NASA TECHNICAL MEMORANDUM

NASA TM X-1501

NASA TM X-1501

(ACCESSION NUMBER)	(THRU)
(PAGES)	(CODE)
(NASA CR OR TMX OR AD NUMBER)	(CATEGORY)

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by James J. Ward and Robert Ruch

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JANUARY 1968

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SUMMARY

The results of an analysis of a radioisotope cascaded thermoelectric generator are presented. The generator consisted of a high-temperature silicon-germanium (Si-Ge) first stage and a lower-temperature lead telluride (PbTe) second stage. The two stages were placed concentrically around a cylindrical fuel block. Heat was rejected from the outer surface of the generator shell, and, in most cases, fins were required to augment the heat-rejection capability of the shell. The Si-Ge hot-junction temperature range was 1089° to 1255° K. The PbTe hot-junction temperature was fixed at 811° K and the PbTe cold-junction temperature varied from 422° to 700° K. The fuel-block length-diameter ratio varied from 0.5 to 10.0. The fuel-block-volume power-density range was 0.5 to 10.0 watts per cubic centimeter. The generator power output was fixed at 250 watts electric. Generator efficiency and specific weight were calculated over the specified range of variables.

The performance of cascaded generators is also compared to the performance of single-stage Si-Ge generators.

The results indicate that the cascaded generator operating at a Si-Ge hot-junction temperature of 1089° K had a minimum specific weight of 220 pounds per kilowatt electric (100 kg/kW_e) at an efficiency of nearly 7 percent. For a Si-Ge hot-junction temperature of 1255° K, the minimum specific weight was 170 pounds per kilowatt electric (77 kg/kW_e) with an efficiency of over 8 percent. The single-stage Si-Ge generator with a hot-junction temperature of 1255° K had a minimum specific weight of 100 pounds per kilowatt electric (45 kg/kW_e) at an efficiency slightly below 6 percent.

INTRODUCTION

Radioisotope thermoelectric generators using lead telluride (PbTe) elements have been used in a number of low-power space missions and, although relatively heavy, appear suitable for future missions requiring electric power levels up to several hundred watts. Studies have shown that substantial weight savings can be expected in advanced generators by using silicon-germanium (Si-Ge) thermoelectric elements and higher-temperature heat sources (ref. 1). It would also appear advantageous to incorporate both Si-Ge and PbTe elements in a two-stage generator with the individual thermoelectric stages operating in the temperature regions in which they are most efficient (ref. 2). The generator considered in this study employs Si-Ge in the high-temperature stage and PbTe in the low-temperature stage. The efficiency and specific weight of this cascaded generator are calculated and the results compared to the performance of a single-stage Si-Ge generator.

A cylindrical heat-source geometry was assumed with the thermoelectric elements located around the lateral surface of the cylinder. Specific radioisotopes were not selected for the analysis; instead the effective volume-power-density of the heat source, defined as the heat generated in the source divided by the source total volume, was used as a parameter.

Generator efficiency and specific weight are presented for a 250-watt-electric generator. Parameters included are heat-source length-diameter ratio (0.5 to 10.0), heat-source-volume power density (0.5 to 10.0 W/cm^3), Si-Ge hot-junction temperature (1089° and 1255° K), and PbTe cold-junction temperature (422° to 700° K). The PbTe hot-junction temperature was assumed equal to the Si-Ge cold-junction temperature and was fixed at 811° K.

Such factors as nuclear shielding, reentry protection, power flattening, and power conditioning, which also affect generator design, were not included in the analysis since they are highly mission dependent. Thus, only the effects of selected design variables on the performance of the basic generator have been determined.

SYMBOLS

a	thickness of fin at tip
b	thickness of fin at root
D	fuel-block diameter, cm
K_n	thermal conductivity of n-type thermoelement, $W/(cm)(^\circ K)$
K_p	thermal conductivity of p-type thermoelement, $W/(cm)(^\circ K)$
L	length of thermoelement, cm
L/D	fuel-block length-diameter ratio
P_d	thermoelectric power density, W_e/cm^2

P_{out} total generator output power, W_e

P_{PbTe} lead telluride stage output power, W_e

P_{SiGe} silicon-germanium stage output power, W_e

Q_{in} total heat generated in fuel block, W_t

Q_{rej} heat rejected from generator, W_t

q_v heat generated in fuel block per unit volume, W_t/cm^3

R_c element contact resistance, (ohm)(cm^2)

S_n Seebeck coefficient of n-type thermoelements, $V/^oK$

S_p Seebeck coefficient of p-type thermoelements, $V/^oK$

T_c lead telluride stage cold-junction temperature, ^oK

T_H silicon-germanium stage hot-junction temperature, ^oK

T_1 element hot-junction temperature, ^oK

T_2 element cold-junction temperature, ^oK

Z thermoelectric figure of merit, $^oK^{-1}$

η_D thermoelectric efficiency

η_G generator efficiency

ρ element electrical resistivity, (ohm)(cm)

ρ_c element electrical resistivity corrected for lead loss and contact resistances, (ohm)(cm)

ρ_n corrected electrical resistivity of n-type elements, (ohm)(cm)

ρ_p corrected electrical resistivity of p-type elements, (ohm)(cm)

τ fin thickness ratio, 1 - a/b

METHOD OF ANALYSIS

A schematic diagram of the generator analyzed is shown in figure 1. The thermal input to the generator is provided by a cylindrical fuel block containing radioisotopic fuel. The high-temperature Si-Ge stage is in contact with the lateral surface of the fuel block and is surrounded by the lower temperature PbTe stage. Fibrous thermal insulation is used to reduce heat loss from areas not covered by the thermoelements. Waste heat from the elements and heat conducted through the insulation must be rejected from the generator. In most cases fins are required to augment the heat-rejection capability of the generator shell. Where necessary, five beryllium fins of triangular cross section are placed around the lateral surface of the generator shell.

Generator efficiency and specific weight were calculated for silicon-germanium-element hot-junction temperatures of 1089° and 1255° K. The cold-junction temperature of the Si-Ge elements, assumed to be the same as the hot-junction temperature of the PbTe elements, was fixed at 811° K. The cold-junction temperature range for the PbTe elements was from 422° to 700° K. The fuel-block effective volume power density q_v varied from 0.5 to 10.0 watts per cubic centimeter. The range of fuel-block length-diameter ratio L/D was 0.5 to 10.0 The PbTe element lengths considered were 0.508, 0.762, 1.016, and 1.27 centimeters while the Si-Ge element length was fixed at 1.27 centimeters.

In the analysis, efficiency and power density were calculated for the thermoelectric elements from the material Seebeck coefficient, and thermal conductivity, and an effective electrical resistivity. The effective electrical resistivity used in the thermoelectric performance calculations included a 10 percent lead loss and junction-contact resistances. The contact resistance is the resistance of the interface between the thermoelectric element and either the hot or cold plate to which it is attached. Equation (1) indicates the method of determining the effective resistivity:

$$\rho_c = 1.1\,\rho + \frac{R_c}{L} \tag{1}$$

The contact resistance was assumed to be 50 microhm - centimeter squared per junction for both p- and n-type Si-Ge elements. For PbTe, a contact resistance of 200 microhm - centimeter squared per junction was assumed for the p-type elements and 112.5 microhm - centimeter squared per junction for the n-type elements. These contact resistances are considered to be representative for currently available elements. The following equations (from ref. 3) are used to calculate the thermoelectric figure of merit, power density, and efficiency, respectively:

$$Z = \frac{\left(|S_p| + |S_n|\right)^2}{\left(\sqrt{\rho_n K_n} + \sqrt{\rho_p K_p}\right)^2} \tag{2}$$

$$P_d = \frac{K_p}{4L} Z(T_1 - T_2)^2 \left(\frac{1 + \sqrt{\frac{\rho_n K_n}{\rho_p K_p}}}{1 + \sqrt{\frac{\rho_n K_p}{\rho_p K_n}}} \right) \tag{3}$$

$$\eta_D = \frac{Z}{4} (T_1 - T_2) \frac{1}{1 + \frac{ZT_1}{2} - \frac{Z(T_1 - T_2)}{8}} \tag{4}$$

The thermoelectric power density and efficiency are used in the heat-balance equations of the system in order to determine the dimensions of the generator. These equations are derived from the heat-flow diagram (fig. 2). The equations reduce to the form of two simultaneous cubic equations in two unknowns: fuel-block diameter and Si-Ge stage electric power output. Once the values of these parameters have been determined, generator efficiency may be calculated directly from the following equations:

$$Q_{in} = q_v \pi \frac{L}{D} \frac{D^3}{4} \tag{5}$$

$$P_{PbTe} = P_{out} - P_{SiGe} \tag{6}$$

$$Q_{rej} = Q_{in} - P_{out} \tag{7}$$

$$\eta_G = \frac{P_{out}}{Q_{in}} \tag{8}$$

In calculating the heat flux through the thermal insulation, thermal conductivity was fixed at 2.6×10^{-4} watt per centimeter - $^{\circ}$K for temperatures up to 1251° K. For temperatures above 1251° K the conductivity was fixed at 4.8×10^{-4} watt per centimeter - $^{\circ}$K.

In the heat-rejection analysis, the lateral surface area of the generator was assumed to be the only area contributing to heat rejection, and the shell temperature was taken equal to the PbTe cold-junction temperature. Where fins were required, the design technique of reference 4 was used, assuming five tapered beryllium fins having an emissivity of 0.9 and a thickness ratio τ of 0.99. Parameters required to calculate fin weight are given in table A2 of reference 4.

The generator specific weight was calculated by summing all component weights and dividing by the total electric power output. In the weight calculations, the physical density of the fuel block was fixed at 10 grams per cubic centimeter over the entire q_v range, a value that was considered representative for most of the isotopes of interest. The Si-Ge element density was taken as 4.31 grams per cubic centimeter compared to PbTe element density of 11.5 grams per cubic centimeter. The density of the thermal insulation was taken as 0.03 gram per cubic centimeter.

In the generator design, shown in figure 1, René 41 was selected as the outer shell material because of its high strength and resistance to oxidation at the temperatures of interest. The outer shell was made thick enough to withstand a pressure differential of 1 atmosphere (10.1 N/cm^2). However, a lower limit on thickness of 0.152 centimeter was assumed. An 0.152-centimeter-thick sleeve of René 41 was also placed between thermoelectric-element stages to serve as the cold plate for the Si-Ge stages and the hot plate for the PbTe stage.

RESULTS AND DISCUSSION

Generator Design Considerations

Effect of thermoelectric element coverage. - In some cases it was found that the thermoelectric element coverage and/or generator heat-rejection requirements limit the available range of generator design variables. For this reason, some of the generator performance curves do not extend over the full range of input variables.

In figure 3, the fractional area coverage of the Si-Ge elements is shown as a function of fuel-block L/D with q_v as a parameter. Only data for a 0.508-centimeter-long PbTe element are presented since the Si-Ge fractional coverage was quite insensitive to variations in PbTe element length. In this reference case, the hot-junction temperature was 1255° K and the cold-junction temperature was 589° K. For such a condition, the Si-Ge element power density was 0.831 watt per centimeter squared and the Si-Ge stage electrical power output was within 5 percent of 140 watts in all cases considered. The fractional area coverage is therefore inversely proportional to the lateral surface area of the fuel block. Note that in all cases the fractional coverage is well below the limiting value of 1.0. Therefore, coverage in the Si-Ge stage is not a limiting factor in generator design. However, at a q_v of 5.0 watts per cubic centimeter, the curves do not cover the full range of input variables. This is due to a limitation in PbTe element coverage which is discussed in the following paragraph.

Figure 4 shows the fractional coverage of PbTe elements as a function of fuel-block L/D for the reference case with q_v and PbTe element length as parameters. Note that at a q_v of 5.0 watts per cubic centimeter, the PbTe element fractional coverage reaches

1.0 at fuel-block L/D's of 1.1 and 2.8 for element lengths of 0.508 and 0.762 centimeter, respectively.

The L/D range for generators with longer PbTe elements at a q_v of 5.0 watts per cubic centimeter was so severely restricted by coverage limitations that the longer elements were not considered in the reference case analysis. Therefore, PbTe element coverage, at times, imposes a limit on generator design.

Heat-rejection consideration. - The analysis indicated that for the reference case ($T_H = 1255^{\circ}$ K, $T_c = 589^{\circ}$ K) fins are required over the entire range of q_v and L/D considered. To illustrate this, the ratio of the heat that can be rejected by the generator shell to the heat that must be rejected by the system is presented in figure 5(a) as a function of fuel-block L/D. The PbTe element length and fuel-block q_v are included as parameters. Because this ratio is less than 1.0 in all cases, fins must be used to augment the shell heat-rejection capability. The generators with the longer PbTe elements are capable of rejecting a higher fraction of the total waste heat because the longer PbTe elements are more efficient, and because these generators have larger shells. The other variations are the results of changes of lateral surface area with fuel-block L/D and q_v.

In the analysis, it was seen that some generators would require fins with bases too thick to be accommodated on the generator shell. Figure 5(b) indicates the ratio of total fin root thickness to generator shell circumference. Smaller fins are indicated at high L/D's and low fuel-block q_v's since the generator shell lateral surface area is larger at these conditions. At a q_v of 5.0 watts per cubic centimeter a fin root thickness to shell circumference ratio of 1.0 was reached at an L/D slightly below 3.0. Therefore, fin base size is a limiting factor in generator design for some conditions.

Figure 5(c) indicates the ratio of fin weight to generator total weight as a function of fuel-block L/D with PbTe element length and fuel-block q_v included as parameters. At a q_v of 0.5 watt per cubic centimeter and high L/D values, the fin weight is insignificant; however, in some cases severe fin weight penalties are indicated. For example, at a PbTe element length of 0.508 centimeter, a q_v of 5 watts per cubic centimeter, and an L/D of 3.0, the fin weight is three-fourths of the total generator weight.

Figures 3 to 5 indicate that PbTe element coverage and fin-root thickness may impose limitations on a generator design of this type, while no such restrictions are indicated regarding Si-Ge element coverage. In addition, the fin weight can represent a significant fraction of the total generator weight.

Effect of fuel-block geometry and volume power density. - Generator efficiency for the reference case is presented in figure 6 as a function of fuel-block L/D with q_v and PbTe element length as parameters. Note that in the cases where the L/D range is not limited by element coverage or heat-rejection considerations, the efficiency maximizes at an L/D near 1.0. Here, the minimum area-volume ratio of the fuel block is achieved and the parasitic heat losses are at a minimum. Designs with more compact (higher q_v) fuel blocks are also more efficient because of lower parasitic heat losses. In addition, the generators with longer PbTe elements have a higher fractional diode coverage in the PbTe stage and higher element efficiency, which results in lower parasitic heat losses and higher efficiencies.

The generator specific weights are presented as a function of L/D in figure 7. Note that the highest generator weights always occur at the lowest fuel-block L/D values. This is the result of the high fin weight which was shown to occur at low L/D values. For a q_v of 0.5 watt per cubic centimeter, the generator specific weight minimizes at an L/D of about 4.0. The slight weight increase at higher L/D's is due to larger fuel blocks. The generators with a q_v of 5.0 watts per cubic centimeter are considerably lighter, principally because of the smaller, lighter fuel blocks. There are no minimums observed in the specific-weight curves for these generators. This is due to the fact that the fin weight is a significant fraction of the total generator weight and decreases sharply as L/D increases.

Performance Summary Curves

In figure 8, generator minimum specific weights are presented for Si-Ge hot-junction temperatures of 1089° and 1255° K and a wide range of PbTe cold-junction temperatures. In most cases, the specific weight is high at low q_v's and minimizes in the q_v range of 1.0 to 7.0 watts per cubic centimeter. The exception is the curve representing generators with a hot-junction temperature of 1089° K and a cold-junction temperature of 700° K (fig. 8(a)). In this case, the useful volume power density is restricted to 3.0 watts per cubic centimeter or less because of element coverage limitations. The high specific weights at low q_v's are primarily due to the heavy fuel blocks. The high specific weights observed at high q_v's are due to the large heavy fins required on these generators. Also, high specific weights are observed at low rejection temperatures because of the fin weight penalties incurred.

Figure 9 shows generator maximum efficiencies and efficiencies of generators at minimum specific weight as functions of fuel-block q_v. Figure 9(a) represents the case in which the hot-junction temperature is 1089° K, while figure 9(b) represents the case in which the hot-junction temperature is 1255° K. For a given fuel-block q_v, generator efficiency increases as cold-junction temperature decreases. The fuel-block q_v has little effect on generator efficiency except at low q_v's, where increased parasitic heat losses lower the efficiency slightly. It is important to note that there is little difference in efficiency between generators designed for minimum specific weight and those designed for maximum efficiency, the largest relative difference being less than 10 percent. On the other hand, generators designed for maximum efficiency are often much heavier than those designed for minimum specific weight. For instance, at a hot-junction temperature of 1255° K, a cold-junction temperature of 422° K, and a fuel-block q_v of 1.0 watt per cubic centimeter, the generator designed for maximum efficiency weighs 1300 pounds per kilowatt electric (589 kg/kW_e); while the generator designed for minimum specific weight weighs 440 pounds per kilowatt electric (199 kg/kW_e).

A comparison of figures 8 and 9 indicates that higher efficiencies and lower weights are achievable by operating at higher hot-junction temperatures. For instance, at a hot-junction temperature of 1255° K, a generator could be built which would weigh 170 pounds per kilowatt electric (77 kg/kW_e) and have an efficiency of 8.2 percent. At a hot-junction temperature of 1089° K, the lightest generator would weigh 220 pounds per kilowatt electric (100 kg/kW_e) and have an efficiency of 6.7 percent. An actual generator then would be designed to operate at the highest possible hot-junction temperature consistent with the fuel-block temperature capability. However, such specific information as mission requirements and isotope availability is needed in order to establish firmly the optimum cold-junction temperature.

System Comparisons

In reference 1, the results of a parametric analysis of a single-stage 250-watt-electric Si-Ge generator are presented. Figure 10 presents generator minimum specific weight for both the single-stage generator and the cascaded generator as functions of fuel-block q_v with Si-Ge hot-junction temperature as a parameter. The figure indicates that at low fuel-block q_v, the cascaded generator is somewhat lighter than the single-stage generator. However, at high fuel-block q_v, the single-stage generator is lighter than the cascaded generator. The crossover point is at a fuel-block q_v of approximately 3.0 watts per cubic centimeter.

Figure 11 presents the efficiencies of both minimum weight generators as functions of fuel-block q_v with Si-Ge hot-junction temperature as a parameter. As indicated, the cascaded generator is more efficient in all cases considered. Therefore, if high generator efficiency is the prime requirement, a cascaded generator would be most suitable.

However, isotope fuels having high volume power density may not be readily available, and such considerations, in addition to weight and efficiency, will influence the selection of a particular type generator.

SUMMARY OF RESULTS

The following results were obtained from a parametric analysis of a cascaded silicon-germanium, lead telluride radioisotope generator which considered the effects of fuel-block volume power density, silicon-germanium hot-junction temperature, lead telluride element length, lead telluride cold-junction temperature, and fuel-block length-diameter ratio:

1. There is an advantage on the basis of both generator efficiency and generator specific weight in achieving a fuel-block volume power density of at least 3.0 watts per cubic centimeter.

2. At a given heat-rejection temperature, the cascaded generator designed for minimum specific weight is considerably lighter than the generator designed for maximum efficiency. The efficiency of the lightweight generator is, however, only slightly below the maximum achievable.

3. The minimum cascaded-generator specific weight and the efficiency corresponding to minimum weight are presented in the following table for silicon-germanium hot-junction temperatures of 1089° and 1255° K:

	Hot-junction temperature, $^{\circ}K$	
	1089	1255
Minimum generator specific weight, lb/kW_e (kg/kW_e)	220 (100)	170 (77)
Generator efficiency at minimum specific weight, percent	6.7	8.2

4. In comparison to single-stage silicon-germanium generators at the same hot-junction temperature, the cascaded generators are typically 40 to 50 percent more efficient over the entire fuel-block volume-power-density range considered. The cascaded generator is also lighter than the single-stage generator at low values of fuel-block volume power density, but somewhat heavier than the single-stage generator at high volume power density, the crossover point being about 3.0 watts per cubic centimeter.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 19, 1967,
120-27-06-06-22.

REFERENCES

1. Ward, James J.; Bifano, William J.; and Blair, Larry S.: Parametric Analysis of Radioisotope-Thermoelectric Generators. NASA TM X-1453, 1967.
2. Freedman, Steven I.: Thermoelectric Power Generation. Direct Energy Conversion. George W. Sutton, ed., McGraw-Hill Book Co., Inc., 1966, pp. 150-155.
3. Cadoff, Irving B.; and Miller, Edward, eds.: Thermoelectric Materials and Devices. Reinhold Publishing Corp., 1960, pp. 227-249.
4. Harris, Dale W.; Burian, R. J.; and Ketchman, J. J.: A Design Procedure for the Weight Optimization of Straight Finned Radiators. NASA TN D-3489, 1966.

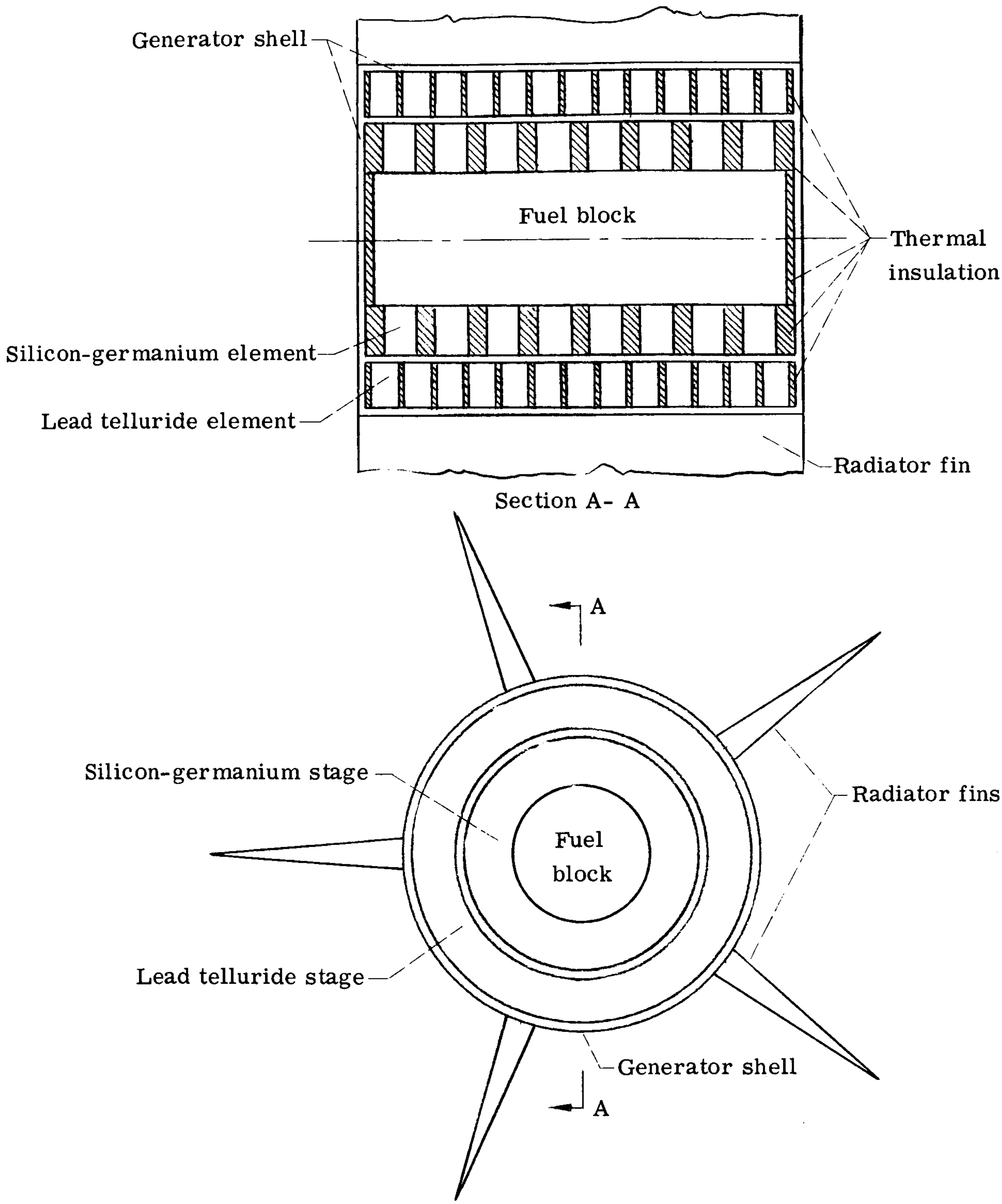


Figure 1. - Conceptual design of cascaded-radioisotope thermoelectric generator.

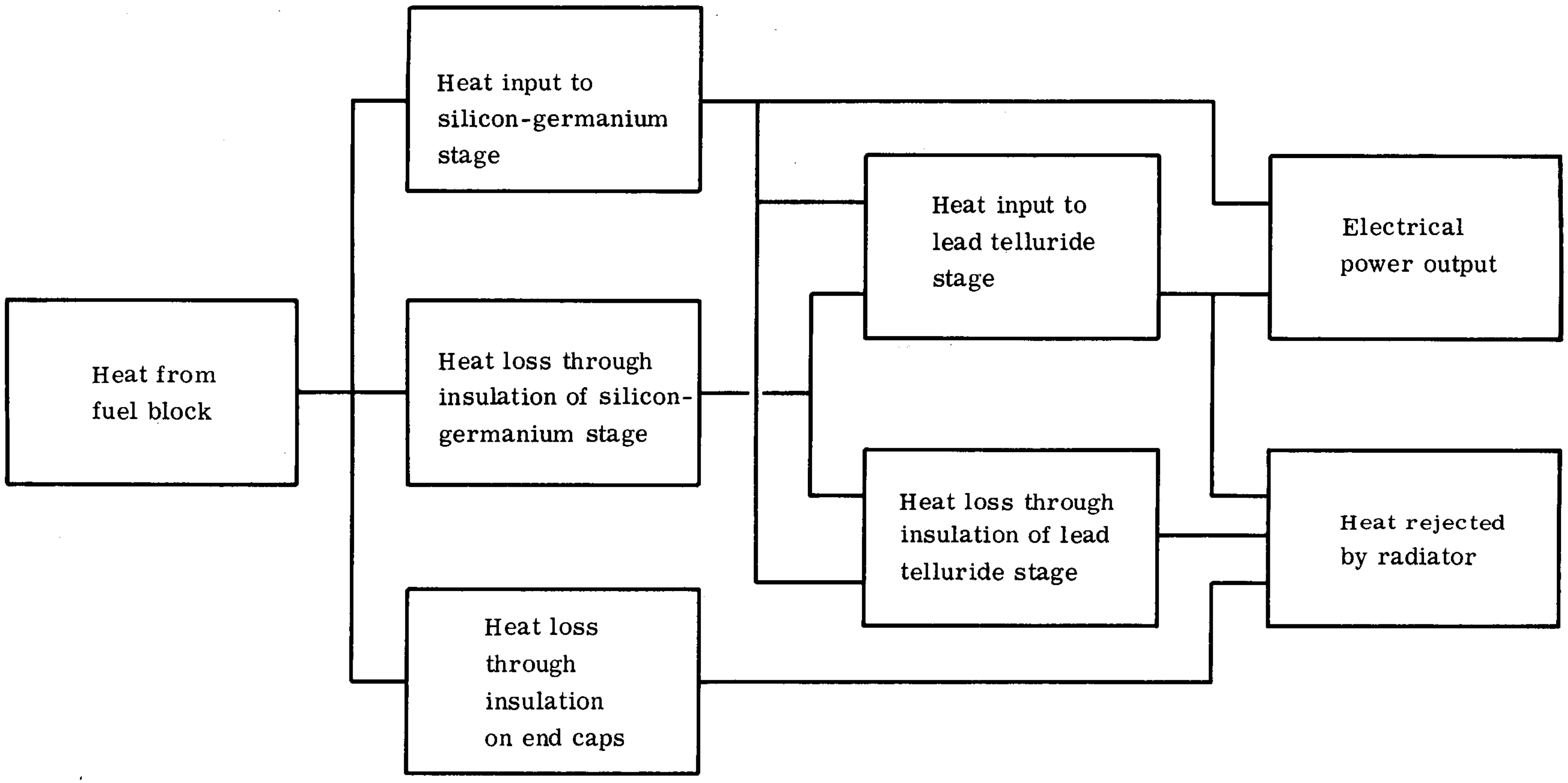


Figure 2. - Heat flow diagram for cascaded generator.

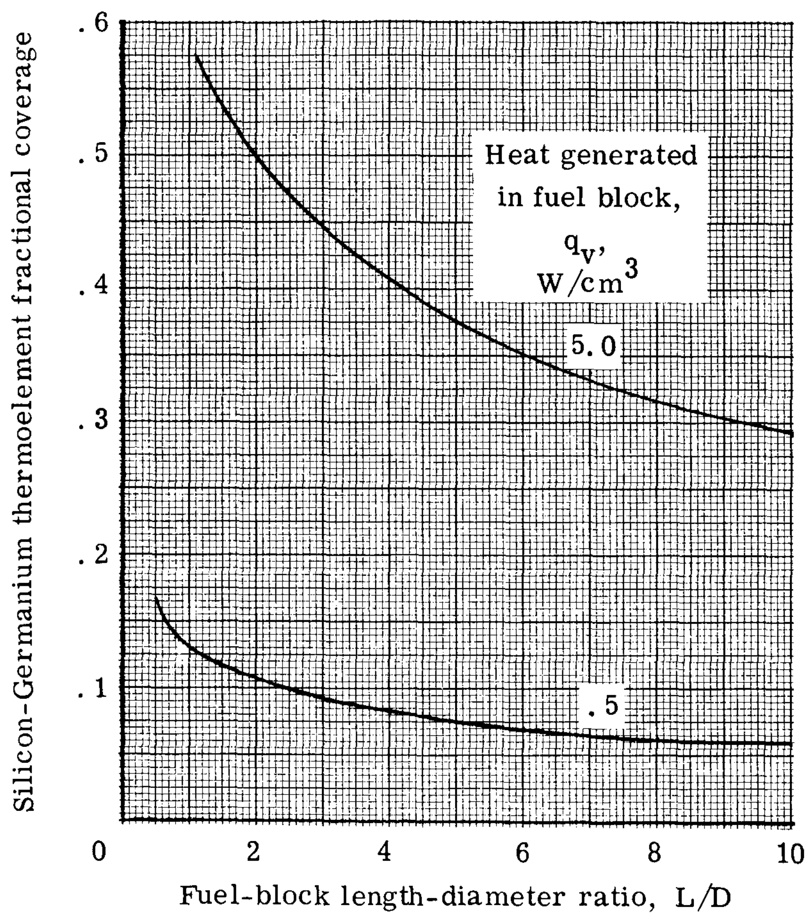


Figure 3. - SiGe fractional coverage as a function of fuel-block length-diameter ratio. Hot-junction temperature, 1255° K; cold-junction temperature, 589° K; PbTe element length, 0.508 centimeter; power output, 250 watts electric.

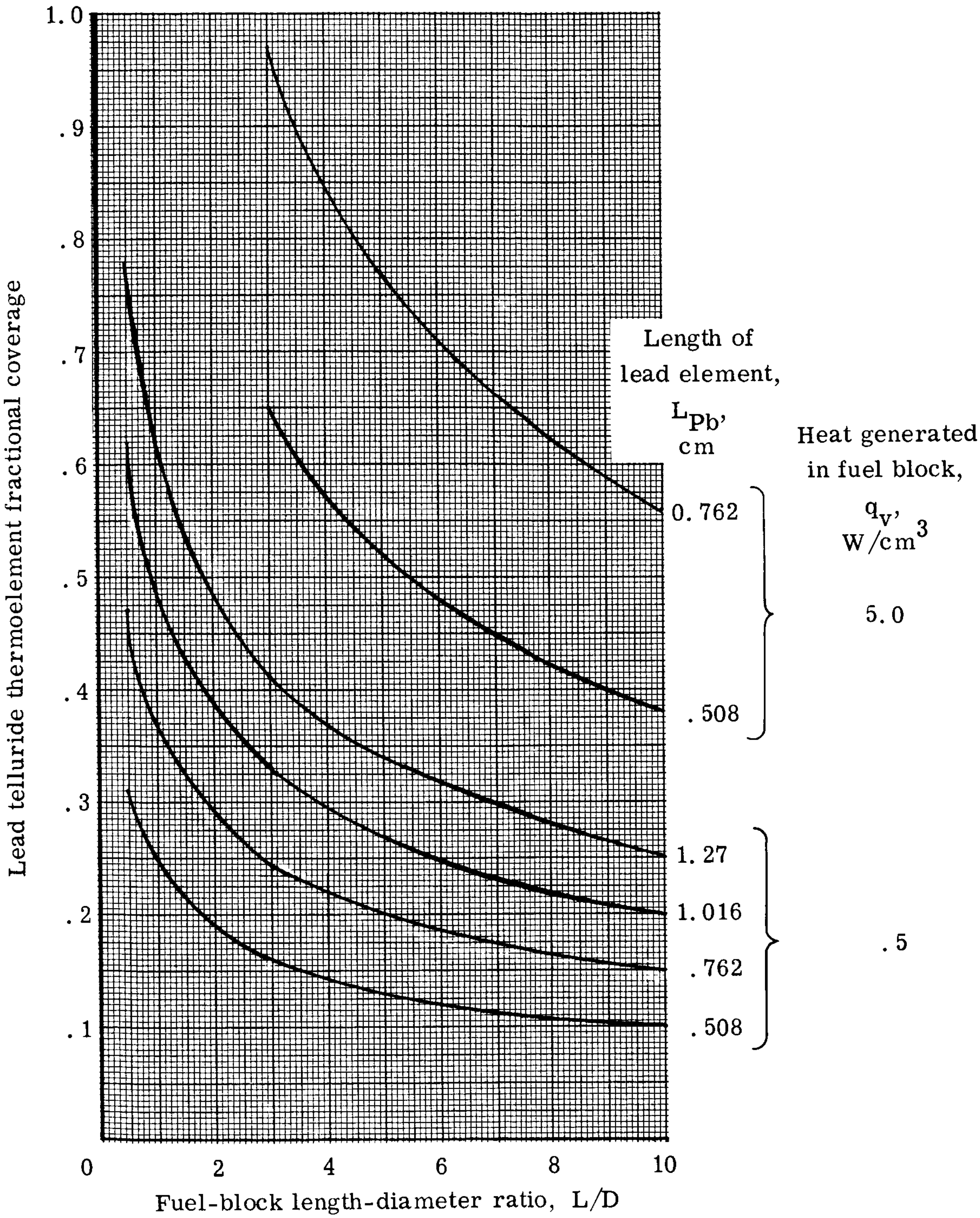
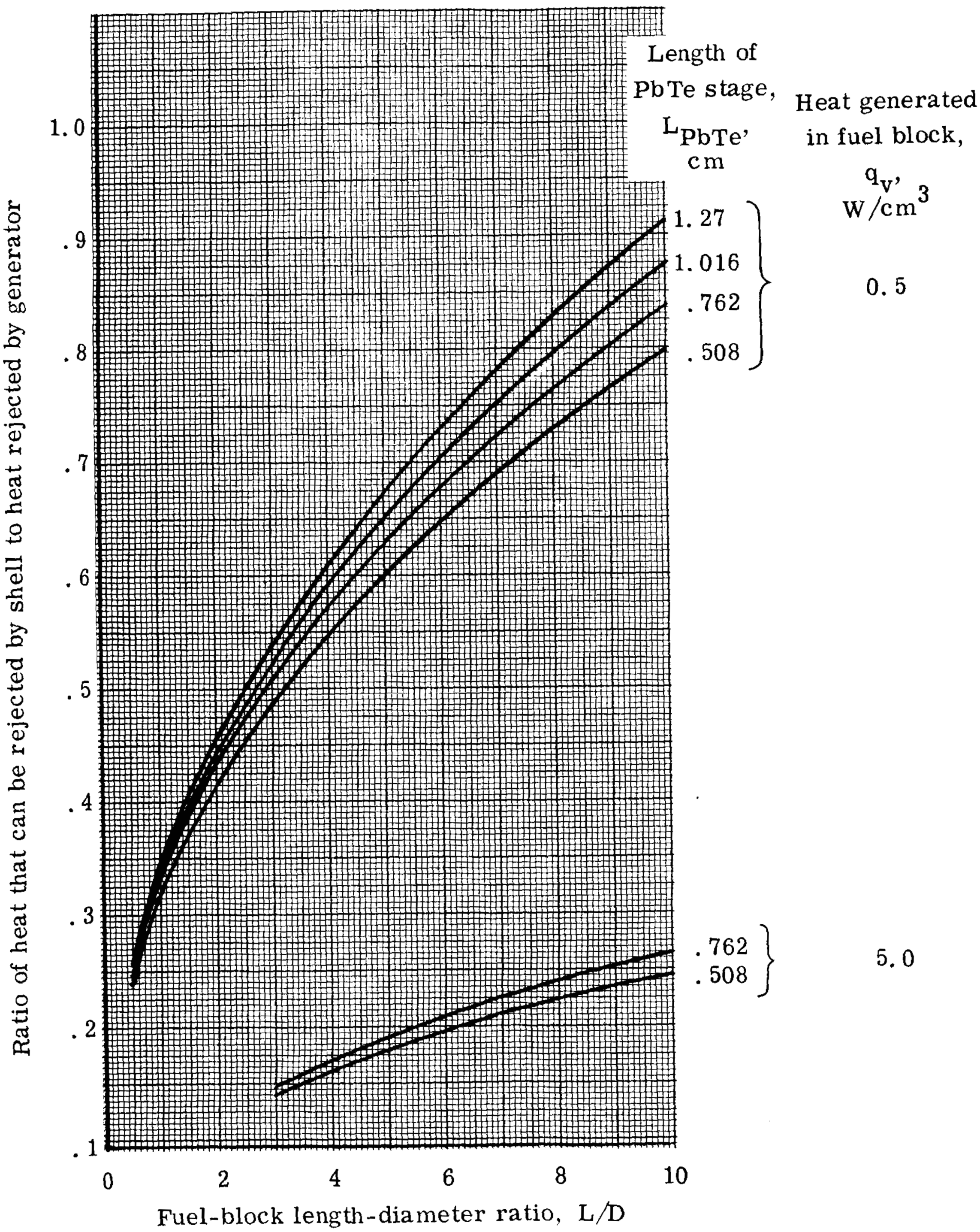
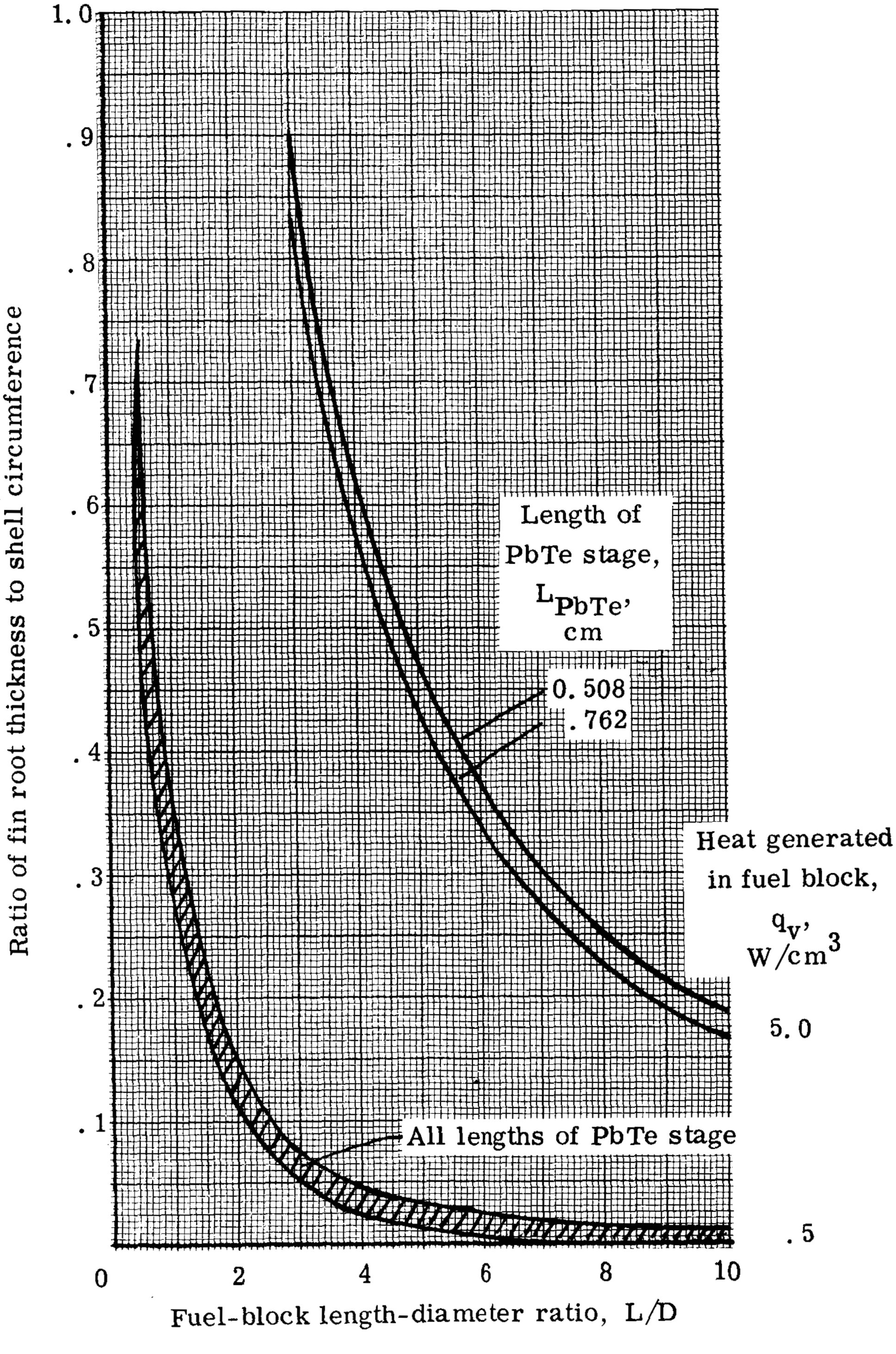


Figure 4. - PbTe element fractional coverage as function of fuel-block length-diameter ratio. Hot-junction temperature, 1255° K; and cold-junction temperature, 589° K; power output, 250 watts electric.



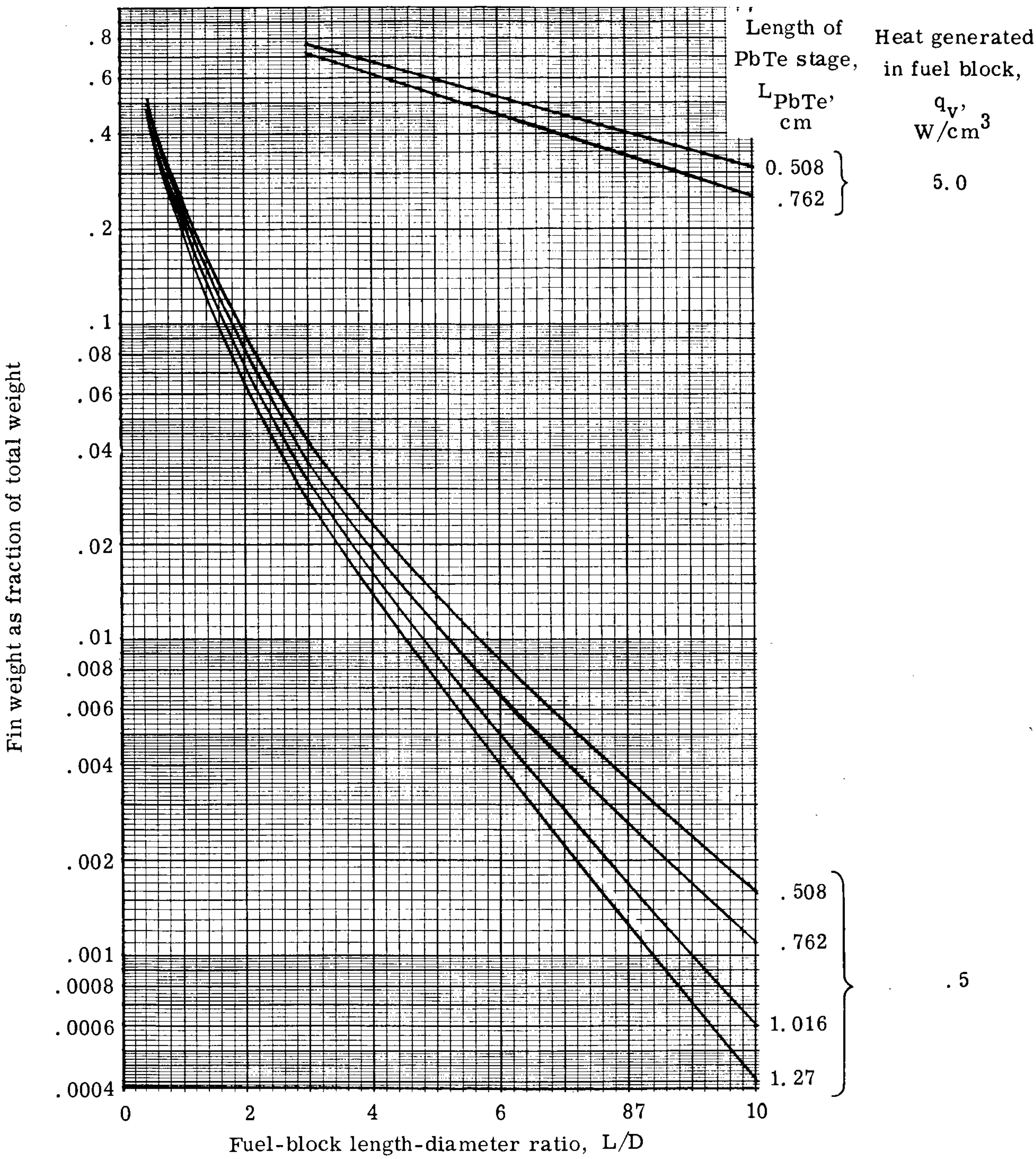
(a) Heat-rejection ratio.

Figure 5. - Generator heat rejection as function of fuel-block length-diameter ratio. Hot-junction temperature, 1255° K; cold-junction temperature, 589° K; power output, 250 watts electric.



(b) Ratio of fin root thickness to shell circumference as function of fuel-block length-diameter ratio.

Figure 5. - Continued.



(c) Ratio of fin weight to generator weight.

Figure 5. - Concluded.

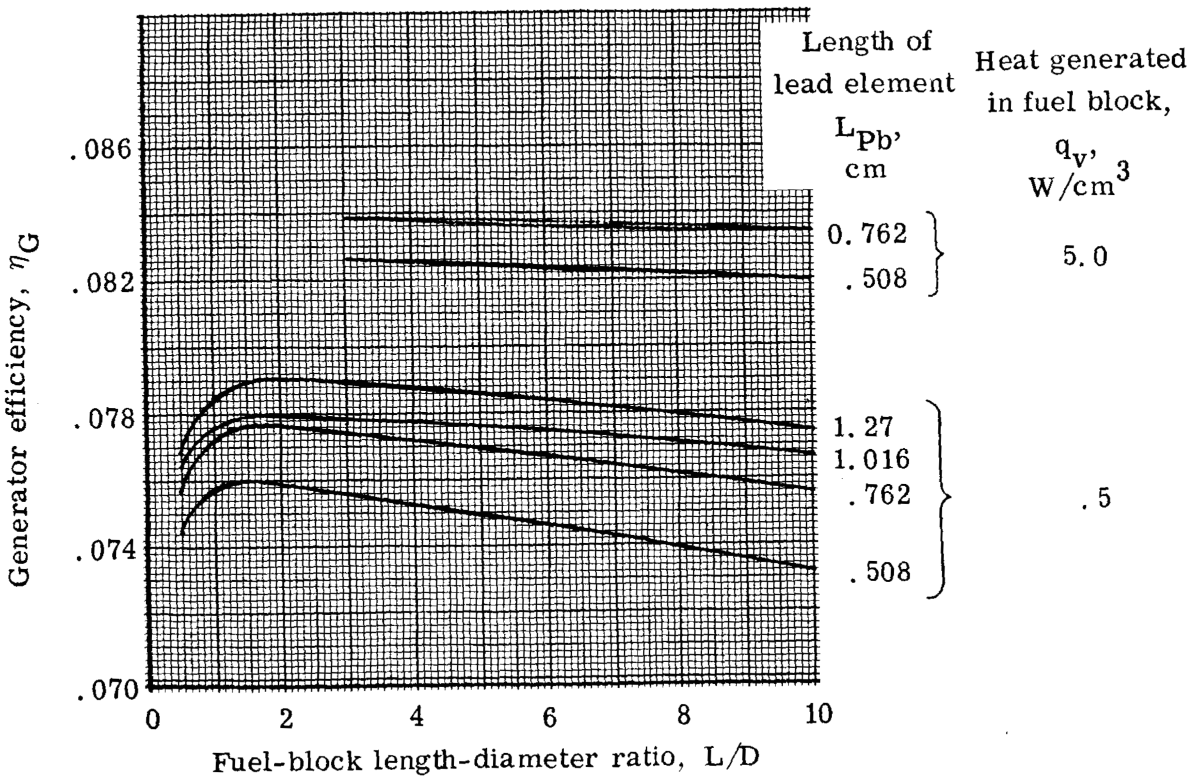


Figure 6. - Generator efficiency as function of fuel-block length-diameter ratio. Hot-junction temperature, 1255° K; cold-junction temperature, 589° K; power output, 250 watts electric.

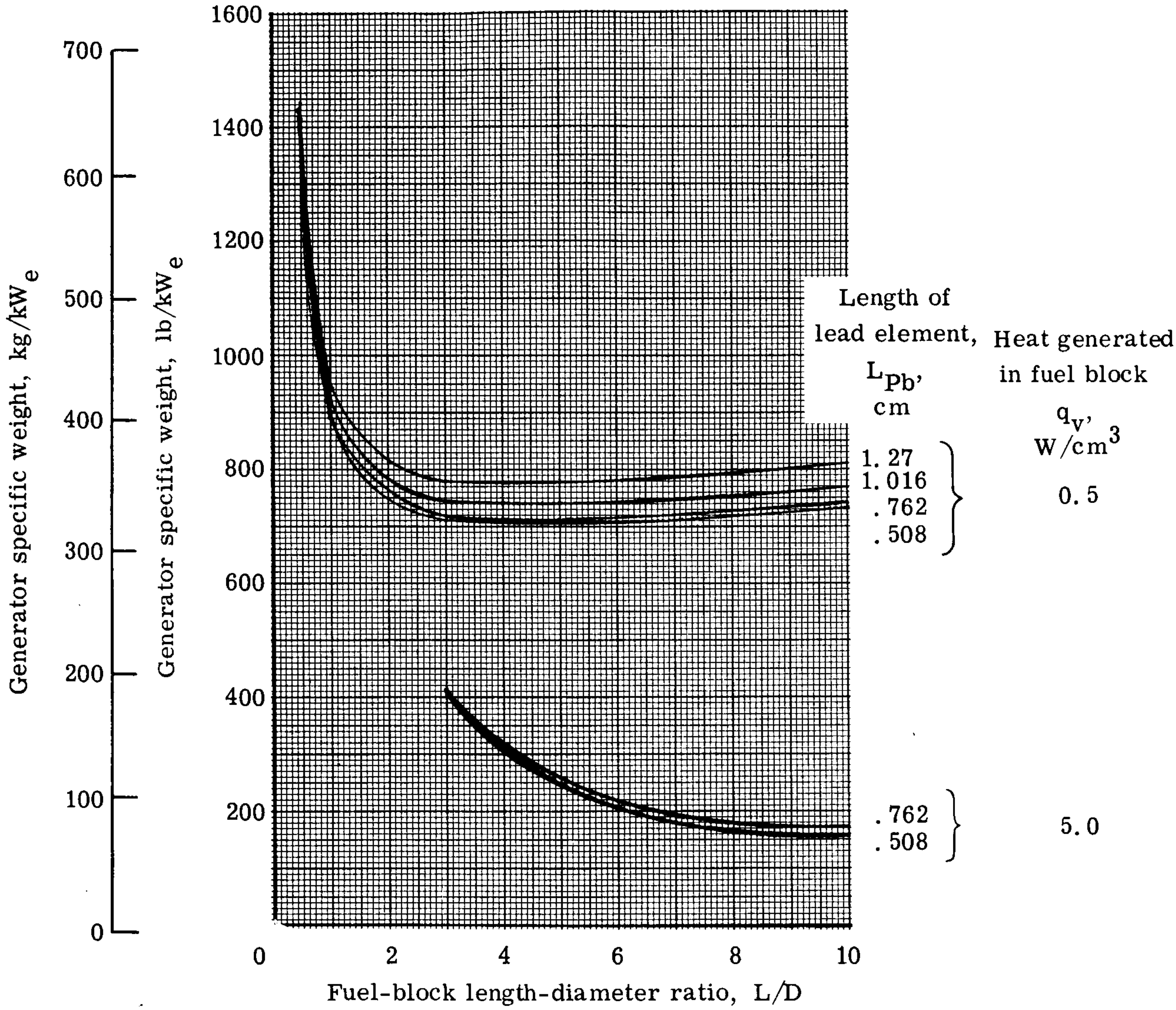
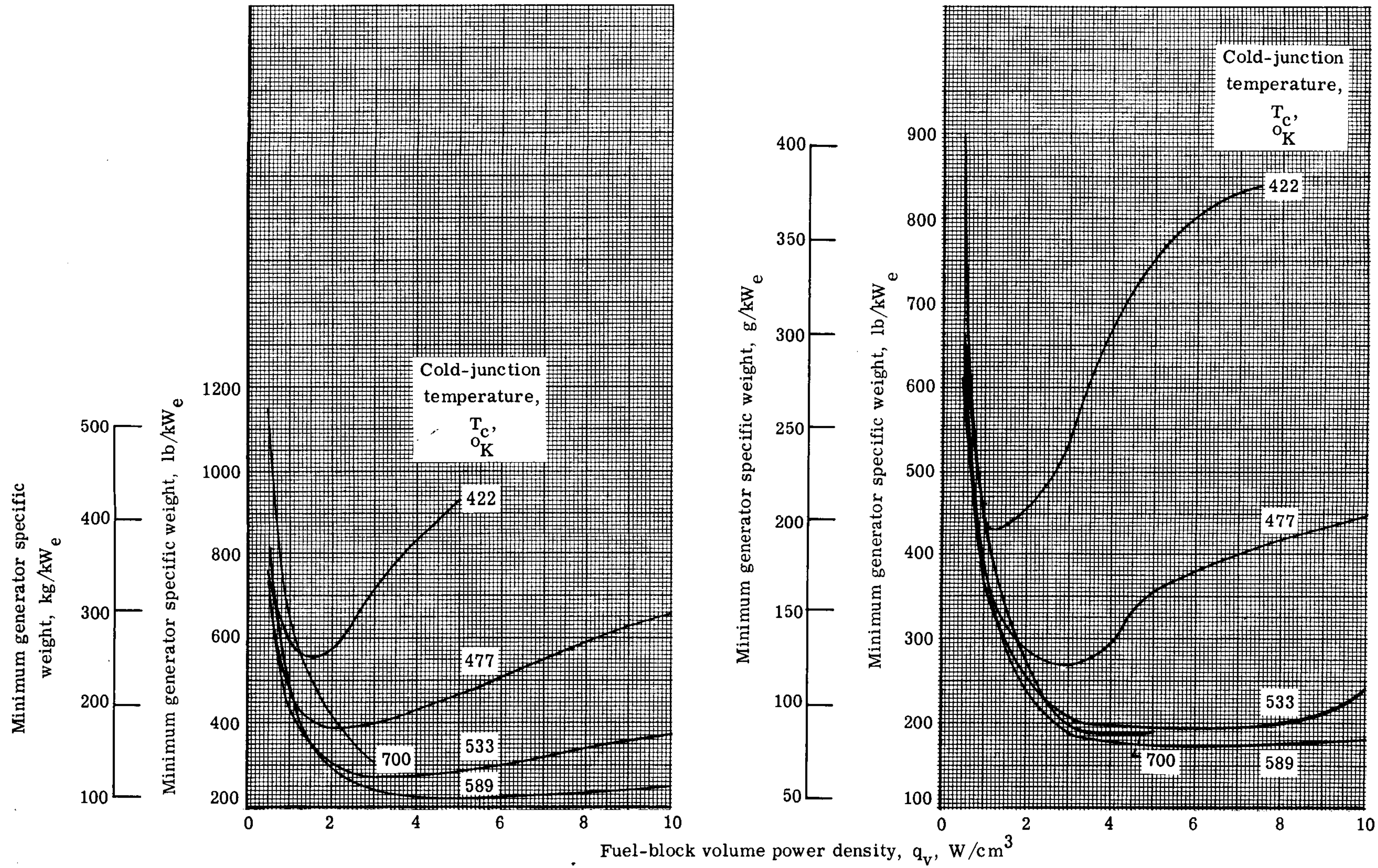


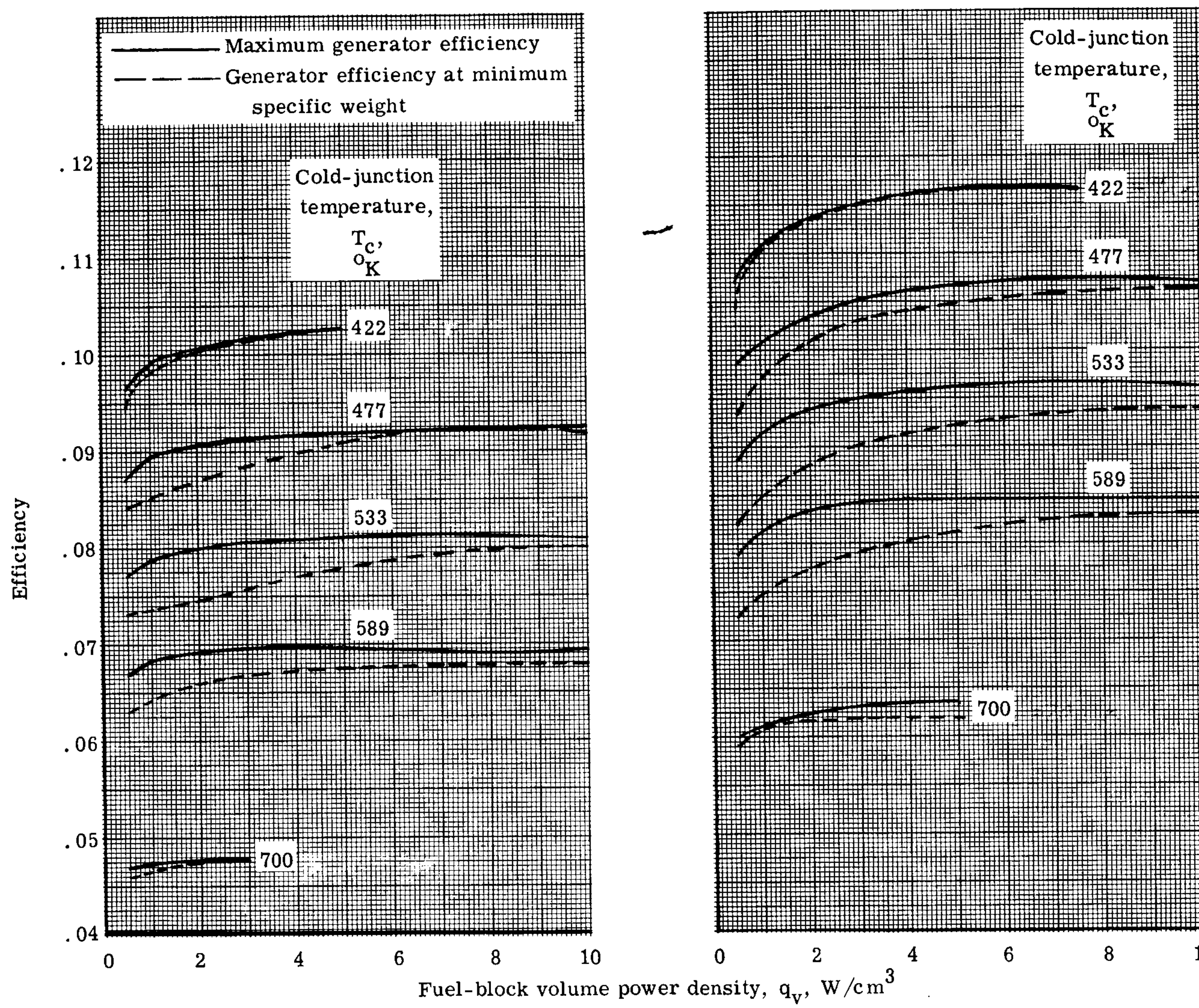
Figure 7. - Generator specific weight as function of fuel-block length-diameter ratio. Hot-junction temperature of 1255° K and cold-junction temperature of 589° K; power output, 250 watts electric.



(a) Hot-junction temperature, 1089° K.

(b) Hot-junction temperature, 1255° K.

Figure 8. - Minimum generator specific weight as function of fuel-block volume power density. Power output, 250 watts electric.



(a) Hot-junction temperature, 1089° K.

(b) Hot-junction temperature, 1255° K.

Figure 9. - Generator efficiency as function of fuel-block volume power density. Power output, 250 watts electric.

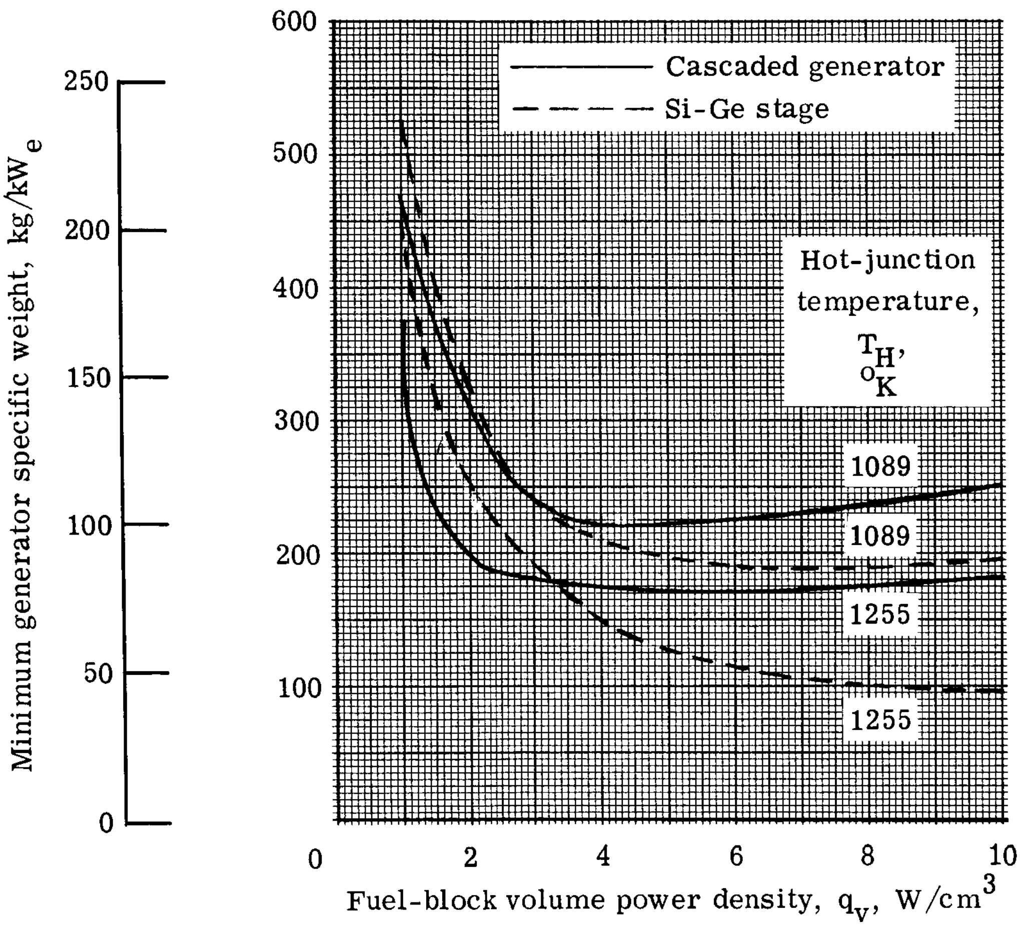


Figure 10. - Minimum generator specific weight as function of fuel-block volume power density. Power output, 250 watts electric.

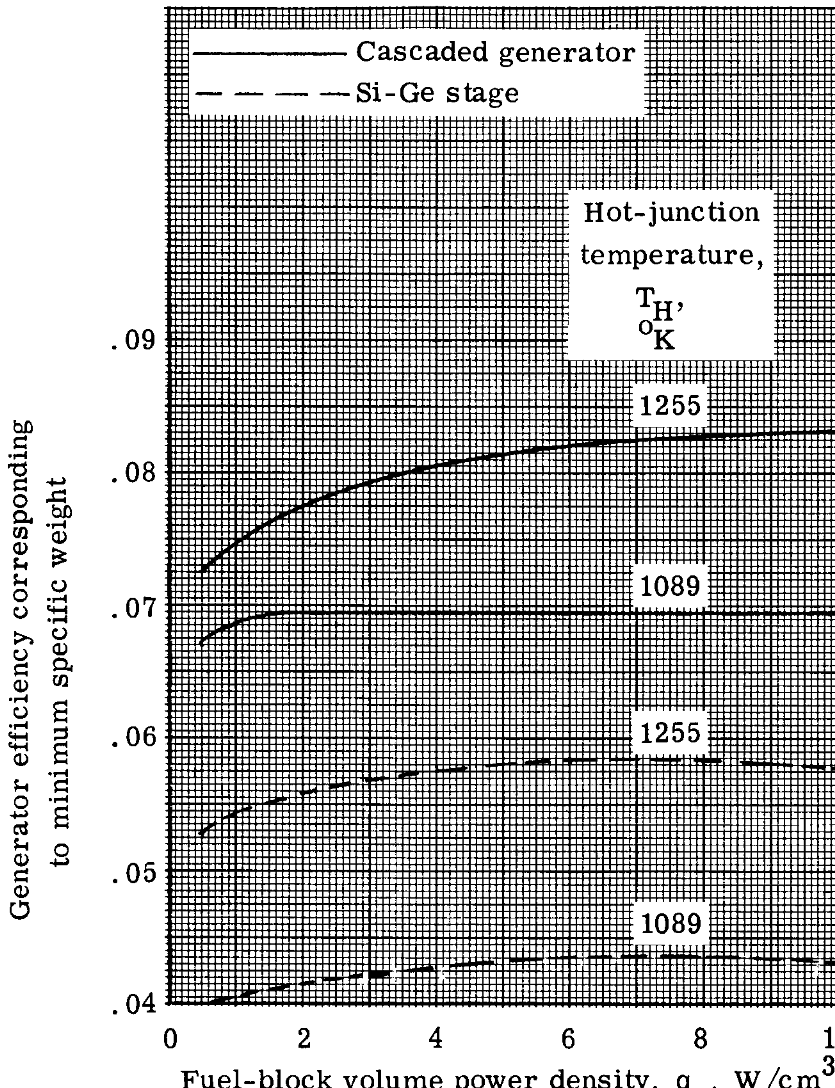


Figure 11. - Generator efficiency corresponding to minimum specific weight as function of fuel-block volume power density. Power output, 250 watts electric.

NASA-Langley, 1968 —— 22 E-4122

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