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SUMMARY

A parametric analysis of a radioisotope-thermoelectric power generator is presented. A cylindrical heat-source geometry was assumed with either lead telluride or silicon-germanium thermoelectric elements located around the lateral surface of the fuel block. Generator performance, rather than overall power-system performance, was analyzed; that is, such mission dependent considerations as nuclear shielding, reentry protection, and power conditioning were not included. The heat source was treated parametrically by using the effective-volume power density of the heat source as a variable. Generator efficiency and specific weight were determined for fuel-block length-to-diameter ratios from 0.5 to 10.0, effective-volume power densities from 0.5 to 10.0 watts per cubic centimeter (W/cc), thermoelectric element hot-junction temperatures of 811° K for lead telluride and 1089° and 1255° K for silicon-germanium, and generator electrical output powers from 100 to 1000 watts.

The results indicate that a substantial specific weight advantage is gained by employing silicon-germanium thermoelectric elements rather than lead telluride. In all cases, however, minimum specific weight is achieved at the lowest output power level, that is, 100 watts electric (W_e). Minimum specific weight for the lead telluride generators occurs at fuel-block effective-volume power densities of from 0.5 to 3.0 W/cc. For a power output of 100 W_e, the minimum specific weight for lead telluride generators is 420 lb/kW_e (191 kg/kW_e) with a generator efficiency greater than 5 percent. For silicon-germanium generators having an output power of 100 W_e, the minimum specific weights are 120 and 88 lb/kW_e (54.5 and 40 kg/kW_e) for hot-junction temperatures of 1089° and 1255° K, respectively, with corresponding generator efficiencies of 4.1 and 5.8 percent.

INTRODUCTION

Radioisotope-thermoelectric power generation systems are particularly attractive for space applications requiring relatively low levels of output power. Such systems offer the advantage of continuous, reliable performance and are independent of the environment in which they operate, requiring neither sunlight nor orientation with respect to the Sun.

Radioisotope-thermoelectric generators (RTG's) used in space to date have employed lead telluride exclusively as the thermoelectric material. The high physical density of the lead telluride elements, however, results in relatively heavy generators. An alternate thermoelectric material having a much lower density is silicon-germanium (Si-Ge). Since the figure of merit of Si-Ge is much lower than for lead telluride (PbTe), however, higher temperatures are required to achieve comparable efficiencies. In order to compare the performance of the systems, a parametric analysis of RTG's employing either PbTe or Si-Ge was made. The elevated temperature capability of the Si-Ge has been demonstrated. Heat sources for this higher temperature level are assumed attainable.

The design variables selected for the analysis are as follows: heat-source geometry, isotope effective-volume power density, thermoelectric hot-junction temperature, and electrical output power. Although mission dependent considerations such as nuclear shielding, reentry protection, power flattening and power conditioning also affect generator design, these factors were not included in the study.

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

Generator efficiency and specific weight are presented as functions of heat-source length-to-diameter ratio over a range from 0.5 to 10.0 at heat-source effective-volume power densities from 0.5 to 10.0 W/cc, hot-junction temperatures of 811° K for PbTe and 1089° and 1255° K for Si-Ge, and electric power outputs from 100 to 1000 W.

SYMBOLS

A_c fuel-block surface area covered by thermoelectric elements, cm^2

A_L fuel-block lateral surface area, cm^2

A_s total fuel-block surface area, cm^2

D fuel-block diameter, cm

L/D fuel-block length-to-diameter ratio

P_g generator output power (electrical), W_e

p_d thermoelectric power density, W_e/cm^2

Q_{in} heat generated in fuel block, W

Q_l heat lost through thermal insulation, W

Q_r heat rejected from generator, W

Q_s heat radiated from generator shell, W

q_l heat flux through thermal insulation, W/cm^2

q_v fuel-block effective-volume power density, W/cc

T_C thermoelectric-element cold-junction temperature, ^oK

T_H thermoelectric-element hot-junction temperature, ^oK

η_d thermoelectric efficiency

η_g generator efficiency

METHOD OF ANALYSIS

A schematic diagram of the generator analyzed is shown in figure 1. The thermal input to the generator is provided by the decay of radioisotope fuel that is encapsulated in a cylindrical block. It was assumed that the thermoelectric elements would be bonded through an electrical insulator to the lateral surface of the fuel block. Thermal insulation was used to minimize stray heat losses from the fuel-block surface area not covered by thermoelectric elements. Waste heat from the elements, as well as the heat lost through the thermal insulation, must then be rejected from the generator. In most cases, fins are required to augment the heat-rejection capability of the shell.

The parameters considered in the analysis are the fuel-block length-to-diameter ratio L/D, thermoelectric-element hot- and cold-junction temperatures T_H and T_C, the effective-volume power density of the fuel block q_v, and the generator output power P_g. The geometrical requirements of the fuel block is developed in the following paragraphs.

The heat flux available to the thermoelectric elements is given by

$$\text{Available heat flux} = \frac{Q_{in} - Q_l}{A_c} \tag{1}$$

where

$$Q_{in} = \frac{\pi}{4} q_v D^3 \frac{L}{D} \tag{2}$$

$$Q_l = q_l(A_s - A_c) \tag{3}$$

and

$$A_c = \frac{P_g}{p_d} \tag{4}$$

$$A_s = \frac{\pi}{2} D^2 \left(2 \frac{L}{D} + 1\right) \tag{5}$$

The heat flux required by the elements is

$$\text{Required heat flux} = \frac{p_d}{\eta_d} \tag{6}$$

If equation (1) is set equal to equation (6) and the relations in equations (2) to (5) are used, the following expression for the fuel block is obtained:

$$D^3 - \frac{2q_l\left(2 \frac{L}{D} + 1\right)}{q_v \frac{L}{D}} D^2 + \frac{4P_g}{\pi q_v \frac{L}{D}} \left(\frac{q_l}{p_d} - \frac{1}{\eta_d}\right) = 0 \tag{7}$$

Hence, for each set of parameters, the fuel-block diameter was calculated from equation (7) and the generator efficiency was then calculated from

$$\eta_g = \frac{P_g}{Q_{in}} \tag{8}$$

with Q_{in} determined from equation (2).

The thermoelectric-element power density and efficiency characteristics used in the analysis are presented in figure 2. For the Si-Ge elements, performance characteristics were calculated assuming a contact resistance of 50 microhm-centimeter squared (μohm-cm^2) per junction for both n- and p-type elements. For PbTe, a contact resistance of 200 μohm-cm^2 per junction was assumed for the p-type PbTe elements and a contact resistance of 100 μohm-cm^2 per junction was assumed for the n-type PbTe elements. In both cases, the element length was fixed at 1.27 cm.

Over the range of cold-junction temperatures from 422° to 700° K, the PbTe element power density ranged from 0.47 to 0.075 W/cm^2 at a hot-junction temperature of 811° K. The corresponding efficiency range was 0.075 to 0.0215. At a hot-junction temperature of 1255° K, the Si-Ge power density varied from 3.1 W/cm^2, at a cold-junction temperature of 422° K to 0.88 W/cm^2 at a cold-junction temperature of 811° K with a corresponding efficiency variation of 0.092 to 0.048.

In calculating the heat flux through the thermal insulation, the insulation thermal conductivity was fixed at 2.6×10^{-4} watts per centimeter per $^\circ$K (W/cm-$^\circ$K) for temperatures up to 977° K. For temperatures above 977° K, the thermal conductivity was fixed at 4.8×10^{-4} W/cm-$^\circ$K.

The heat-rejection analysis was conducted with the assumption that only the lateral surface area of the generator shell, with a length equal to the length of the fuel block, would contribute to heat rejection. In the heat-rejection calculations, the generator shell was assumed to be at the cold-junction temperature. The shell and radiator fins, where required, were coated to provide an emissivity of 0.9, and 0° K space environment was assumed. The radiator fin lengths were determined by the method described in reference 1 that takes into account the temperature drop along the fin and the fin view factor. In all cases, five tapered fins were used.

In estimating generator weight, the fuel-block physical density was fixed at 10 grams per cubic centimeter (g/cc) over the entire q_v range. This value was considered to be representative for most of the isotopes of interest. The density of the thermal insulation was taken as 0.03 g/cc.

In a design of the type shown in figure 1, the generator shell would serve as the primary containment vessel, and a high-strength oxidation-resistant alloy would be required. Rene 41 was selected as the shell material (density, 8.22 g/cc). Calculations were then made to determine the shell thickness required to withstand a pressure differential of 1 atmosphere (1.01×10^5 N/m^2), and the shell was sized accordingly. However, a lower limit on thickness of 0.152 cm was assumed. To accommodate the thermoelectric elements, a separation distance of 1.27 cm was required between the shell and the fuel block.

The fin weights were determined by the method described in reference 1. Beryllium (density, 1.86 g/cc) was the fin material.

RESULTS AND DISCUSSION

Thermoelectric Fractional Area Coverage

The effects of variations in fuel-block geometry can be shown by considering, as a reference case, a Si-Ge generator having a hot-junction temperature of 1089° K and a power output of 250 watts electric (W_e). The fraction of the lateral surface area of the fuel block covered by thermoelectric elements is presented in figure 3 as a function of fuel-block length-to-diameter ratio for fuel-block effective-volume power densities of 0.5 and 10 W/cc with cold-junction temperature as a parameter.

At a fixed cold-junction temperature and effective-volume power density, the fractional coverage decreases with increasing L/D since the lateral area of the fuel block increases with L/D while A_c remains fixed. For a fixed L/D and cold-junction temperature, the fractional coverage increases rapidly with increasing effective-volume power density q_v, since the lateral surface area of the fuel-block decreases. At a cold-junction temperature of 700° K and a q_v of 0.5 W/cc, a maximum fractional coverage of 0.24 is reached at a fuel-block length-to-diameter ratio of 0.5, while at a q_v of 10 W/cc, the fractional coverage limits the fuel block L/D to a value of 3 or greater.

Increasing the cold-junction temperature at a fixed L/D and q_v results in an increase in fractional coverage due to the decrease in element power density. For example, for a q_v of 0.5 W/cc and an L/D of 10, the fractional coverage increases from 0.039 for a cold-junction temperature of 422° K to 0.14 when the cold-junction temperature is increased to 811° K. Note that, at the higher effective-volume power density, the fractional coverage limits the useful fuel block L/D for the reference case at higher cold-junction temperatures.

For higher power systems, the fuel block becomes more compact (i.e., the fuel-block surface-area-to-volume ratio decreases) and the fractional coverage increases. As a result, the choice of fuel block L/D is even more restricted. Similar constraints regarding fuel block L/D occur when considering PbTe generators because of their lower element power density.

Generator Efficiency

Generator efficiency is presented for the reference case in figure 4 as a function of fuel-block length-to-diameter with cold-junction temperature for fuel-block effective-volume power densities of 0.5 and 10 W/cc as a parameter. For all conditions, the efficiency exhibits a maximum at an L/D of 1.0 followed by a gradual decrease with increasing L/D. For example, at a q_v of 0.5 W/cc and a cold-junction temperature of

533° K, the efficiency is 0.056 at an L/D of 1.0 while at an L/D of 10, the efficiency drops to 0.052. Increasing the effective-volume power density to 10 W/cc produces the same general trend although the absolute level of efficiency is higher. Increasing the cold-junction temperature lowers the generator efficiency. Note that, at a q_v of 10 W/cc and a cold-junction temperature of 700° K, efficiency data are not presented below an L/D of 3 since the required thermoelectric fractional area coverage of the fuel block exceeded 1 in this case.

Similar behavior in generator efficiency was observed at the other output power levels considered for Si-Ge as well as for PbTe generators.

Generator Heat Rejection

The capability of the generator to reject waste heat is strongly dependent on the length-to-diameter ratio of the fuel-block. As mentioned in the section METHOD OF ANALYSIS, it was assumed that only the lateral surface area of the generator shell would contribute to heat rejection. On this basis, the highest practical L/D configuration would be most suitable for rejecting heat.

Heat rejection is considered for the reference case (250-W_e Si-Ge generator, T_H = 1089° K) in figure 5(a), in which the ratio of the heat that can be rejected from the generator shell Q_s to the heat that must be rejected from the system Q_r is presented as a function of fuel-block L/D. For cases in which this ratio is less than 1.0, fins must be incorporated to augment the shell heat-rejection capability. The weight penalties associated with the addition of fins are shown in figure 5(b). The fraction of total generator weight contributed by the fins can be determined by referring to figure 6 which shows the corresponding total generator specific weight as a function of fuel-block L/D.

As shown in figure 5(a), the heat-rejection capability increases with increasing fuel block L/D. At a q_v of 0.5 W/cc, waste heat can be rejected solely by the shell at the higher cold-junction temperatures if the fuel block is sufficiently long. At a cold-junction temperature T_C of 811° K, a heat-rejection ratio of 1.0 is achieved at an L/D of about 2.4, while at a T_C of 700° K an L/D of 7.2 is required. If, for any reason, the fuel block is limited to L/D's lower than these values, the fin weight penalty (fig. 5(b)) would be incurred. As the volume power density increases, the shell surface area decreases, and the cooling problem becomes more severe. At a q_v of 10 W/cc (fig. 5(a)) fins are required to augment the shell heat rejection over the entire cold-junction temperature range. Note, for example, that, at a cold-junction temperature of 700° K, the shell is capable of rejecting only 0.21 of the waste heat at an L/D of 10. The corresponding weight penalty associated with the addition of fins (fig. 5(b)) is 110 lb/kW_e (50 kg/kW_e), which represents more than half of the total generator weight.

Note the restricted range of fuel-block L/D's indicated in figure 5(b). This results because L/D cases in which the total root thickness of the five heat-rejection fins exceeds the outer circumference of the generator were not considered for this study. For a q_v of 10 W/cc, such constraints limit the allowable cold-junction temperatures to values greater than 589° K and an L/D of about 10 or more. (Since no intermediate L/D between 5 and 10 was considered in this analysis, it is not possible to determine exactly the minimum allowable L/D.)

In order, then, to minimize fin weight, or, in some cases, to completely eliminate fins, fuel-block L/D's of the order of 10 would seem desirable. However, as pointed out in the section Generator Efficiency, the peak system efficiency occurs at an L/D of 1.0. Thus, in some cases, minimum generator specific weight occurs at intermediate values of L/D (i.e., between 1.0 and 10.0).

Generator Specific Weight

Generator specific weight for the silicon-germanium reference case (i.e., a hot-junction temperature of 1089° K and a power output of 250 W_e) is presented in figure 6 as a function of fuel-block length-to-diameter ratio for fuel-block effective-volume power densities of 0.5 and 10 W/cc with cold-junction temperature as a parameter. Again, note the restricted range of fuel-block L/D (previously explained in the description of fig. 5(b)). In general, the specific weight decreases with increasing L/D, in some cases going through a minimum, followed by a gradual increase. For example, at an effective-volume power density of 0.5 W/cc, generator weights minimize at an L/D of about 3.0 at cold-junction temperatures of 700° and 811° K. In these cases, fin weights are low and the decrease in efficiency with increasing L/D for L/D's greater than 3.0 offsets the reduction in fin weight. At cold junction temperatures of 533° K or less, however, it can be seen that, by selecting the fuel block L/D that yields the lowest generator weight, significant weight savings are realized with very small penalties in efficiency indicated in figure 4 (less than 10 percent). This effect is even more pronounced for the PbTe generators which operate at lower heat-rejection (cold junction) temperatures. In this case, extremely high fin weights result at the lower values of fuel-block L/D and the weight savings realized at the higher L/D's are even more substantial, again with very small penalties in efficiency. The same conditions exist, in general, regarding the higher temperature Si-Ge generators; however, due to their higher heat-rejection temperatures, minimum specific weight does occur at fuel-block L/D's less than 10 in some instances (e.g., low P_g and low q_v). Therefore, it is concluded that radioisotope-thermoelectric generators can be designed for minimum weight with only slight penalties in efficiency.

Specific-Weight Summary Curves

Minimum generator specific weights (assuming fuel block L/D's restricted to the range of 0.5 to 10) are presented for the reference case in figure 7 as a function of cold-junction temperature. At all values of fuel-block effective-volume power density, except 10 W/cc, the specific weight reaches a minimum which decreases and shifts toward higher cold-junction temperatures as q_v is increased. At a q_v of 10 W/cc, no minimum in weights is observed because element coverage requirements limit the cold-junction temperature to a maximum of 700° K. For q_v's between 3 and 10, curves are terminated at the lower values of cold-junction temperature because of geometrical heat-rejection limitations (i.e., the generator circumference is not large enough to accommodate the 5 triangular fin system). Similar trends are observed at other power levels for both the higher temperature Si-Ge generators and the PbTe generators. For PbTe systems, however, geometry considerations become more restrictive regarding allowable system designs. Both thermoelectric area coverage and heat-rejection fin limitations result in the effective-volume power density being restricted to 5 W/cc or less for a 100 W_e PbTe system with even more severe geometry restrictions at the higher power levels.

Minimum generator specific weights of from 180 to 200 lb/kW_e (82 to 91 kg/kW_e) are indicated for the Si-Ge reference case in figure 7 at effective-volume power densities of between 5 and 10 W/cc. For the lower effective-volume power densities such as 0.5 and 1.0 W/cc, generator specific weights of between 500 and 1000 lb/kW_e are indicated.

System Comparison

The minimum achievable generator specific weights are presented as a function of effective-volume power density in figure 8 for each of the three systems considered. The generator efficiencies at which minimum specific weight occurs is listed in table I corresponding to the nominal cold-junction temperatures and fuel-block length-to-diameter ratios chosen for the study. Exact values of these parameters (i.e., T_C and q_v) could be determined; however, since, in general, regions of minimum specific weight occur over a relatively broad range of variables, the assumed discrete values of T_C and q_v chosen for the study are adequate for comparison purposes.

As seen in figure 8(a), the 100-W_e generator specific weight is lowest of the PbTe systems and the minimum specific weight increases with increasing power level. A minimum specific weight for the 100-W_e generator of 420 lb/kW_e (191 kg/kW_e) was calculated at a volume power density of 3.0 W/cc. For the 250-W_e generator, the minimum increases to about 740 lb/kW_e (336 kg/kW_w) at an effective-volume power density of between 1.0 and 2.0 W/cc. Note that the specific weight is presented over a very limited range of effective-volume power density due to the previously discussed geometry limitations. At a 1000-W_e power output, such limitations restrict the effective-volume power density to less than 1.0 W/cc. The specific weight (1650 lb/kW_e; 750 kg/kW_e) is presented for a q_v of 0.5 W/cc only because no intermediate values (i.e., between 0.5 and 1.0 W/cc) were considered in this study. Referring to table I, note that the minimum weights for the PbTe generators occur at relatively low values of cold-junction temperature (in the range of 477° to 589° K) and in all cases at a fuel-block length-to-diameter ratio of 10. Generator efficiencies range from a maximum of 0.068 (P_g of 100 W_e and q_v of 0.5 W/cc) to 0.042 (P_g of 1000 W_e and q_v of 0.5 W/cc).

For the Si-Ge generator with a hot-junction temperature of 1089° K, the 100-W_e generator specific weight is again the lowest over the effective-volume power density range and the minimum weight increases with increasing power level as shown in figure 8(b). For the 100-W_e generator, the lowest weight (120 lb/kW_e; 54.5 kg/kW_e) occurs at a volume power density of 10.0 W/cc. As the power level increases, the minimum weights shift to lower volume power densities. At the 250-W_e level, a minimum weight of 185 lb/kW_e (84 kg/kW_e) is indicated at an effective-volume power density of 7.5 W/cc, while, for the 500-W_e generator, the minimum weight (250 lb/kW_e; 113 kg/kW_e) occurs at an effective-volume power density of 4.0 W/cc. The 1000-W_e generator is limited by thermoelectric-element area coverage to effective-volume power densities of 3.0 W/cc or less, and the lowest specific weight calculated is 370 lb/kW_e (168 kg/kW_e). Again, referring to table I, note that, in this case, the weights minimize at relatively high values of cold-junction temperature, particularly at the higher values of effective-volume power density. With the exception of the 100-W_e generator at a q_v of 0.5 W/cc, the minimum weights occur at fuel-block L/D's of 10.0. The generator efficiencies range from a maximum of 0.053 (P_g of 100 W_e and q_v's of 1.0 to 3.0 W/cc) to 0.031 (P_g of 500 W_e and q_v of 5.0 W/cc).

For the Si-Ge generator with a hot-junction temperature of 1255° K, similar trends are observed. The 100-W_e generator specific weight is again lowest over the effective-volume power density range, exhibiting a minimum of 88 lb/kW_e (40 kg/kW_e) at a q_v of 10.0 W/cc. At 250 and 500 W_e, minimum weights (94 and 125 lb/kW_e or 42.6 and 56.6 kg/kW_e, respectively) also occur at a q_v of 10.0 W/cc. For the 1000-W_e generator, the minimum specific weight of 190 lb/kW_e (86.4 kg/kW_e) occurs at a q_v of 6.0 W/cc. Unfortunately, these minimum weight systems may not be readily achievable since very few radioisotopes having the required effective-volume power density exist.

As shown in table I, the generator weights minimize at even higher cold-junction temperatures than indicated for 1089° K hot-junction temperature; however, in general, an L/D of 10.0 is still required for minimum weight. The generator efficiencies in this case vary from 0.045 to 0.066.

SUMMARY OF RESULTS

Results of the parametric analysis of a radioisotope-thermoelectric generator over a power output range of 100 to 1000 watts electric (W_e), are summarized as follows:

Lead telluride Generators Having Hot-Junction Temperature of 811° K:

1. Generator weights minimize at relatively low values of fuel-block effective-volume power density.

2. Minimum generator weight increases with increasing power output level; the minimum weights ranging from 420 pounds per kilowatt electric (lb/kW_e) (191 kg/kW_e) at 100 W_e to over 1600 lb/kW_e (725 kg/kW_e) at 1000 W_e.

3. The efficiency of the generators at minimum specific weight varies from 0.061 at 100 W_e to 0.042 at 1000 W_e.

Silicon-Germanium Generators Having Hot-Junction Temperature of 1089° K:

1. Generator weights minimize at fuel-block effective-volume power densities higher than those observed for the lead telluride (PbTe) generator.

2. Minimum generator specific weight again increases with increasing power output level. The minimum weights are much lower than for the PbTe generators ranging from 120 lb/kW_e (54.5 kg/kW_e) at 100 W_e to 370 lb/kW_e (168 kg/kW_e) at 1000 W_e.

3. The efficiency at minimum specific weight varies from 0.041 at 100 W_e to 0.032 at 1000 W_e.

Although maximum generator efficiency occurs at a fuel-block length-to-diameter ratio of 1.0, very little penalty in efficiency is incurred in choosing higher generator length-to-diameter ratios corresponding to minimum specific weight.

Silicon-Germanium Generators Having Hot-Junction Temperature of 1255° K:

1. Generator specific weights minimize at slightly higher effective-volume power densities than observed at a hot-junction temperature of 1089° K.

2. The minimum generator specific weights are lower than those calculated for the 1089° K case ranging from 88 lb/kW_e (40 kg/kW_e) at 100 W_e to 190 lb/kW_e (86.4 kg/kW_e) at 1000 W_e.

3. Over the range of output power from 100 to 1000 W_e, the generator efficiency at minimum generator weight ranges from 0.058 to 0.046.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, May 23, 1967,
120-27-05-01-22.

REFERENCE

1. 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.

TABLE I. - GENERATOR EFFICIENCIES CALCULATED FOR MINIMUM SPECIFIC WEIGHT CASES[a]

Generator output power, P_g, W_e	Lead telluride				Silicon Germanium							
	Thermoelectric-element hot-junction temperature, T_H, ^oK											
	811				1089				1255			
	Effective fuel-block volume power density, q_v, W/cc	Thermo-electric cold-junction temperature, T_c, ^oK	Fuel-block length-to-diameter ratio, L/D	Generator efficiency, η_g	Effective fuel-block volume power density, q_v, W/cc	Thermo-electric cold-junction temperature, T_c, ^oK	Fuel-block length-to-diameter ratio, L/D	Generator efficiency, η_g	Effective fuel-block volume power density, q_v, W/cc	Thermo-electric cold-junction temperature, T_c, ^oK	Fuel-block length-to-diameter ratio, L/D	Generator efficiency, η_g
100	0.5	422	10.0	0.68	0.5	533	5.0	0.051	0.5	533	3.0	0.062
	1.0	477		.62	1.0	533	10.0	.053	1.0	589	5.0	.060
	3.0	533		.53	3.0	589		.053	3.0	589	10.0	.066
	5.0	477		.59	5.0	700		.043	5.0	700		.055
	---	---	----	----	7.5	700		.043	7.5	700		.057
	---	---	----	----	10.0	700		.041	10.0	700		.058
250	0.5	477	10.0	0.060	0.5	589	10.0	0.049	0.5	589	5.0	0.061
	1.0	533	10.0	.052	1.0	589		.052	1.0	589	10.0	.062
	3.0	477	10.0	.064	3.0	700		.042	3.0	700		.057
	---	---	----	-----	5.0			.043	5.0	700		.058
	---	---	----	-----	7.5			.044	7.5	811		.047
	---	---	----	-----	10.0			.043	10.0	811		.046
500	0.5	533	10.0	0.052	0.5	589	10.0	0.051	0.5	589	10.0	0.061
	1.0	589	10.0	.042	1.0	700		.043	1.0	700		.055
	---	---	----	-----	3.0	700		.043	3.0	700		.057
	---	---	----	-----	5.0	811		.031	5.0	811		.046
	---	---	----	-----	7.5	700		.044	7.5	811		.046
	---	---	----	-----	---	---	----	-----	10.0	811		.045
1000	0.5	589	10.0	0.042	0.5	700	10.0	0.042	0.5	700	10.0	0.054
	---	---	----	-----	1.0	700	10.0	.037	1.0	700		.055
	---	---	----	-----	3.0	811	10.0	.032	3.0	811		.047
	---	---	----	-----	---	---	----	-----	5.0			.046
	---	---	----	-----	---	---	----	-----	7.5			.048
	---	---	----	-----	---	---	----	-----	10.0			.046

[a]Values presented in table I correspond to the nominal cold-junction temperatures and fuel-block length-to-diameter ratios chosen for the study.

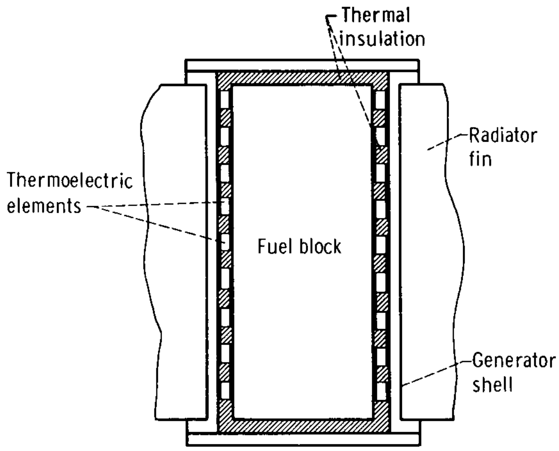
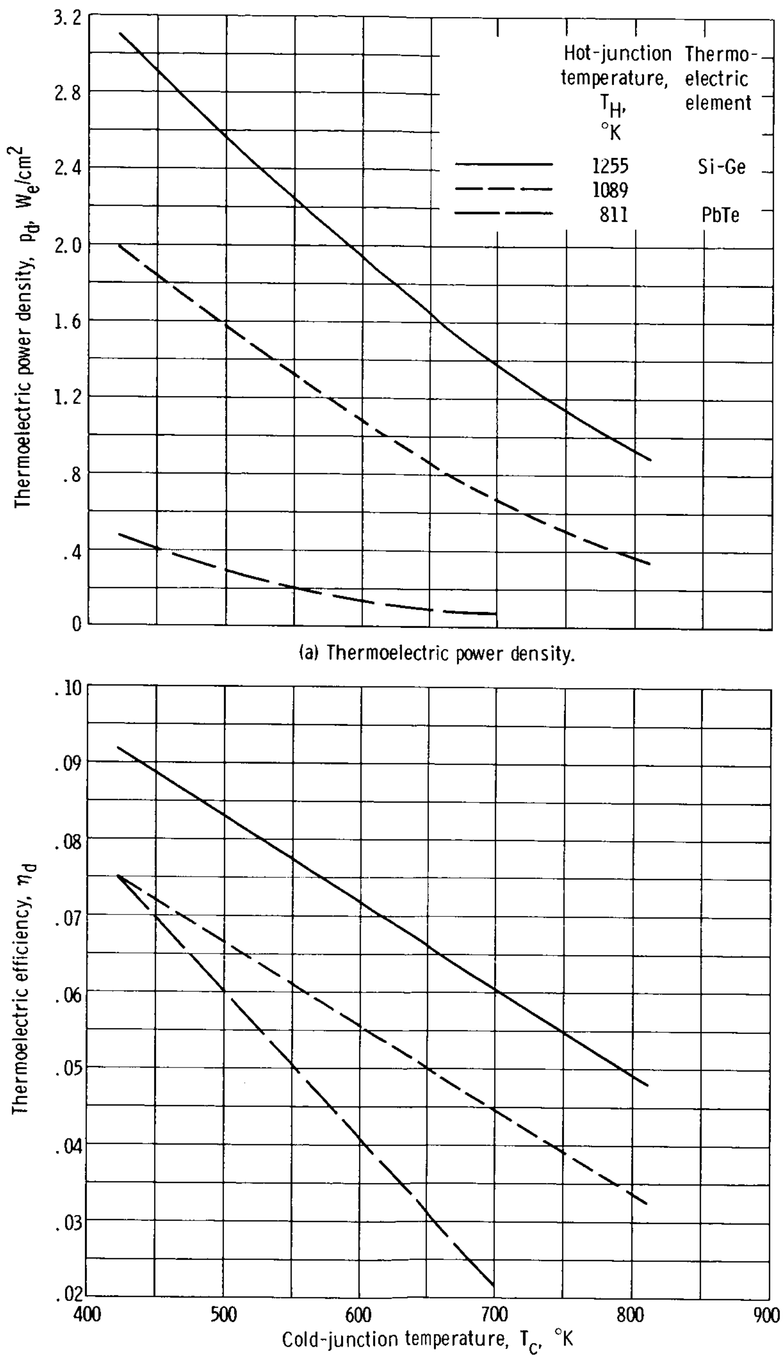


Figure 1. - Conceptual design of radioisotope thermoelectric generator.



(a) Thermoelectric power density.

(b) Thermoelectric efficiency.

Figure 2. - Lead telluride and silicon-germanium thermoelectric performance as function of cold-junction temperature.

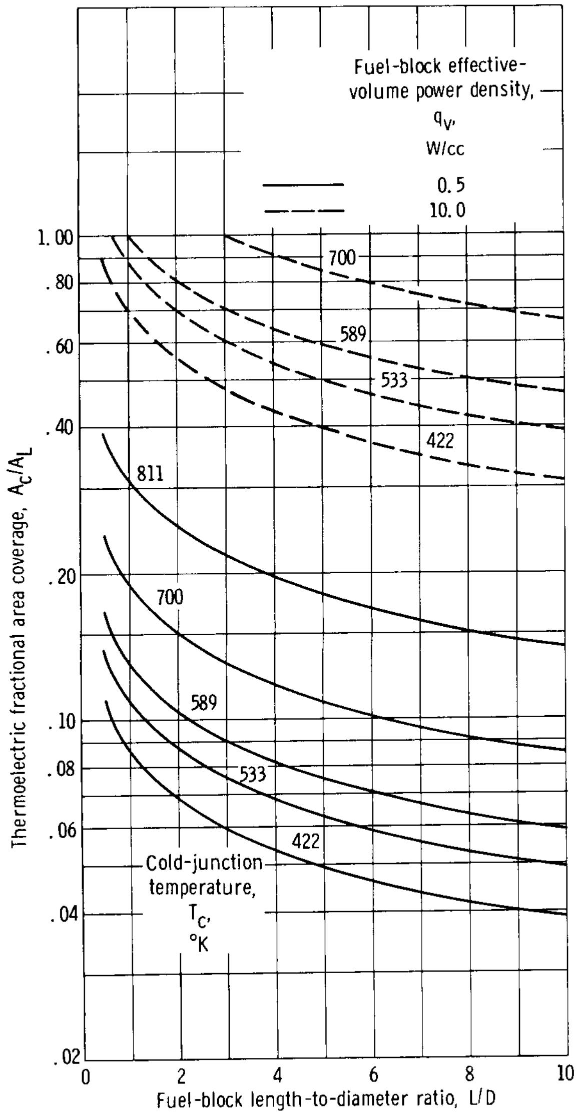


Figure 3. - Thermoelectric fractional area coverage as function of fuel-block length-to-diameter ratio for 250-W_e silicon-germanium generator at hot-junction temperature of 1089° K.

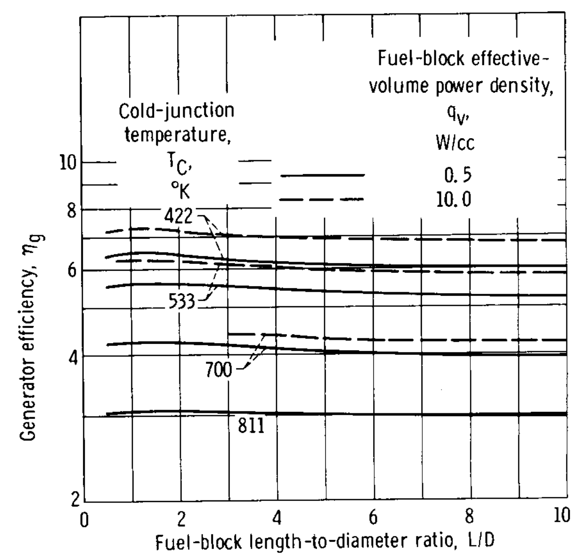
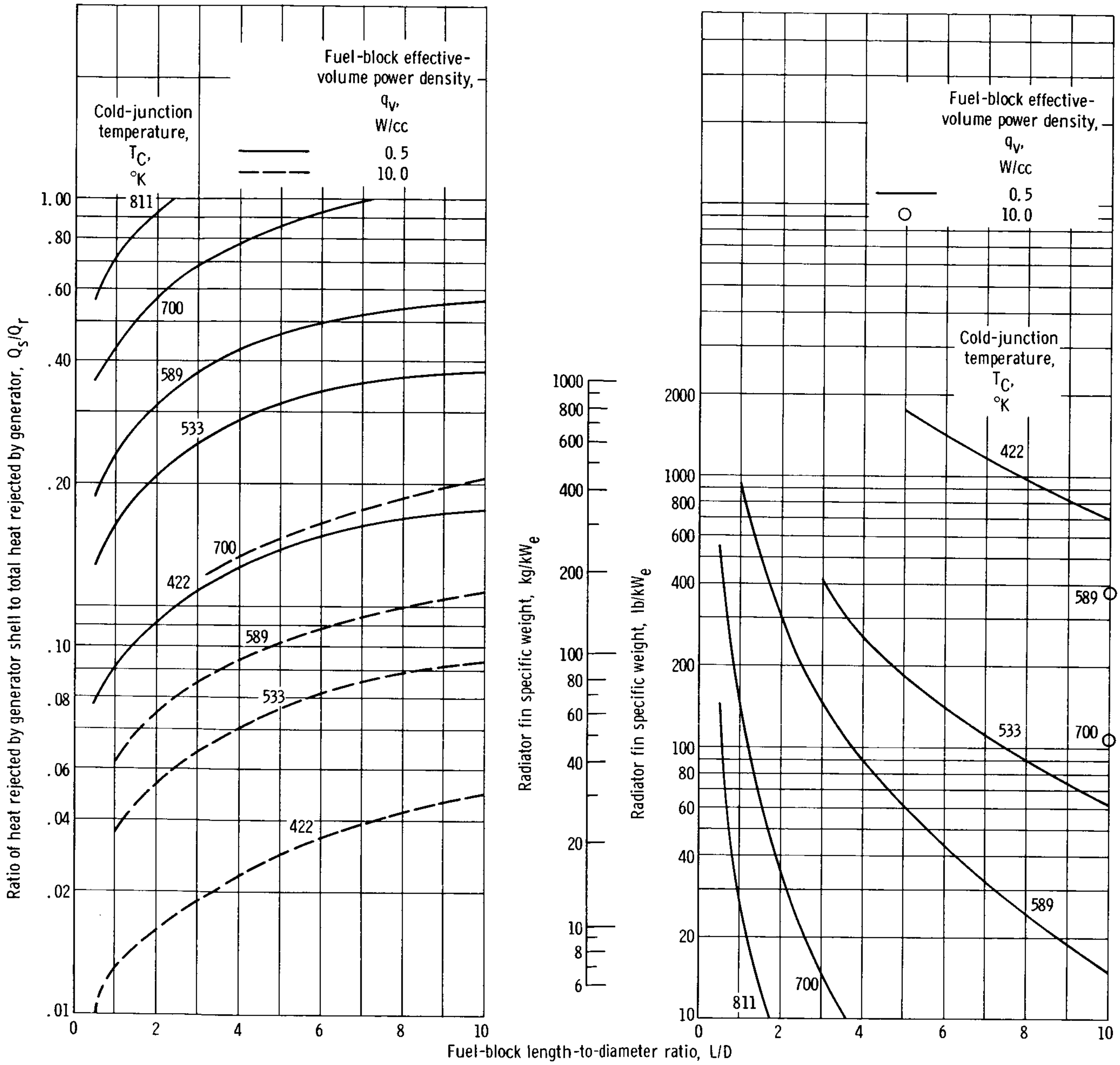


Figure 4. - Generator efficiency as function of fuel-block length-to-diameter ratio for 250-W_e silicon-germanium generator at hot-junction temperature of 1089° K.



(a) Heat rejection ratio.

(b) Radiator fin specific weight.

Figure 5. - Generator heat rejection as function of fuel-block length-to-diameter ratio for 250 W_e silicon-germanium generator at a hot junc-temperature of 1089° K.

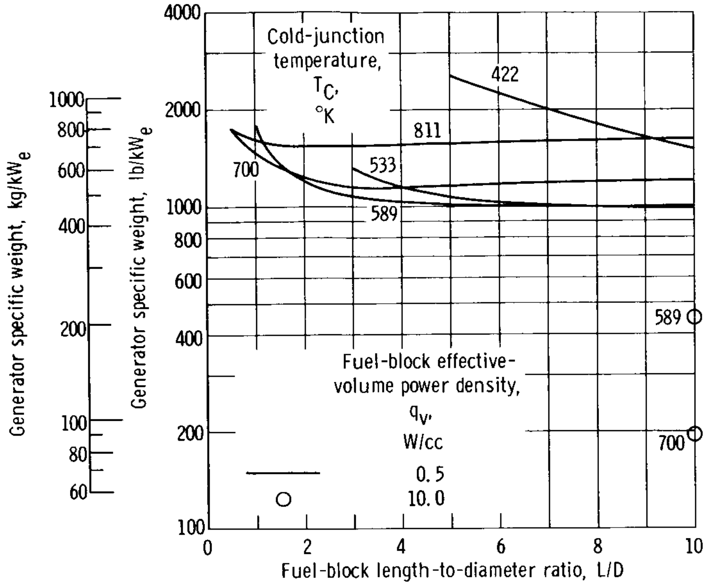


Figure 6. - System specific weight as function of fuel-block length-to-diameter ratio for 250-W_e silicon-germanium generator at hot-junction temperature of 1089° K.

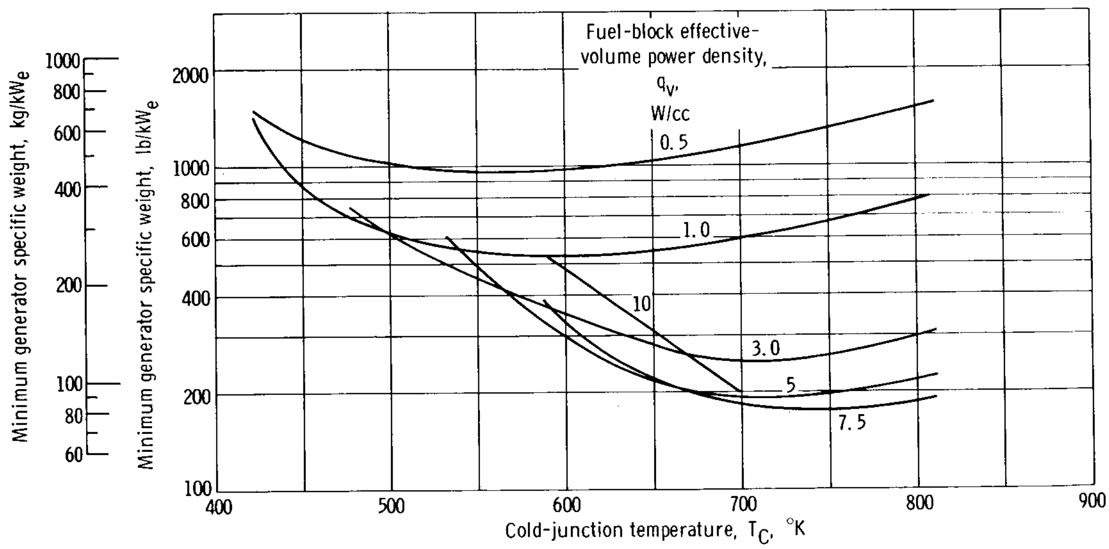
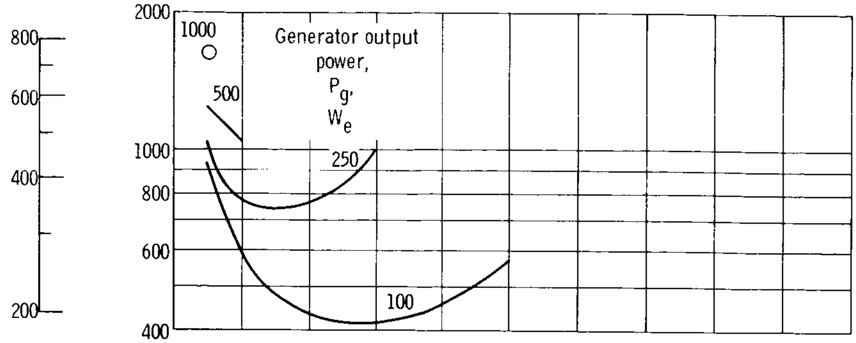
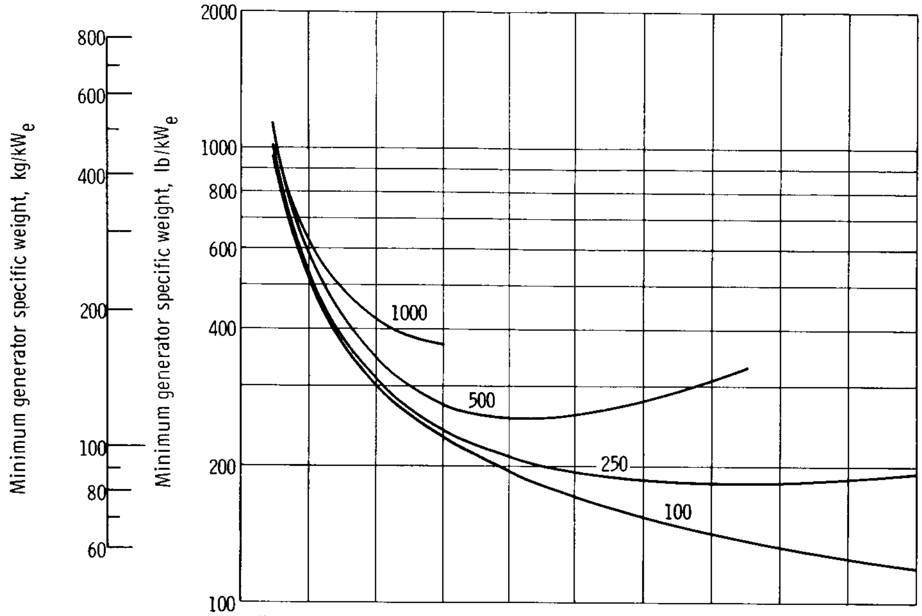


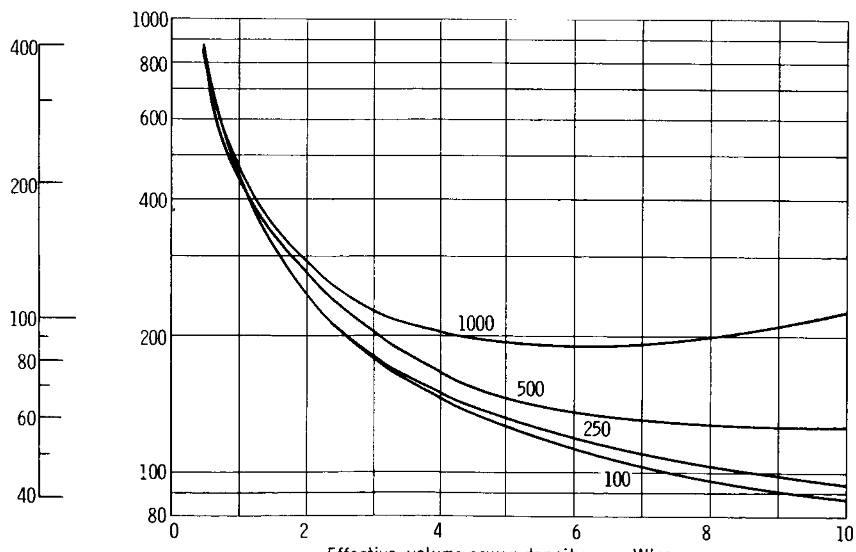
Figure 7. - Minimum specific weight as function of cold-junction temperature for 250-W_e silicon-germanium generator at hot-junction temperature of 1089° K.



(a) For lead telluride generator. Hot-junction temperature, 811° K.



(b) For silicon-germanium generator. Hot-junction temperature, 1089° K.



(c) For silicon-germanium generator. Hot-junction temperature, 1255° K.

Figure 8. - Minimum specific weight as function of effective-volume power density.