790	1984
Sr Ti O_3	X	-	-
Ce O_2	X	-	-
Tm_2^{170} O_3	X	-	-
Tm_2^{171} O_3	X	-	-
Pu O_2	X	X	X
Pu-Alloy	X	X	X
Cm_2^{244} O_3	X	-	-

* Except Pu^{238} compounds where all information quoted corresponds to 3 year mission data.

TABLE II—Data on Radioisotopes Useable as Heat Sources

Isotope	Properties									Production Capability [illegible]			Isotopic Fuel Costs [$/watt(th)]			Isotope
	Half-life (yr)	Isotopic purity %	Compound form	Density of compound (gm/cc)	Power Density of compound (at end of 1 year) watts/cc	Decay Mode (-Energy (Mev)) Primary	Decay Mode (-Energy (Mev)) Secondary	Melting point of Compound (°c)	Curies per watt (th)	Present	Planned	Future	Present	Planned	Future	
Co^{60}	5.3	10	Metal	8.9	15.5	β(.31)	γ(1.33)	1480	65	Large[a]	[illegible]	[illegible]	32	–	–	Co^{60}
Sr^{90}	28	24	$SrTiO_3$	4.6	1.14	β(.54)	–	~1900	149	20.13	[illegible]	[illegible]	447	149	19.58	Sr^{90}
Cs^{137}	30	35	Glass	3.2	0.215	β(.52)	γ(.662)	~1275	209	–	[illegible][b]	[illegible]	–	104	–	Cs^{137}
Ce^{144}	0.78	80	CeO_2	6	12.6	β(.31)	γ(.034)	~1950	135	–	[illegible]	[illegible]	64	64	0.92	Ce^{144}
Pm^{147}	2.7	95	Pm_2O_3	6.6	1.8	β(.23)	γ(.12)	1027	2400	–	[illegible]	[illegible]	–	485	–	Pm^{147}
Tm^{170}	0.348	100	Metal	9.32	19.95	β(.96)	γ(.084)	1525	500	–	–	[illegible]	50[d]	–	10	Tm^{170}
Tm^{170}	0.348	100	Tm_2O_3	8.6	12.5	β(.96)	γ(.084)	~2400	500	–	–	[illegible]	50	–	–	Tm^{170}
Tm^{171}	1.9	100	Metal	9.32	1.86	β(.097)	γ(.067)	1525	5600	–	–	[illegible]	1100	–	400	Tm^{171}
Tm^{171}	1.9	100	Tm_2O_3	8.6	0.95	β(.097)	γ(.067)	~2400	5600	–	–	[illegible]	1100	–	400	Tm^{171}
Po^{210}	0.378	–	Metal	9.4	1320	α(5.3)	γ(.8)	~170	31	–	[illegible]	[illegible]	–	190	–	Po^{210}
Ac^{227}	21.2	–	AcO	8.15	110	α(4.94)	β(.043)	~1600	34	–	–	–	–	1000[e]	–	Ac^{227}
Th^{228}	1.9	95	ThO_2	9	1270	α(5.42)	γ(.08)	3050	31	–	–	–	–	100	–	Th^{228}
U^{232}	74	85	UO_2	10	33	α(5.32)	γ(.057)	>2000	31	–	–	–	–	–	–	U^{232}
Pu^{238}	86.4	80	PuO_2	11.46	4.4	α(5.49)	γ(.044)	~2000	30	1.16	[illegible]	[illegible]	1285	1285	695	Pu^{238}
Pu^{238}	86.4	80	Metal	17	9.3	α(5.8)	γ(.043)	635	30	1.77	4.42	[illegible]	895	895	695	Pu^{238}
Cm^{242}	0.444	–	CmO_2	8.4	1000	α(6.11)	γ(.044)	2240	28	–	9.50	9.50	–	165	–	Cm^{242}
Cm^{244}	17.6	90	Cm_2O_3	11.75	27	α(5.8)	γ(.043)	~1500	29	0.46	3.45	Large	–	4350	1100	Cm^{244}

Notes: (a) Co^{60}, Sr^{90}, Ce^{144}, Pu^{238} (dioxide), Pu^{238} (metal), and Cm^{244} production capability and isotopic fuel costs were obtained from preliminary information provided by R. W. Shivers, Production & Materials Branch, Division of Isotopes Development, United States Atomic Energy Commission, 10/17/63.

(b) Cs^{137}, Pm^{147}, Po^{210} and Cm^{242} production capability and isotope fuel costs were obtained from Nucleonics article "Isotope Costs and Availability," Vol. 21, No. 3–March, 1963 authored by Harold L. Davis.

(c) Tm^{170} and Tm^{171} production estimates indicated in Report No. TE-2026-120, "Analyses of Costs in the Production of Tm-170 and Tm-171," November 1963, ISO/Serve Inc., Cambridge, Mass. and Thermo Electron Eng. Corp., Waltham, Mass.

(d) Tm^{170} and Tm^{171} cost estimates verified by W. K. Eister, Production & Materials Branch, Division of Isotopes Development, United States Atomic Energy Commission, in a private communication, 9/16/63.

(e) Ac^{227} and Th^{228} cost estimates from T. Slosek, General Electric Company, Vallecitos, via private communication, 8/22/63.

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TABLE III

Variation of Cost per 50 Watts-Electrical Output (P_{out}) for the Various Isotopes Listed in Increasing Value of Power Density

Isotope	Present		Planned		Future	
	Mission Time		Mission Time		Mission Time	
	1 yr.	3 yr.	1 yr.	3 yr.	1 yr.	3 yr.
Tm^{171}	.946	1.058	--	--	.344	.385
Sr^{90}	.375	.377	.125	.126	.016	.017
Pu^{238} (Oxide)	.986	.986	.986	.986	.768	.768
Pu^{238} (Alloy)	.669	.669	.669	.669	.520	.520
Tm^{170}	.036	.007	--	--	.039	.008
Ce^{144}	.046	.050	.046	.050	.001	.001
Cm^{244}	--	--	3.059	3.071	.703	.706

NOTES:

(a) Emitter temperature for all cases is 1700° K.

(b) Units in millions of dollars.

TABLE IV

Variation of Available Electric Power, KW for the Various Isotopes Listed in Increasing Value of Power Density

Isotope	Present		Planned		Future	
	Mission Time		Mission Time		Mission Time	
	1 yr.	3 yr.	1 yr.	3 yr.	1 yr.	3 yr.
Tm^{171}	--	--	--	--	.21	.20
Sr^{90}	1.20	1.19	2.00	1.19	4.01	3.97
Pu^{238} (Oxide)	.08	.08	.19	.19	.75	.75
Pu^{238} (Alloy)	.15	.15	.38	.38	1.52	1.52
Tm^{170}	--	--	--	--	2.80	2.58
Ce^{144}	--	--	1.91	1.76	5.47	5.02
Cm^{244}	.03	.03	.25	.24	*	*

NOTE:

(a) Emitter temperature for all cases is 1700° K.

* Predicted to be large.

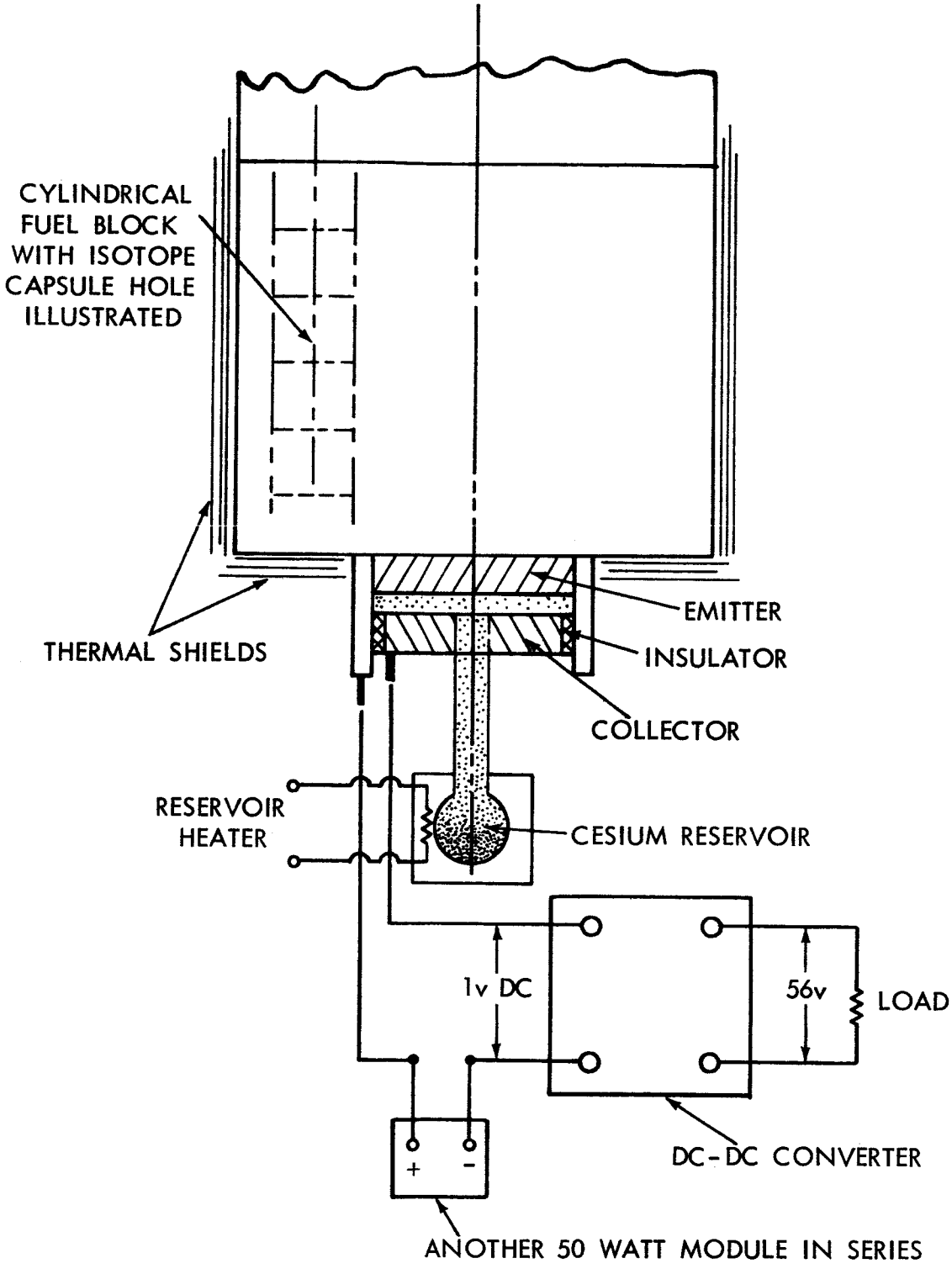

Figure 1-Schematic of isotope fueled thermionic power supply system

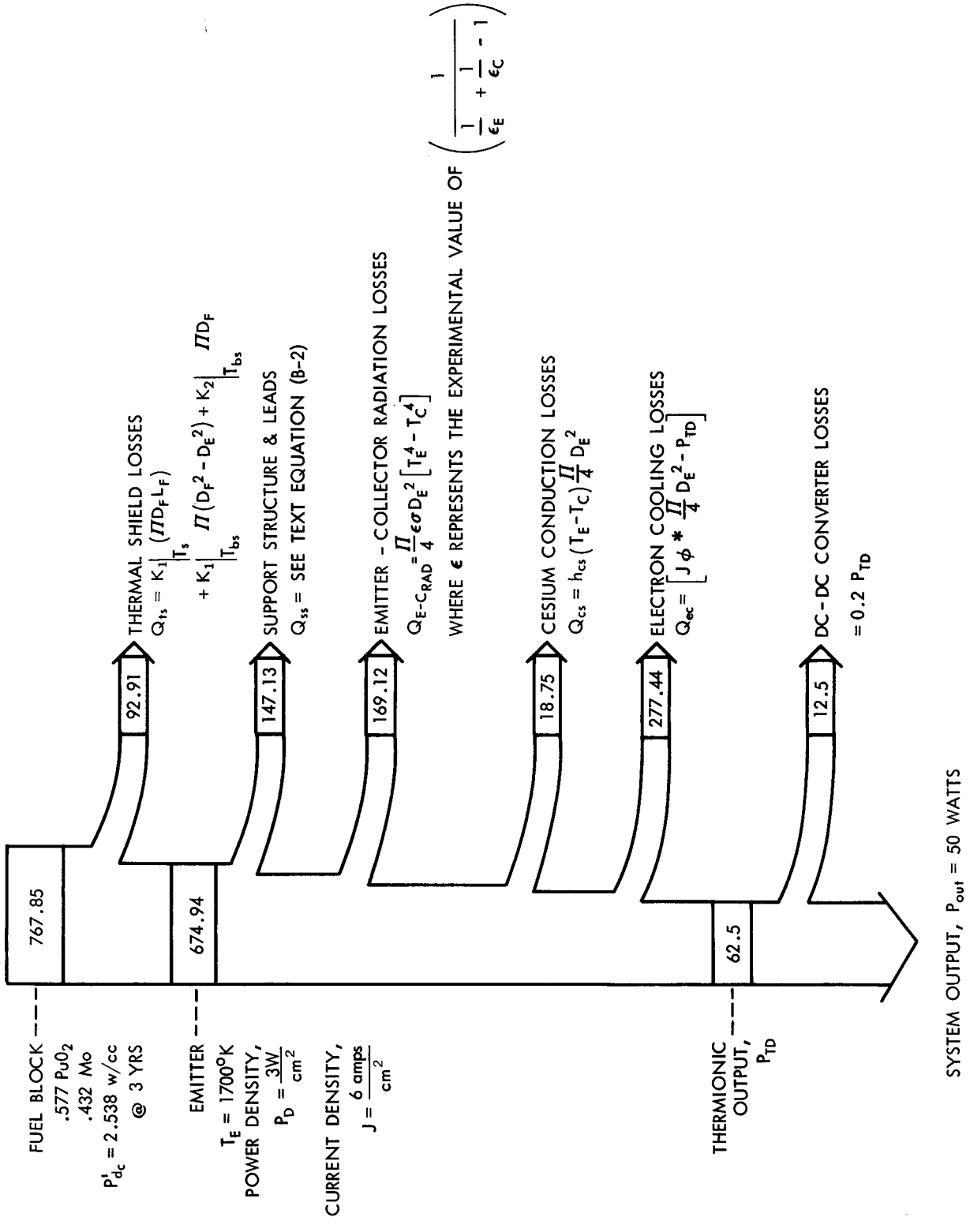

Figure 2–Thermal power flow diagram for PuO_2–fueled-thermionic power supply system (Rhenium emitter-molybdenum collector)

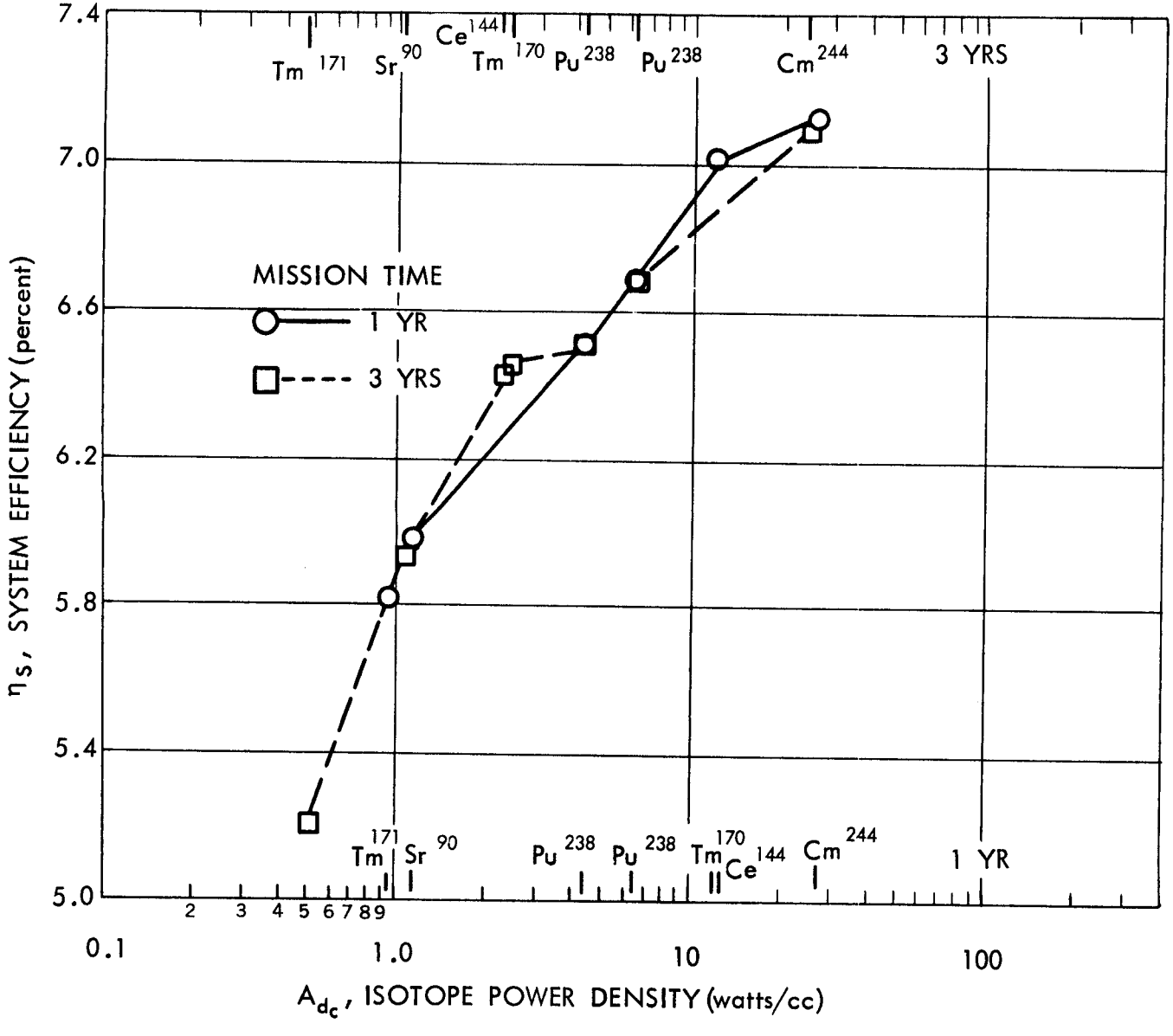

Figure 3-System efficiency versus isotope power density

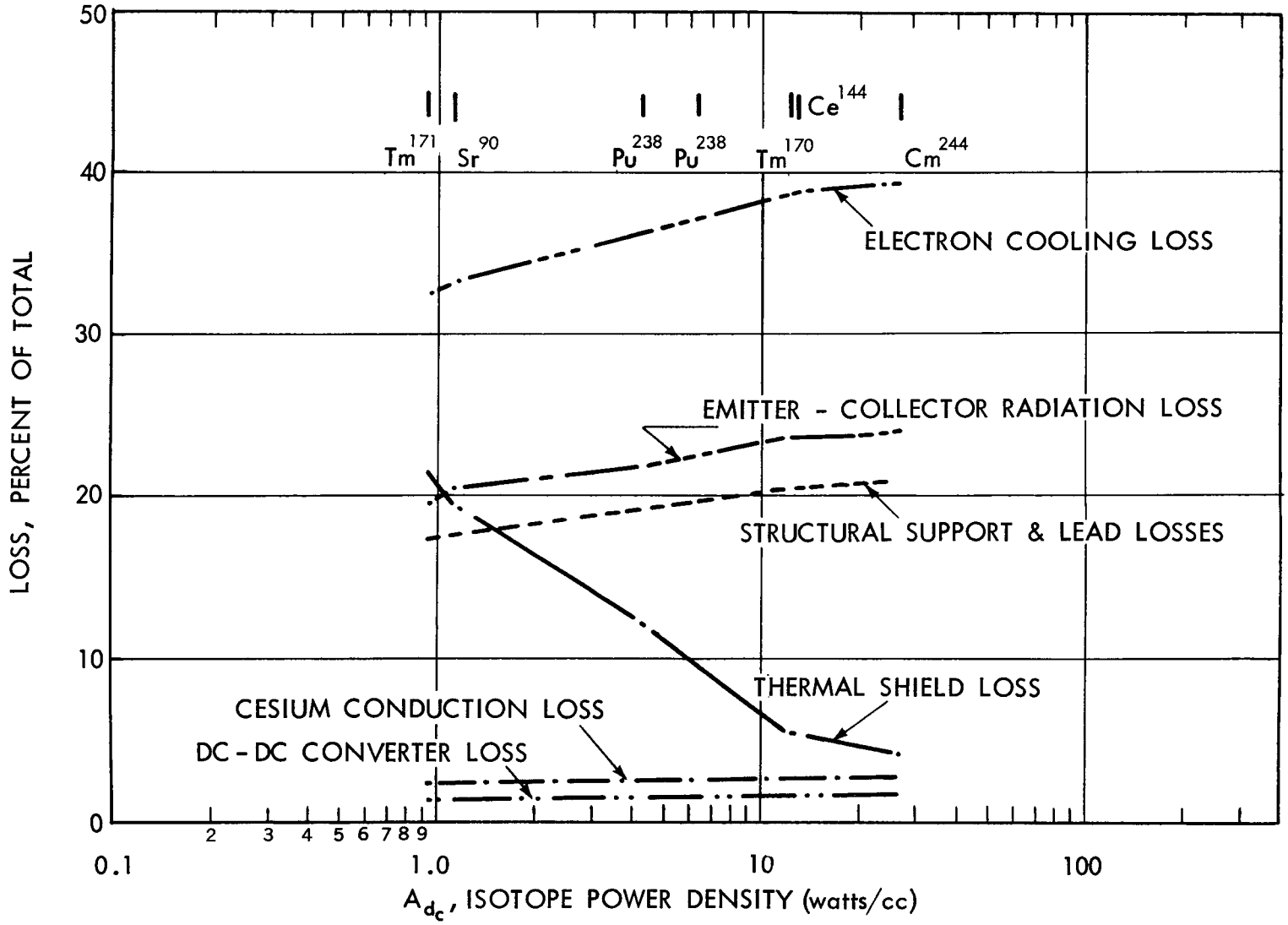

Figure 4(a)-Mission time 1 year Loss, percent of total versus isotope power density

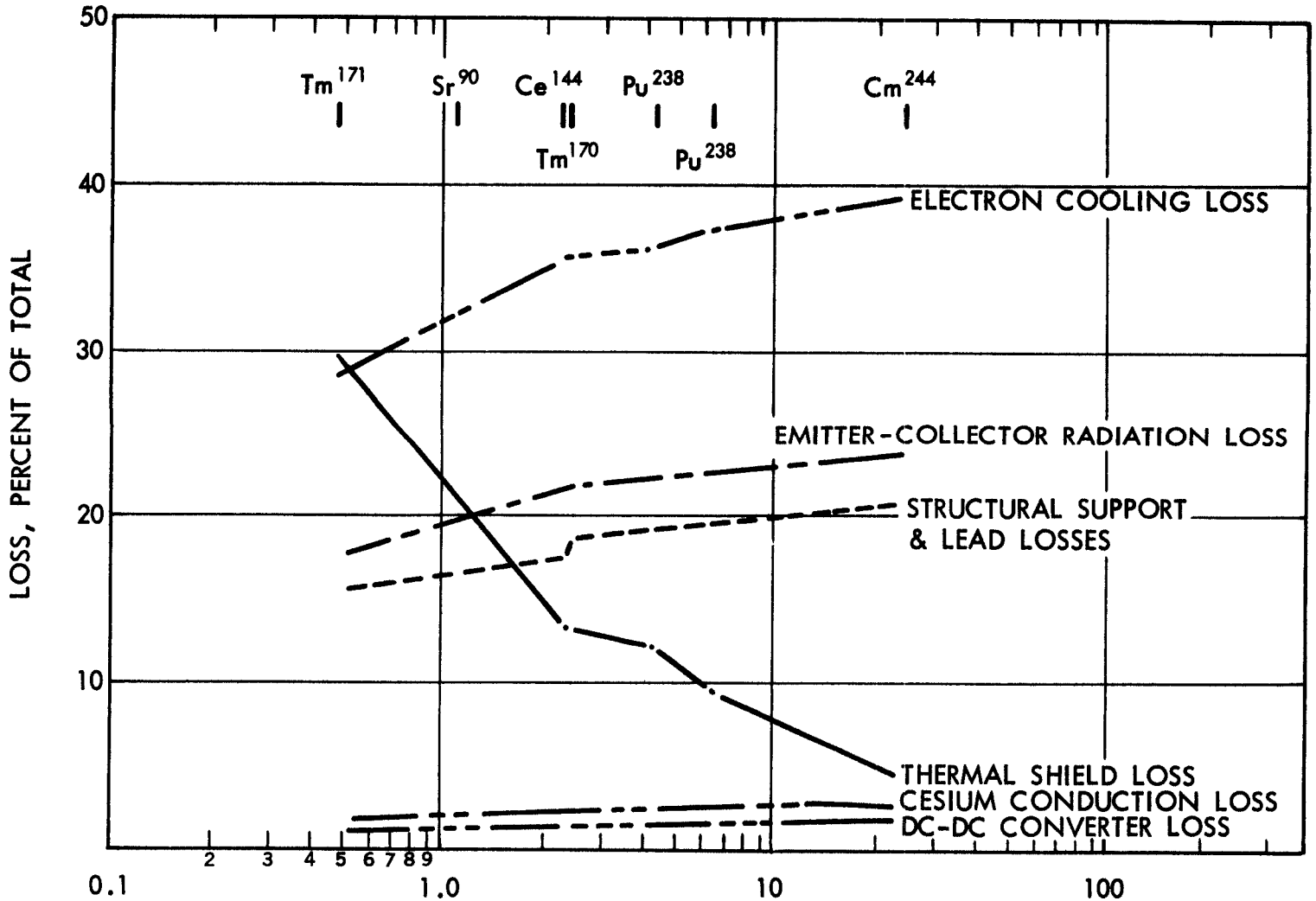

Figure 4(b)-Mission time 3 years Loss, percent of total versus isotope power density

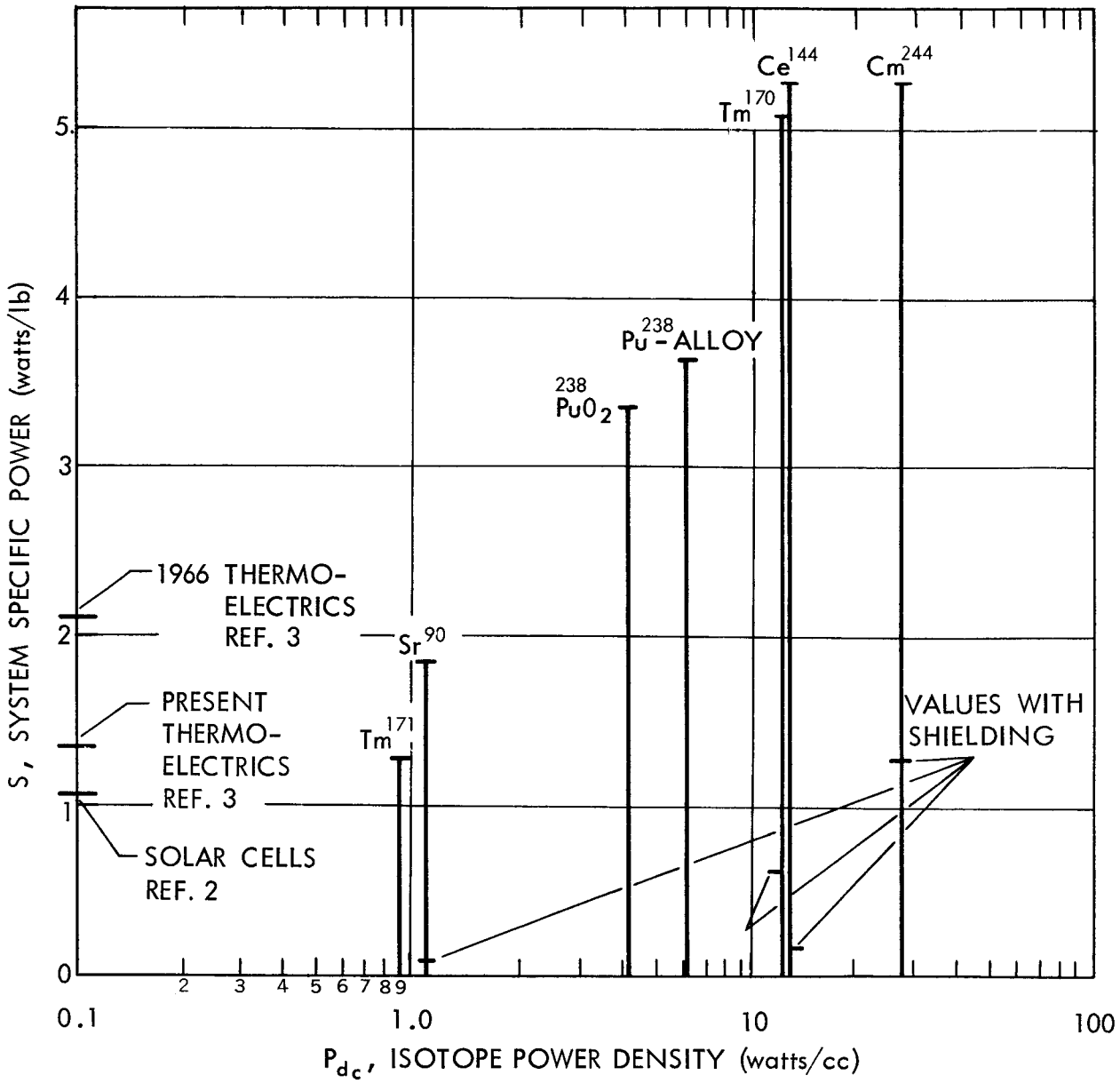

Figure 5(a)-Mission time 1 year System Specific Power versus isotope power density

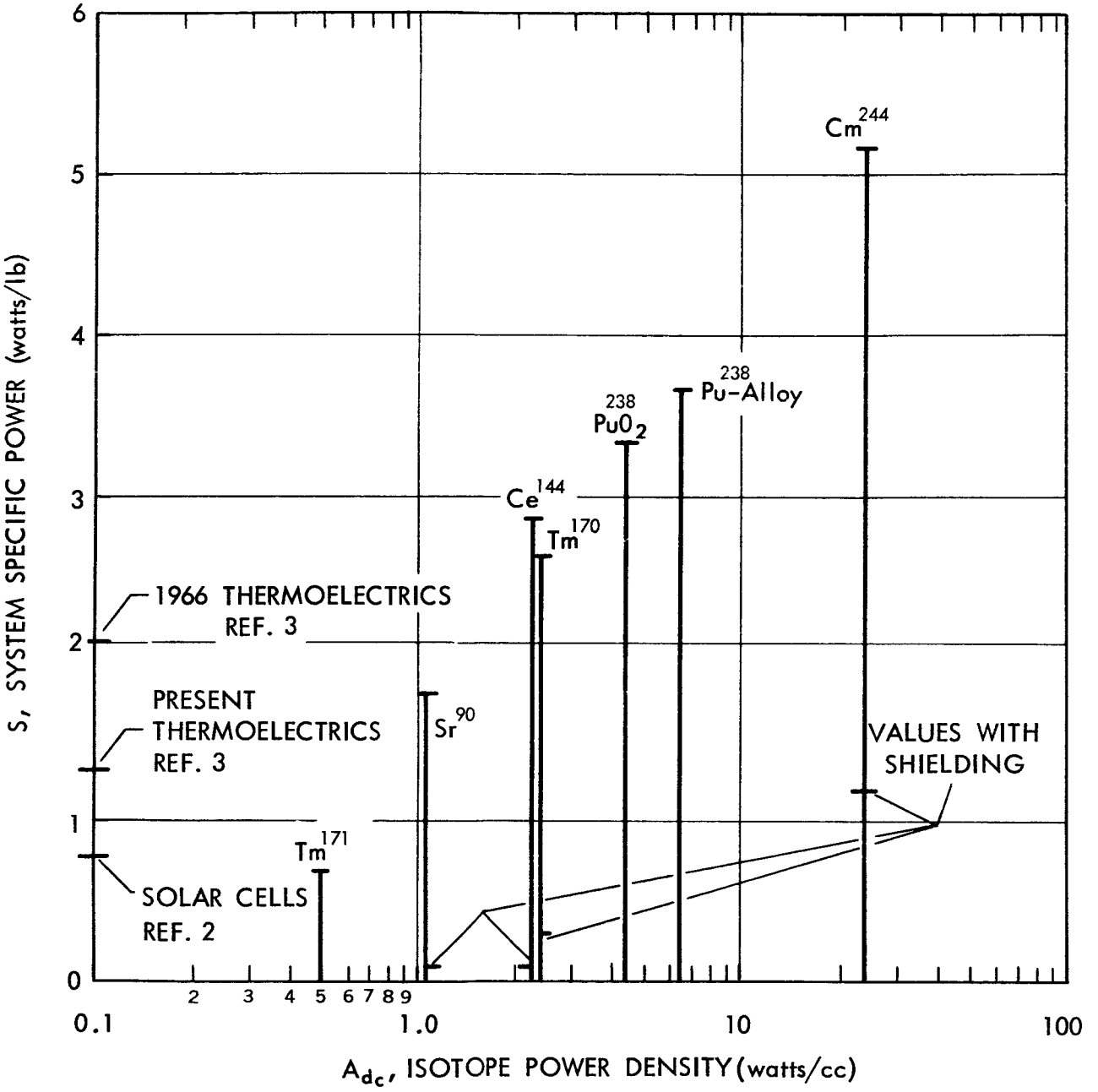

Figure 5(b)–Mission time 3 years System Specific Power versus isotope power density

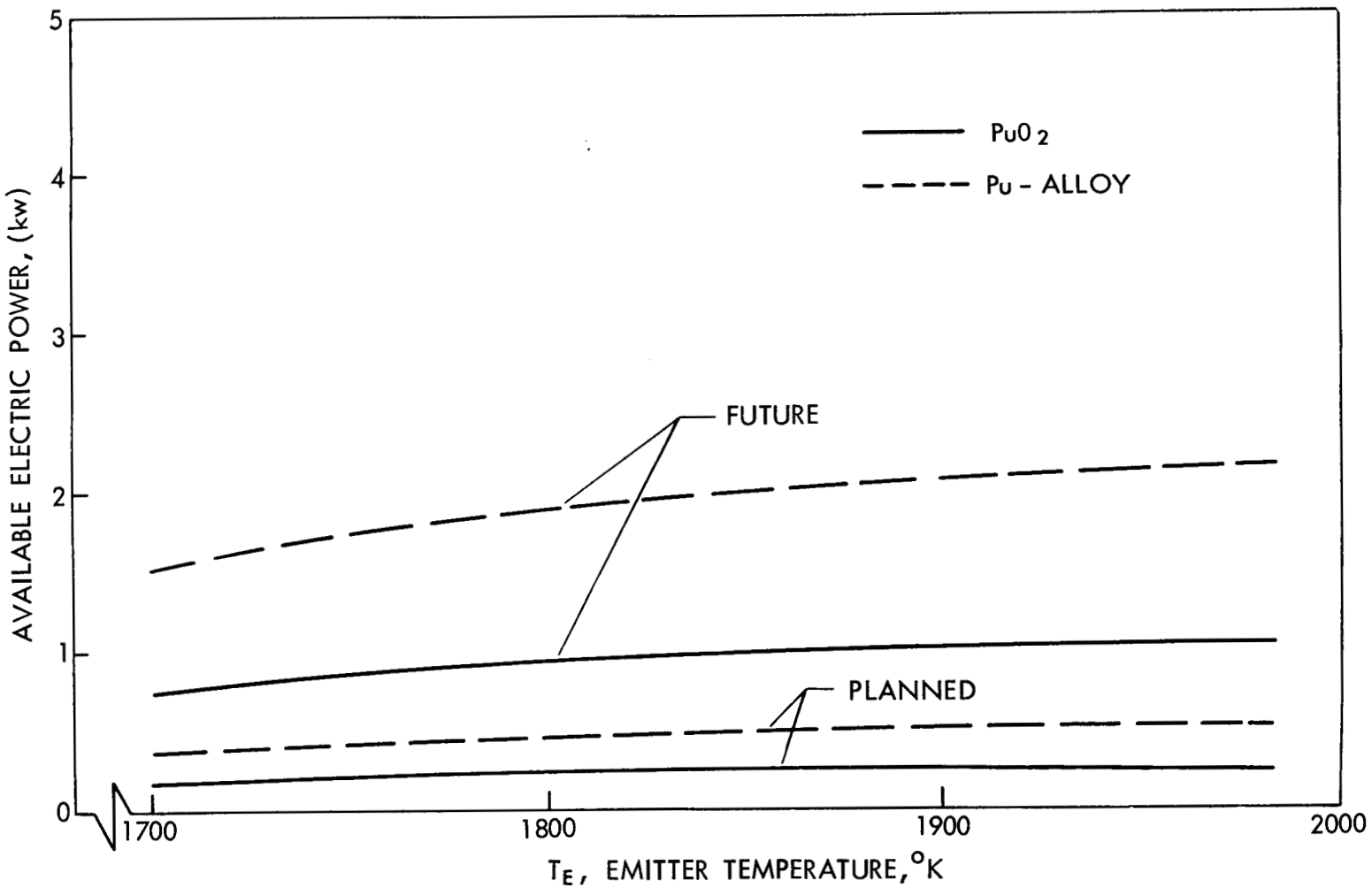

Figure 6–Available electric power, KW versus emitter temperature for plutonium compounds

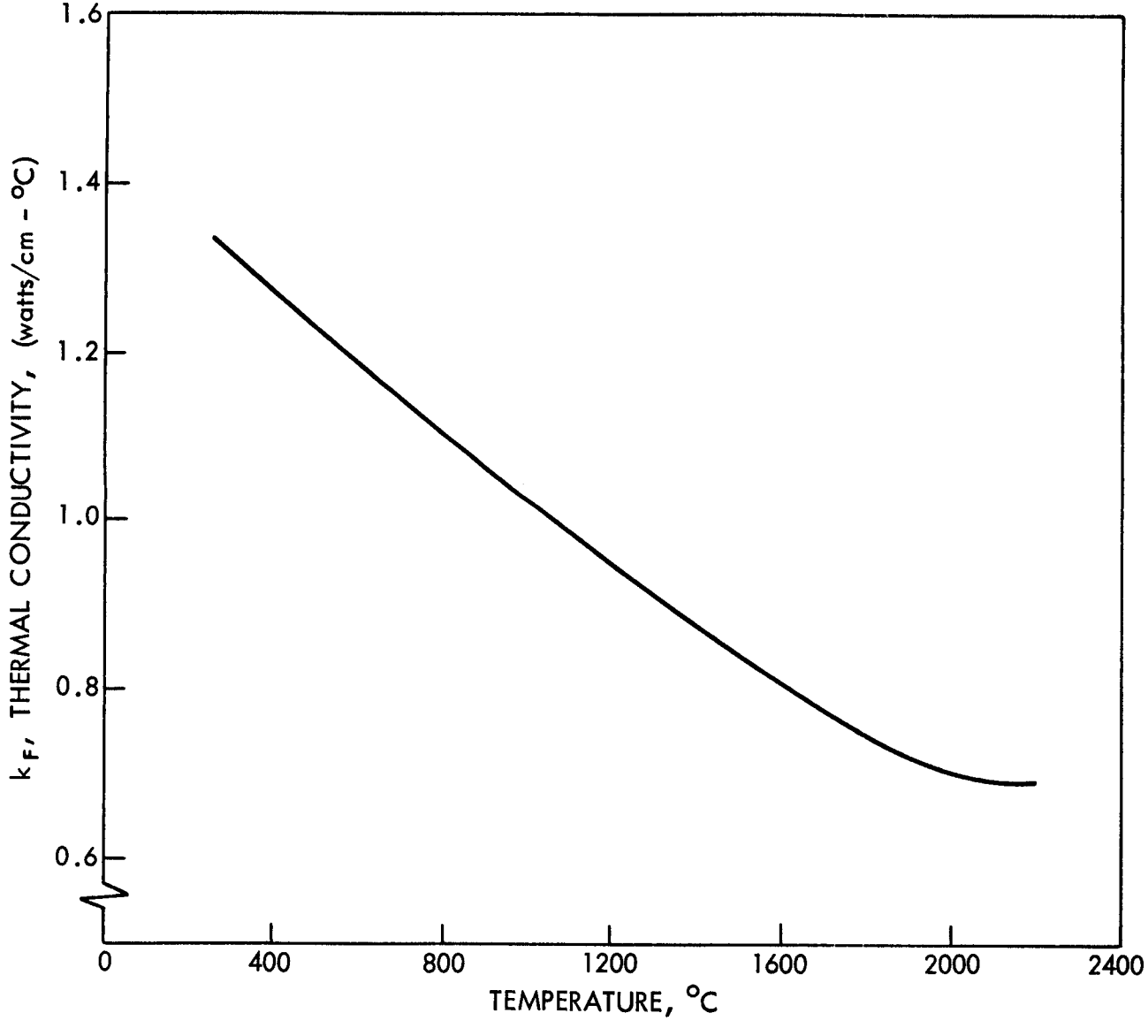

Figure 7-Thermal conductivity of molybdenum versus temperature

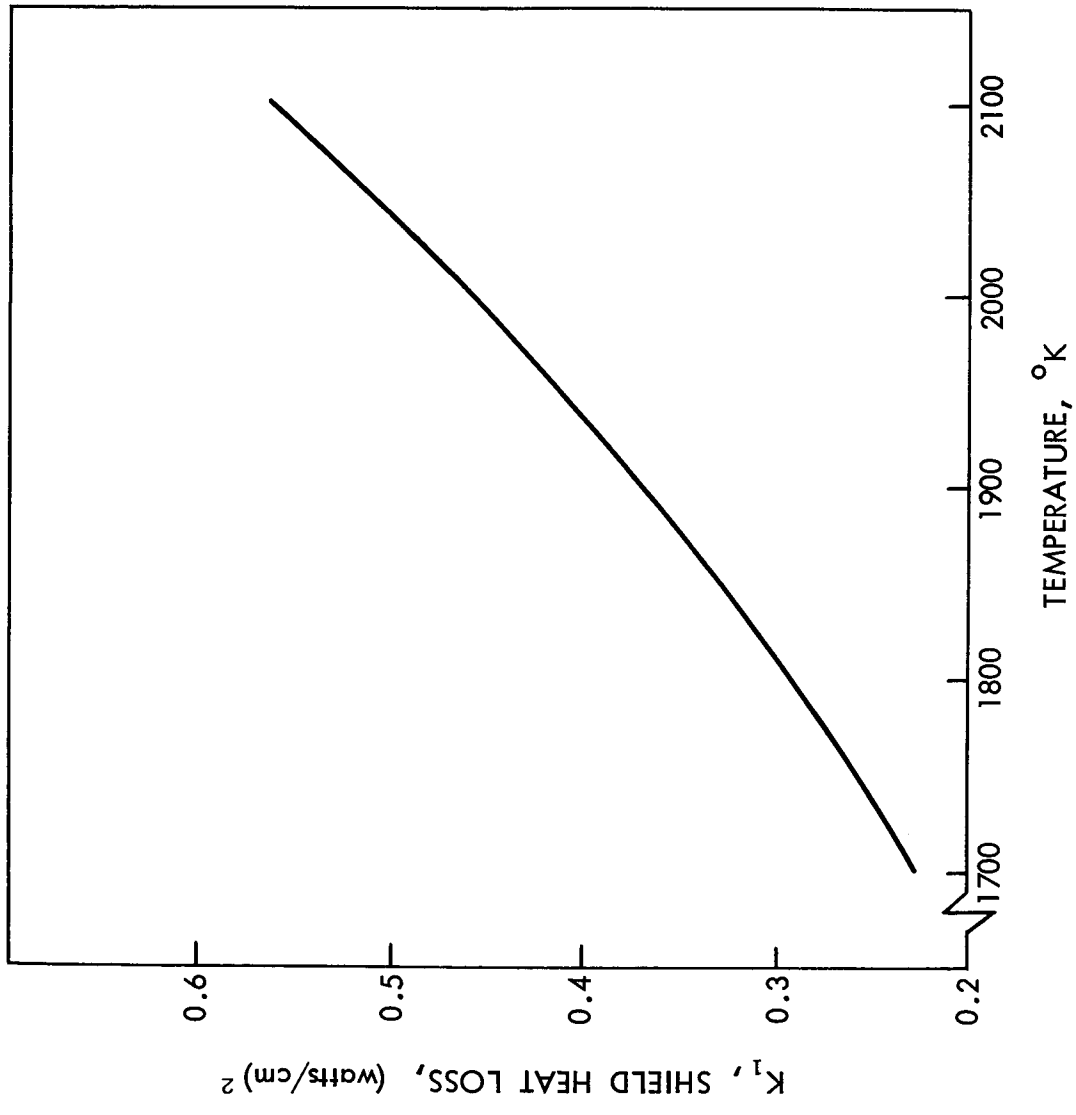

Figure 8-Thermal Shield Loss Constant versus temperature

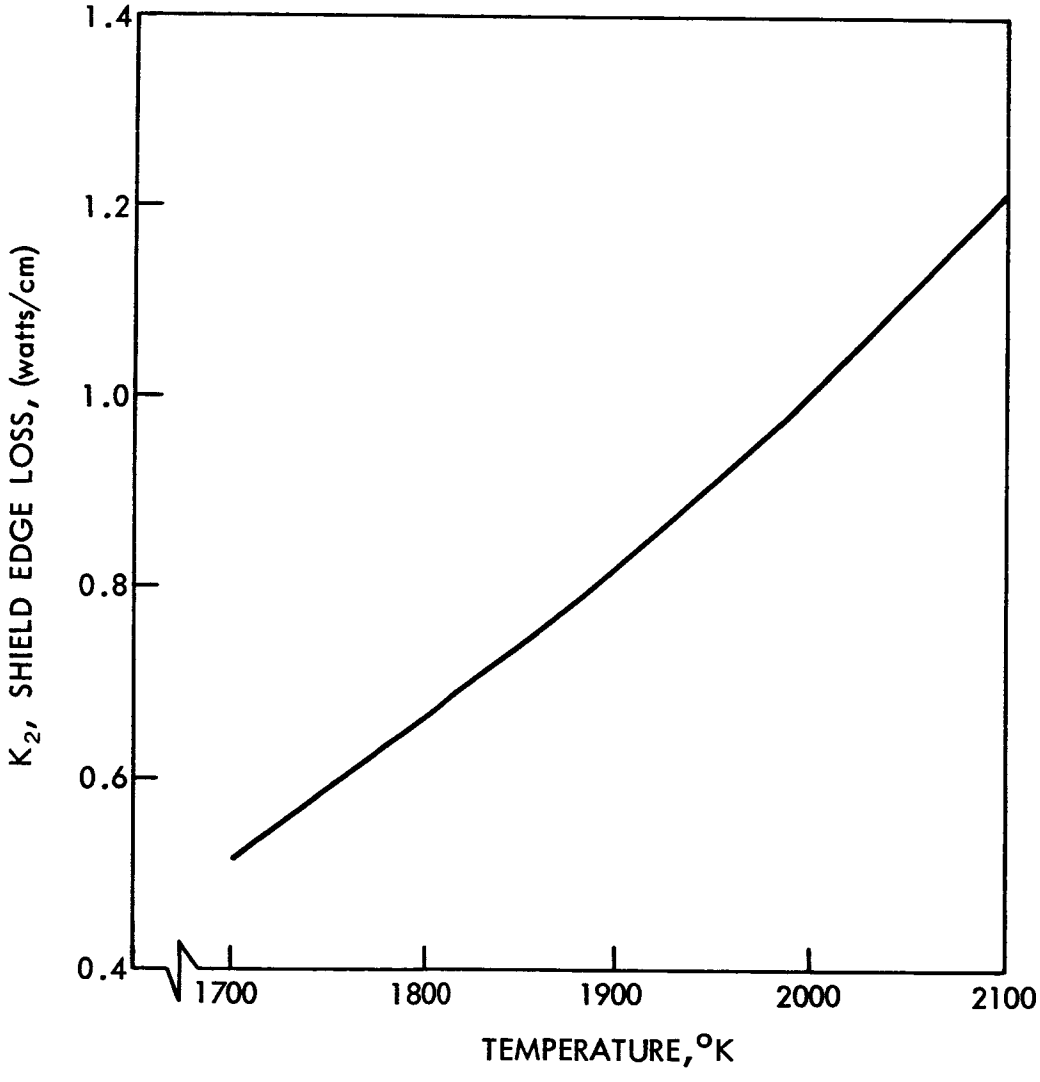

Figure 9–Thermal Shield Edge Loss Constant versus temperature