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PARAMETRIC ANALYSIS OF RADIOISOTOPE THERMIONIC GENERATORS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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SUMMARY

A parametric analysis of a radioisotope-thermionic electric power generator is presented. A cylindrical heat-source geometry was assumed with thermionic diodes located either around the lateral surface of the fuel block or on the flat ends. Generator 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), thermionic diode emitter temperatures from 1600° to 2000° K, and generator electrical output powers from 100 to 1000 watts.

The results generally indicate that for each configuration a performance advantage is gained by achieving fuel-block effective-volume power densities in the range 3.0 to 5.0 W/cc, a diode emitter temperature of approximately 1800° K, and an electrical output power of about 500 watts. Generator specific weights on the order of 100 pounds per electric kilowatt (lb/kW_e) and generator efficiencies greater than 10 percent were calculated at these operating conditions.

INTRODUCTION

For space missions that require continuous, relatively low levels of electric power for more than a few months, either radioisotope or solar-powered conversion systems will be needed. The performances of both isotope-fueled thermoelectric and thermionic systems are independent of the environment in which they operate, and neither requires orientation with respect to the Sun. Such systems may therefore be particularly useful for applications in which (1) large variations in solar flux are encountered, (2) prolonged periods of operation in the shadow of a celestial body are required, or (3) prolonged periods of operation in the presence of energetic charged particles are required. In comparison with the thermoelectric system, the thermionic system offers several potential advantages including lower weight, higher efficiency, and lower projected area because of the higher heat rejection temperatures achievable.

In the design of a radioisotope-thermionic system, a number of factors directly affect the performance of the basic generator. For example, the heat-source geometry, the isotope power density, the thermionic diode operating temperature, and the electrical output power directly influence generator efficiency and weight.

The performance of the overall power system is influenced, in addition, by such mission dependent considerations as nuclear shielding, reentry protection, power flattening, and power conditioning. Since the mission requirements are not as yet defined, only the effects of design variables on the performance of the basic generator have been determined.

A cylindrical heat-source geometry was assumed with planar thermionic diodes located either around the lateral surface or on the flat ends of the cylinder. Specific radioisotopes were not considered in the analysis since fuel technology has not been developed for the temperatures required in a thermionic system. This technology would include methods for defining encapsulation techniques, void volume requirements for the helium resulting from the decay of α-emitting isotopes, and maximum allowable fuel centerline temperatures. Therefore, 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, diode emitter temperatures from 1600° to 2000° K, and electric power outputs from 100 to 1000 watts.

SYMBOLS

A_c fuel-block surface area covered by diodes, sq cm

A_e area of fuel-block ends, sq cm

A_{ℓ} lateral surface area of fuel block, sq cm

A_s total fuel-block surface area, sq cm

D fuel-block diameter, cm

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

P_g	generator output power, W_e
p_d	diode electrical power density, W/sq cm
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/sq cm
q_v	effective fuel-block volume power density, W/cc
T_E	emitter temperature, ^oK
η_d	diode efficiency
η_g	generator efficiency

PROCEDURE

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. In the figure, planar diodes are shown facing the lateral surface of the fuel block although generators with diodes facing the flat ends of the block were also considered in the analysis. That heat would be transferred from the fuel-block surface to the diodes by radiation was assumed, thus allowing series-parallel electrical conditions. Stacked-foil insulation was used to thermally shield the fuel-block surface area not radiating directly to the diodes. Waste heat from the diodes, which is conducted through the support structure to the generator shell, as well as the heat lost through the thermal insulation, must then be rejected from the generator. In some 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, the diode emitter temperature T_E, 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 may be developed in the following manner.

The heat flux available to the thermionic diodes is given by

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

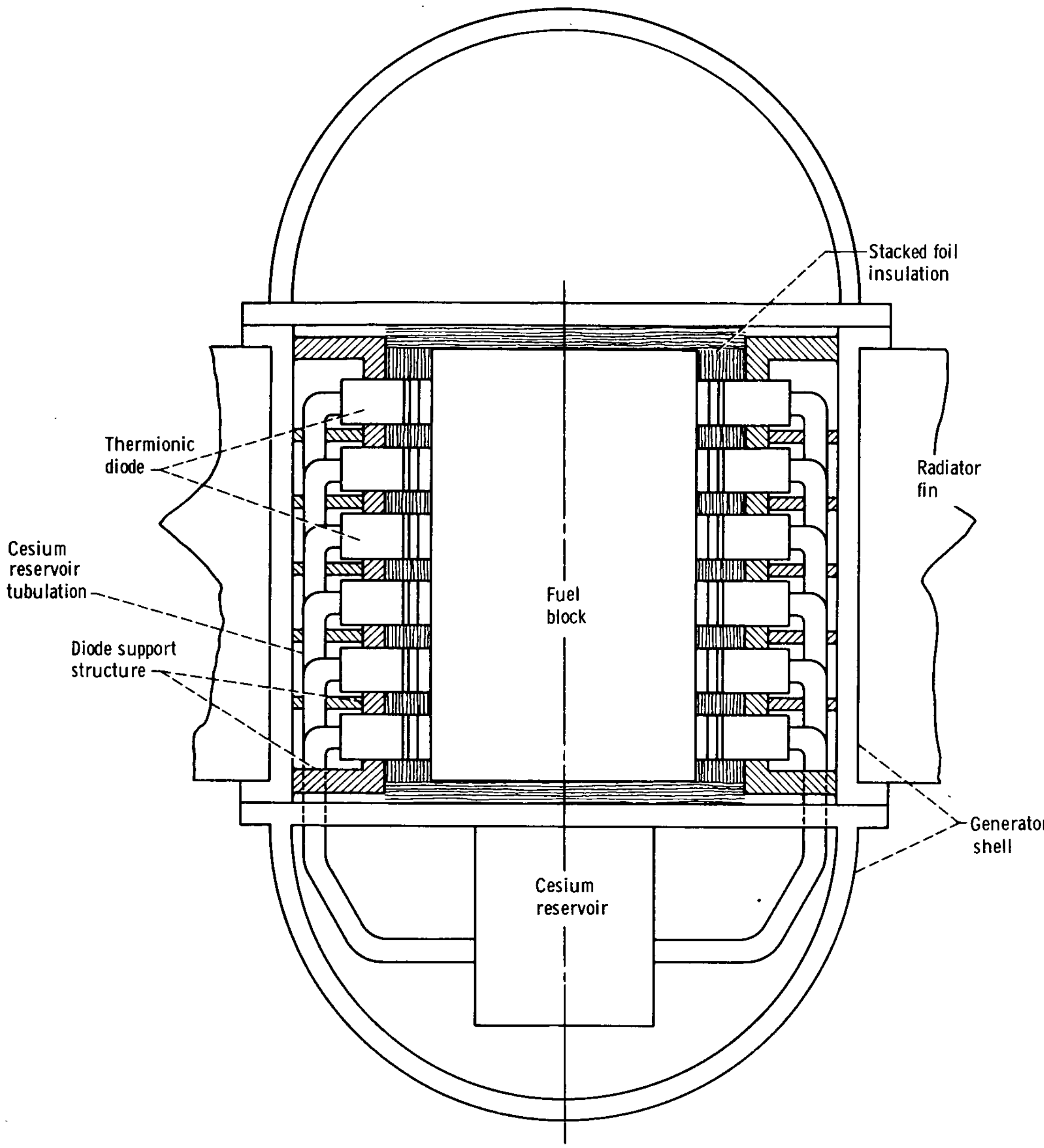


Figure 1. - Conceptual design of radioisotope thermionic generator.

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 converters 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 diameter 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 diode performance characteristics used in the analysis are presented in figure 2. The characteristics that were taken from reference 1 were obtained with a planar converter having a rhenium emitter and a molybdenum collector, and the performance is considered to be typical of present-day thermionic converter technology.

In this case, maximum efficiency was obtained by optimizing the interelectrode spacing at each emitter temperature. Over the range of emitter temperatures from 1600° to 2000° K, the diode efficiency increases from 0.075 to 0.158 with a corresponding power-density increase of 1.2 to 9.0 watts per square centimeter.

The heat flux through the thermal radiation shields was calculated by assuming

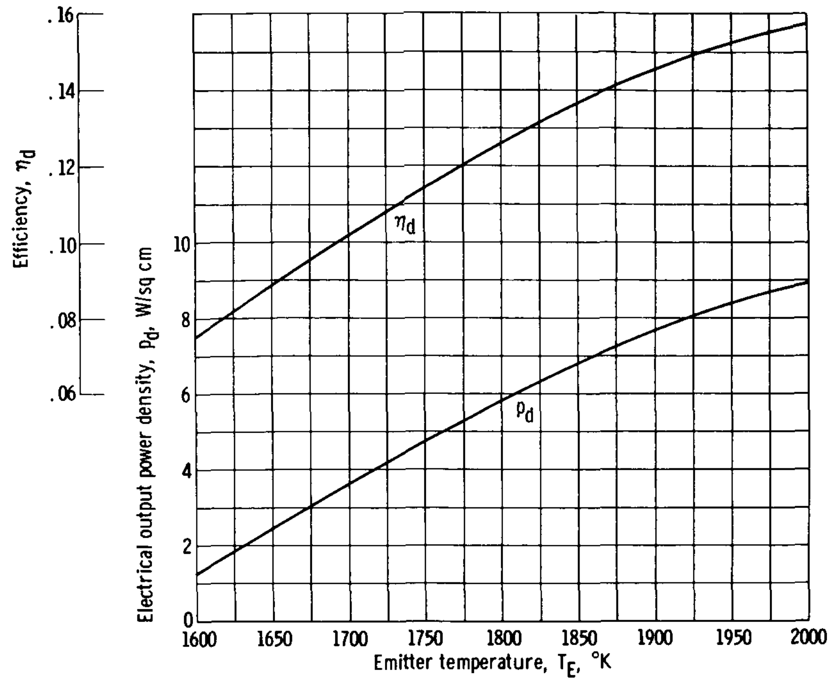


Figure 2. - Diode characteristics, variable spacing, and maximum efficiency.

radiant heat transfer among a series of 25 foils, each having an emissivity of 0.3.

The heat-rejection analysis was conducted with the assumption that, in both the side-mounted and end-mounted configurations, 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. This assumption was based on the fact that the end caps that would house the cesium reservoirs would necessarily be at a temperature near the reservoir temperature and would not be effective as heat radiators. In addition, if protection of the system from aerodynamic heating were necessary during reentry, ablative material having a relatively low thermal conductivity would be added to the end caps.

In the heat-rejection calculations, the generator shell was assumed to be at a uniform temperature taken as 700°, 800°, and 900° K for emitter temperatures of 1600°, 1800°, and 2000° K, respectively. In arriving at these values of shell temperature, a collector temperature equal to one-half the emitter temperature was assumed and a 100° K temperature drop through the diode support was allowed. The shell and radiator fins, where required, were coated to provide an emissivity of 0.9, and a 0° K space environment was assumed. The radiator fin lengths were determined by the method described in reference 2 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 over the entire q_v range, a value that was considered to be representative for most of the isotopes of interest. The converter weight was fixed at 45 grams per square centimeter of emitter area, a typical weight for prototype planar diodes. Tantalum was taken as the thermal shield material, and the shield weight was calculated for twenty-five 0.3-mil-thick (7.62×10^{-4} cm) shields.

The material selected for the diode support structure, which serves as a conduction path for the heat that must be rejected from the collector, was molybdenum (density, 10.2 g/cc), the choice being based on a high ratio of thermal conductivity to weight at collector operating temperatures. The support structure thickness was fixed at 0.152 centimeter for the study.

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. René 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 1.0 atmosphere (14.7 psi), and the shell was sized accordingly. However, a lower limit on thickness of 0.152 centimeter was assumed. Two hemispherical end caps were added to the shell to serve primarily as cesium reservoir containment areas. The caps had an inner diameter equal to the inner diameter of the generator shell and a thickness equal to the shell thickness. To accommodate the thermionic diodes and cesium reservoir tubes, a separation distance of 8.85 centimeters was required between the shell and the fuel block.

The fin weights were determined by the method described in reference 2, and beryllium (density, 1.86 g/cc) was taken as the fin material.

RESULTS AND DISCUSSION

Diode Fractional Area Coverage

Fuel-block geometry requirements for the case in which diodes are mounted only around the lateral surface of the fuel block are shown in figure 3(a) for a diode emitter temperature of 1600° K. The fraction of the lateral surface area covered by diodes is presented as a function of fuel-block length-to-diameter ratio with the fuel-block effective-volume power density and generator output power included as parameters.

At a fixed output power level, the fractional coverage decreases with increasing L/D since the lateral area increases with L/D while A_c remains fixed. As shown, at a power output of 100 electric watts (W_e), the fractional coverage is relatively low at the lower volume power density. For example, the peak coverage at a q_v of 0.5 watt per cubic centimeter (W/cc) reaches about 0.11 at an L/D of 0.5. As the q_v increases, the coverage increases rapidly until, at a q_v of 10.0 W/cc, the coverage fraction reaches 1.0 at an L/D of 0.6. At an L/D of 10.0, however, the coverage at a q_v of 10.0 W/cc is only 0.37.

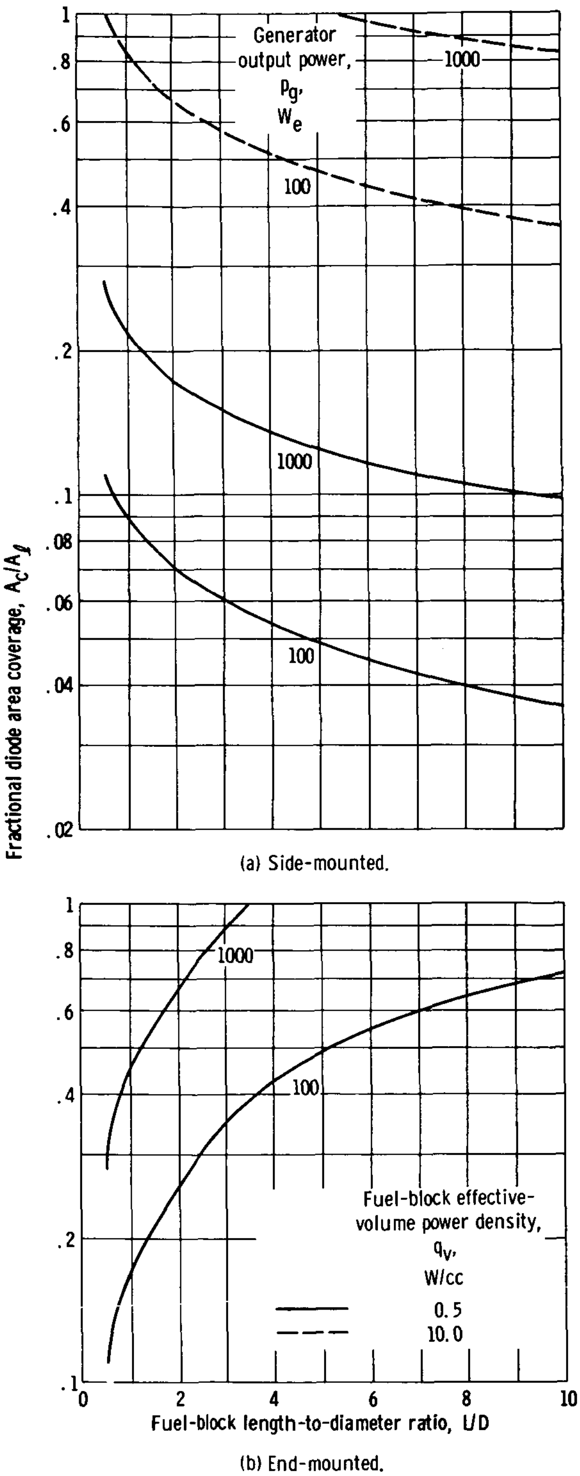


Figure 3. - Diode fractional area coverage as function of fuel-block length-to-diameter ratio for two configurations. Emitter temperature, 1600° K.

As the power output increases, the fuel block becomes more compact (i.e., the fuel-block surface-area-to-volume ratio is decreased), and the fractional coverage increases. At a power level of 1000 W_e and a q_v of 0.5 W/cc, a maximum fractional coverage of 0.28 is reached at a fuel-block length-to-diameter ratio of 0.5, while at a q_v of 10.0 W/cc, the fractional coverage limits the fuel block L/D to a value of 5.4 or greater.

Increasing the emitter temperature and thereby increasing the electrical output power density of the converters reduces the fractional coverage. At an emitter temperature of 1800° K the fractional coverages are reduced by a factor of approximately 2.0, while at an emitter temperature of 2000° K an additional reduction by a factor of about 2.0 is realized. Therefore, diode fractional coverage, although restricting the available fuel-block length-to-diameter ratio over the entire output power range at an emitter temperature of 1600° K and a q_v of 10.0 W/cc, is not a significant problem for side-mounted configurations.

When diodes are mounted only on the ends of the fuel block, the fractional coverage trend with L/D is reversed; the coverage increases with increasing fuel-block length-to-diameter ratio. Also, with the exception of the L/D = 0.5 case, where the area of the ends of a cylinder is equal to the lateral surface area, the fractional coverage for an end-mounted configuration is much higher than that for the equivalent side-mounted configuration at a given L/D. In figure 3(b), the fraction of the end surface of the fuel block covered by diodes is shown as a function of fuel-block length-to-diameter ratio for a diode emitter temperature of 1600° K. Fractional coverages are presented for power levels of 100 and 1000 W_e at a fuel-block effective-volume power density of 0.5 W/cc. At a q_v of 0.5 W/cc and an output power of 1000 W_e, the fuel-block L/D is limited to values of 3.5 or less. Fractional coverages are not presented for a q_v of 10.0 W/cc since, in this case, the surface area was less than required for diodes over the entire range of L/D and output power. Again, increasing the emitter temperature will reduce the fractional coverage, but even at an emitter temperature of 2000° K, L/D limitations exist at the higher power levels and higher effective-volume power densities. Therefore, diode fractional coverage is a consideration in the design of end-mounted generators over the entire emitter-temperature range. The importance of restrictions that exist on the fuel-block length-to-diameter ratio is realized when considering generator efficiency and heat rejection.

The total surface area of a fixed volume cylinder is a minimum at a length-to-diameter ratio of 1.0. For a given set of design parameters, maximum generator efficiency (minimum parasitic heat losses) would then be achieved at a fuel-block L/D of 1.0. Therefore, in side-mounted configurations in which the fuel-block length-to-diameter ratio is limited to values greater than 1.0 and in end-mounted configurations in which the L/D is limited to values less than 1.0, efficiency penalties are incurred.

In considering heat rejection, longer fuel blocks may be desirable in order to increase the lateral surface area of the generator shell. In generators that are limited to low values of L/D, radiator fins, with accompanying weight penalties, may be required.

Generator Efficiency

Generator efficiency is presented in figure 4 as a function of fuel-block length-to-diameter ratio for an emitter temperature of 1600° K with output power and fuel-block

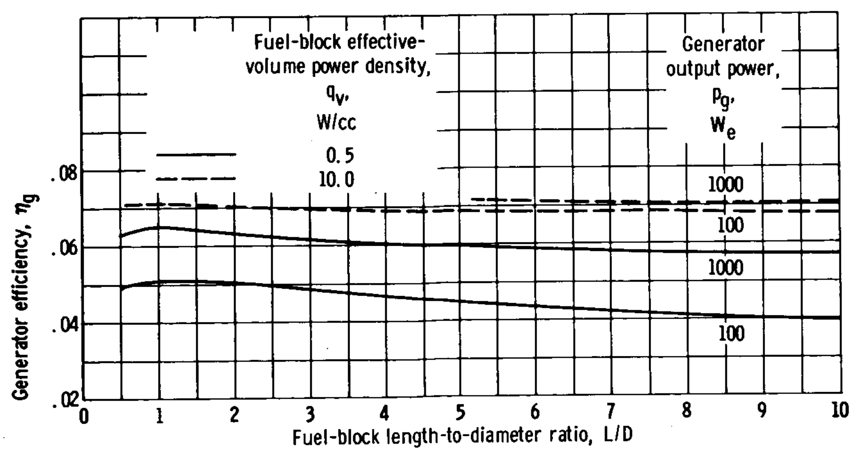


Figure 4. - Generator efficiency as function of fuel-block length-to-diameter ratio. Emitter temperature, 1600° K.

volume power density as parameters. Only a single set of efficiency data is required since at a given L/D with all other design parameters fixed, the total diode coverage of the fuel block is fixed, and the efficiencies for both side- and end-mounted configurations are identical. However, the efficiency curves are terminated at values of L/D at which neither arrangement is possible because of diode coverage limitations. Figure 4 shows that, at a q_v of 0.5 W/cc and a power output of 100 W_e, the efficiency exhibits a maximum at an L/D of 1.0 followed by a decrease with increasing L/D. At an L/D of 1.0 the efficiency is 0.051, while at an L/D of 10.0 the efficiency is 0.040. At the 1000-W_e level, the same general trend is apparent although the absolute level of efficiency is higher; the maximum is 0.065 and the minimum is 0.058 at an L/D of 10.0. Increasing the volume power density to 10.0 W/cc yields a higher peak generator efficiency (0.071 at 100 W_e) and results in the efficiency being less dependent on both L/D and power output. At a q_v of 10.0 W/cc and a power level of 1000 W_e, efficiency data are not presented below an L/D of 5.4 because of diode coverage limitations.

If the emitter temperature is increased, the dependence of efficiency on fuel-block length-to-diameter ratio is more pronounced. For example, at an emitter temperature of 1800° K with a q_v of 0.5 W/cc and a power level of 100 W_e, the efficiency decreases from 0.047 at an L/D of 1.0 to 0.026 at an L/D of 10.0. At 2000° K, the corresponding decrease is from 0.048 to 0.025.

Fractional area coverage limitations result in minor efficiency penalties. For example, side-mounted configurations are restricted to relatively high L/D's at an emitter temperature of 1600° K and a q_v of 10.0 W/cc. As shown in figure 4, however, at 1000 W_e and a limiting L/D of 5.4, the generator efficiency is 0.072, which is only 0.03 below the diode efficiency at this temperature. For end-mounted configurations that are limited to L/D's of less than 1.0, efficiency penalties are also of the order of several percent.

The generator efficiency data are summarized in figure 5. The maximum achievable efficiency, which occurs at an L/D of 1.0 except in cases where converter area coverages restrict the L/D of the fuel block, is presented as a function of fuel-block effective-volume power density with generator output power as a parameter. Again, no distinction is made between end- and side-mounted configurations.

Data for an emitter temperature of 1600° K (diode efficiency of 0.075) are presented in figure 5(a). At each power level, the efficiency increases with increasing q_v initially and begins to level off when the q_v reaches about 5.0 W/cc. For example, at a power level of 100 W_e, the efficiency increases from 0.051 at a q_v of 0.5 W/cc to 0.069 at a q_v of 5.0 W/cc and finally reaches 0.070 at a q_v of 10.0 W/cc. The efficiency improvement, which results from increasing the output power, is particularly evident at the lower values of q_v. At a q_v of 0.5 W/cc, the efficiency increases from 0.051 to 0.064 as the power output increases from 100 to 1000 W_e, while the corresponding change at a q_v of

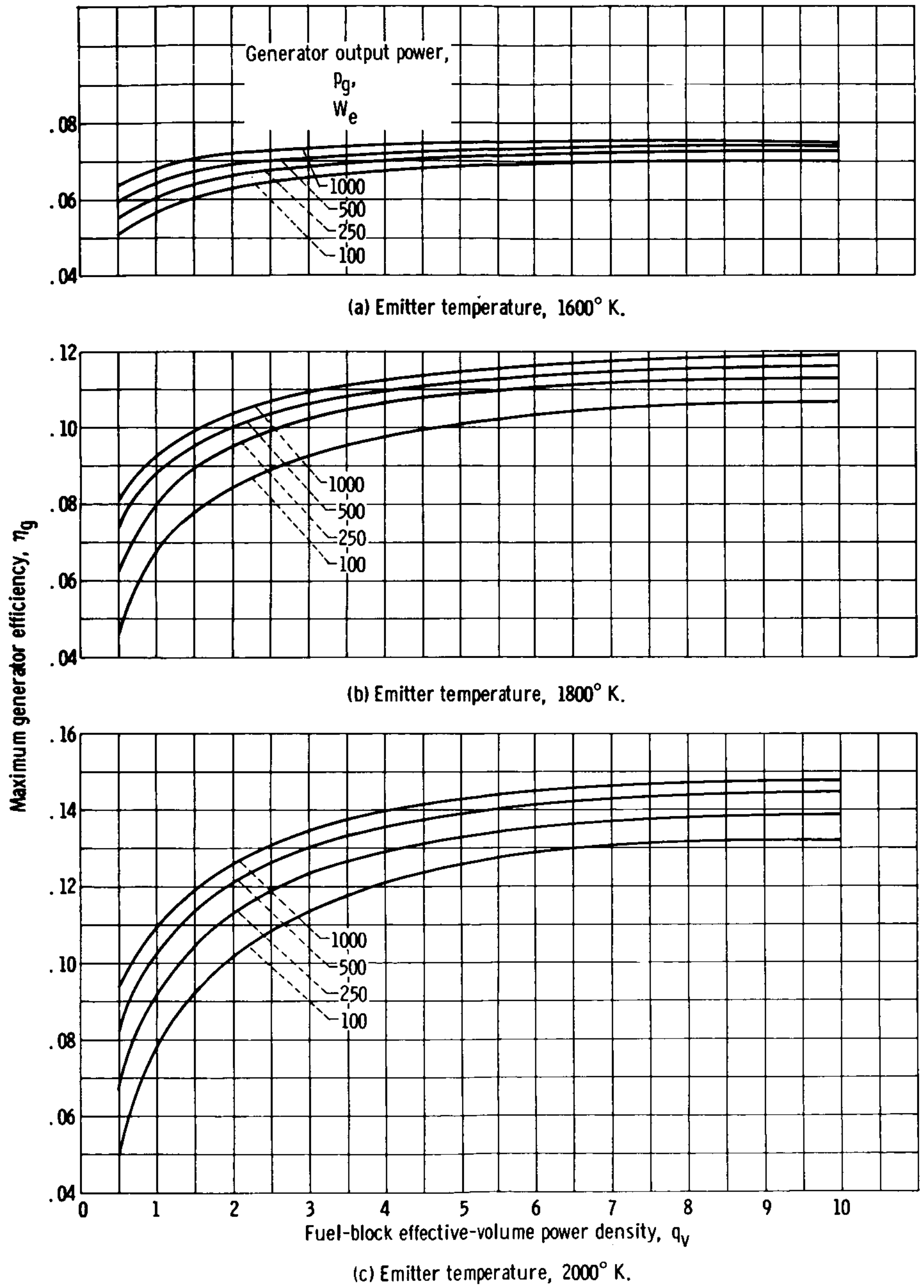


Figure 5. - Maximum generator efficiency as function of fuel-block effective-volume power density.

10.0 W/cc is from 0.070 to 0.074. The increase in efficiency as either the q_v is increased at fixed power output or the power output is increased at fixed q_v is, of course, a result of decreasing parasitic heat losses. If a volume power density of 5.0 W/cc or greater can be achieved, the parasitic losses become quite small and the generator efficiency reaches between 0.93 and 0.97 of the converter efficiency over the output power range.

As the emitter temperature increases, the parasitic heat losses become more significant and the efficiency is more dependent on the volume power density and output power. At an emitter temperature of 1800° K (fig. 5(b)) the sharp increase in efficiency with increasing q_v is still apparent, but in this case, the efficiency increases steadily over the entire q_v range. At the 100-W_e level, for example, the efficiency increases from 0.045 at a q_v of 0.5 W/cc to 0.102 at a q_v of 5.0 W/cc and reaches 0.108 at a q_v of 10.0 W/cc. The efficiency also improves rapidly with increasing power level; as the power output increases from 100 to 1000 W_e, the efficiency increases from 0.045 to 0.081 at a q_v of 0.5 W/cc, while the corresponding increase is from 0.108 to 0.119 at a q_v of 10.0 W/cc.

Figures 5(a) and (b) show that, with the exception of the q_v = 0.5 W/cc case at the 100-W_e level (where the parasitic losses are quite high), the overall efficiency level is higher for the 1800° K case because of the higher converter efficiency (0.128 in this case). The thermal efficiency (ratio of generator efficiency to diode efficiency), however, is lower at a given volume power density and reaches 0.87 at a q_v of 10.0 W/cc for the 100-W_e level and 0.96 for the 1000-W_e level.

As shown in figure 5(c) at an emitter temperature of 2000° K (diode efficiency = 0.158), the trends are identical to those exhibited at 1800° K. As q_v increases from 0.5 to 5.0 W/cc at a power level of 100 W_e, the efficiency increases from 0.048 to 0.126 and finally reaches 0.132 at a q_v of 10.0 W/cc. As the power level increases from 100 to 1000 W_e the efficiency increases from 0.048 to 0.094 at a q_v of 0.5 W/cc and from 0.132 to 0.148 at a q_v of 10.0 W/cc. Once again, figures 5(a) and (c) show that, at a q_v of 0.5 W/cc and a power level of 100 W_e, the efficiency is lower for the 2000° K emitter temperature than for the 1600° K emitter temperature because of the high parasitic heat losses. Also, the thermal efficiency is lower for the higher temperature system. For example, at a q_v of 10.0 W/cc, the 100-W_e generator efficiency reaches 0.84 of the converter efficiency while the 1000-W_e generator efficiency is 0.94 of the converter efficiency.

Briefly, the design variables affect generator efficiency as follows:

(1) At all power levels and emitter temperatures, achieving fuel-block volume power densities of 3.0 to 5.0 W/cc is advantageous. At the higher emitter temperatures, increasing q_v from 5.0 to 10.0 W/cc results in slight performance gains, while at an emitter temperature of 1600° K, the efficiency remains relatively constant over this range.

(2) In all cases, the generator efficiency improves as the output power is increased; the principal gains occur at high emitter temperatures and low volume power densities.

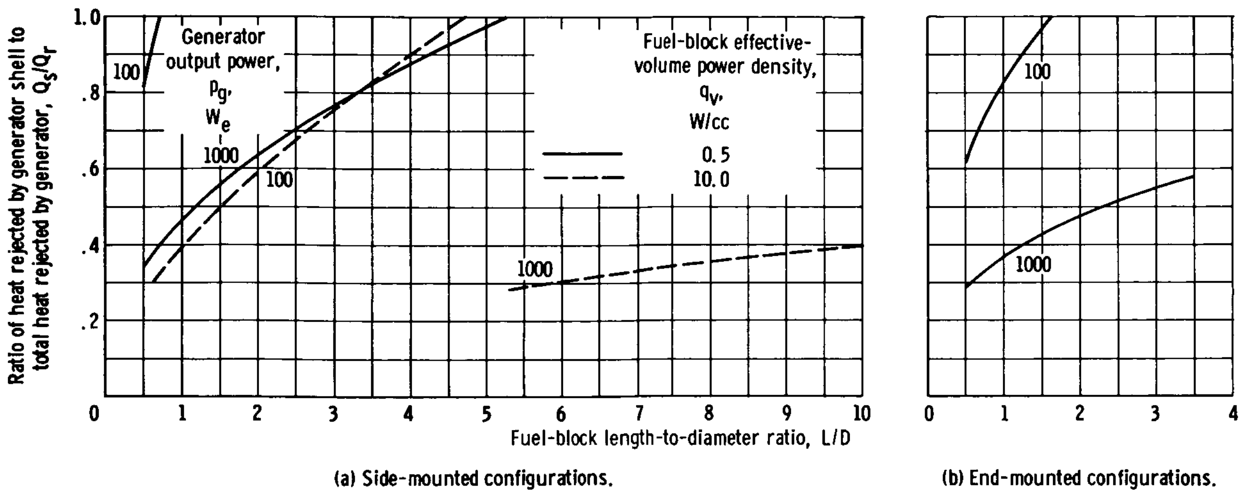
(3) Except for the 100-W_e power output case, in which an emitter temperature of 1600° K yielded the highest efficiency at a q_v of 0.5 W/cc, an advantage can be gained by operating at the highest practical emitter temperature.

Generator Heat Rejection

In addition to the efficiency being geometry-dependent, 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 PROCEDURE, it was assumed that, in either the side- or end-mounted configurations, waste heat would be conducted through the diode support structure to the generator shell, and only the lateral surface area of the 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 side-mounted configuration in figure 6(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 also shown in the figure.

At a q_v of 0.5 W/cc (fig. 6(a)), waste heat can be rejected solely by the shell over the output power range if the fuel block is sufficiently long. At a power output of 100 W_e, a heat-rejection ratio of 1.0 is achieved at an L/D of 0.75, while at the 1000-W_e level, an L/D of 5.3 is required. If, for any reason, the fuel block is limited to L/D's lower



(a) Side-mounted configurations.

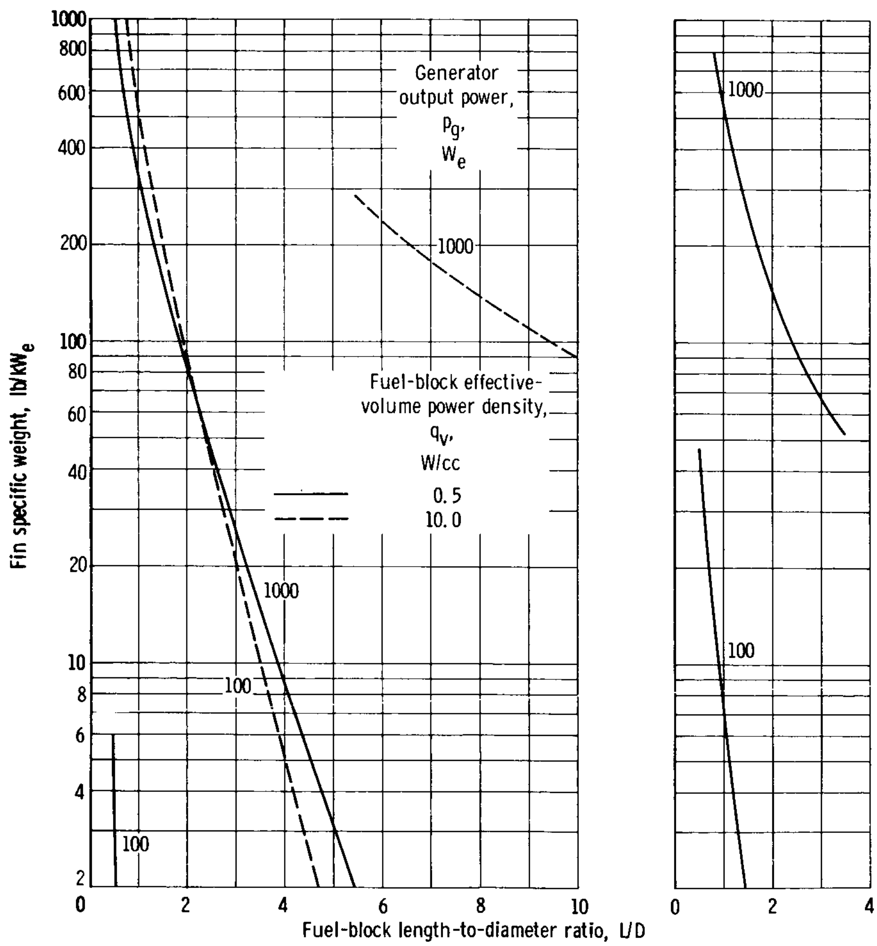
(b) End-mounted configurations.

Figure 6. - Heat rejected from generator by direct radiation to space. Emitter temperature, 1600° K.

than these values, the fin weight penalty shown in figure 7(a) would be incurred. At a power output of 100 W_e the fin weights are negligible, but for the 1000-W_e generator, the fin weight reaches several hundred pounds per electric kilowatt (lb/kW_e) at the lower L/D's.

As the volume power density increases, the ratio of shell surface area to volume decreases, and the cooling problem becomes more severe. At a q_v of 10.0 W/cc (fig. 6(a)) a heat-rejection ratio of 1.0 is achieved for the 100-W_e generator at an L/D of 4.7, but at the 1000-W_e level, the shell is capable of rejecting only 0.40 of the waste heat at a fuel-block length-to-diameter ratio of 10.0, and fins are required. The weight penalty associated with the addition of fins is shown in figure 7(a). The minimum fin weight for the 1000-W_e system (q_v = 10.0 W/cc) is 90 lb/kW_e, which is a significant fraction of the generator weight. Increasing the emitter temperature to 1800° K ($T_{shell} = 800^\circ$ K) virtually eliminates the necessity for fins in side-mounted configurations.

The heat-rejection ratio and corresponding fin weights for an end-mounted configuration are presented in figures 6(b) and 7(b) for an emitter temperature of 1600° K. At a



(a) Side-mounted configurations.

(b) End-mounted configurations.

Figure 7. - Fin specific weight as function of fuel-block length-to-diameter ratio.

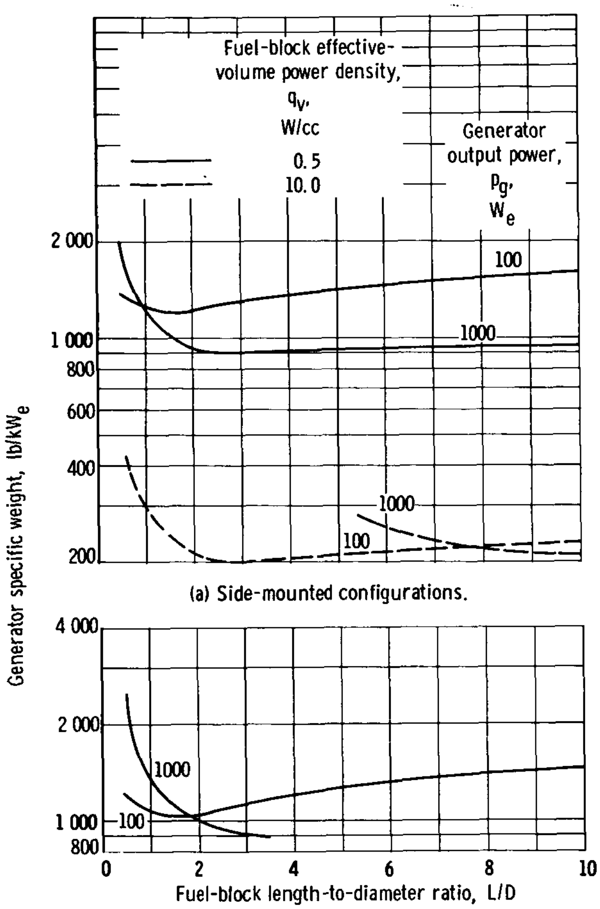
q_v of 0.5 W/cc, the 100-W_e generator requires an L/D of 1.6 to reject all the waste heat, while the 1000-W_e generator, which is limited to an L/D of 3.5 by diode coverage, can reject a maximum of 0.58 of the waste heat (fig. 6(b)). No heat-rejection data are presented for a q_v of 10.0 W/cc because of diode coverage limitations. As shown in figure 7(b) the minimum fin weight for the end-mounted 1000-W_e generator is about 50 lb/kW_e, whereas in the equivalent side-mounted case, fins are not required if the fuel block is made suffuciently long. Again, increasing the emitter temperature permits direct cooling (no fins) of the end-mounted generator over most of the design parameter ranges, although at an emitter temperature of 2000° K, fins are still required at a q_v of 10.0 W/cc for system power levels of 250 W_e and above. In these cases, however, the fin weights are generally low.

In review, the heat-rejection problem is significant only at an emitter temperature of 1600° K. At emitter temperatures of 1800° K and above, fins are required only in a few cases (at higher q_v for the end-mounted configurations).

Another important fact regarding generator heat rejection is that in order to minimize fin weight or completely eliminate fins, the fuel-block L/D can be increased; however, as pointed out in the section Generator Efficiency, the peak system efficiency occurs at an L/D of 1.0. In some cases, particularly at the lower volume power densities, the decrease in efficiency with increasing L/D is quite significant. Therefore, on the basis of overall generator performance, incorporation of fins and operation at lower L/D's may be necessary to improve the generator specific weight. These tradeoffs are illustrated in the next section.

General Specific Weight

Specific weights for generators in which the thermionic converters are mounted around the lateral surface area of the fuel block are presented for an emitter temperature of 1600° K in figure 8(a) as a function of fuel-block length-to-diameter ratio. The general pattern is one in which the weight is relatively high at an L/D of 0.5, and as L/D increases, the weight drops and goes through a minimum that is followed by a gradual increase. At a power level of 100 W_e and an emitter temperature of 1600° K, the generator weight minimizes near an L/D of 1.0 for a volume power density of 0.5 W/cc, but the minimum shifts to higher L/D's as the volume power density increases. At a q_v of 10.0 W/cc, the minimum weight is reached at an L/D of about 3.0. The trend toward minimizing weight at the higher L/D's for the higher powered isotopes arises because of the tradeoff between fin weight required to cool the generator and generator efficiency. The minimum specific weight ranges from 200 lb/kW_e at a q_v of 10.0 W/cc to over 1200 lb/kW_e at a q_v of 0.5 W/cc.



(a) Side-mounted configurations.

(b) End-mounted configuration.

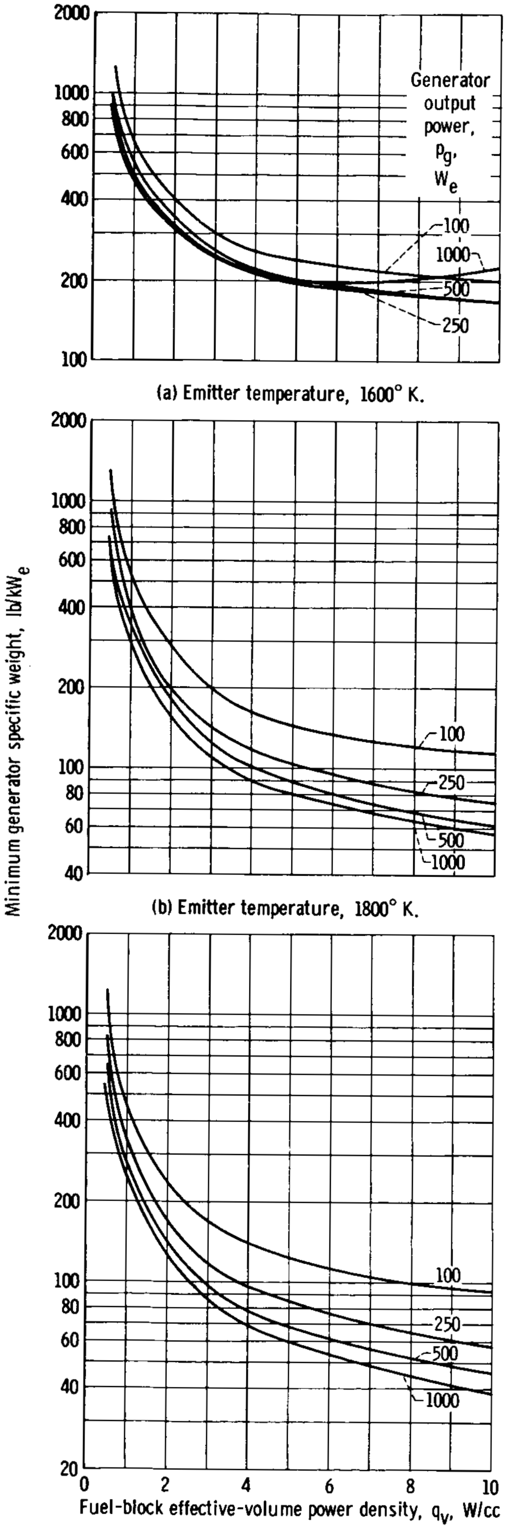
Figure 8. - Generator specific weight as function of fuel-block length-to-diameter ratio. Emitter temperature, 1600° K.

At the 1000-W_e power output level, the fin weight is even more dominant, and at a q_v of 0.5 W/cc, the generator weight minimizes at an L/D of about 3.0, while at a q_v of 10.0 W/cc, the lowest generator weight occurs at an L/D of 10.0. In this case, the minimum weights vary from 210 lb/kW$_e$ at a q_v of 10.0 W/cc to 900 lb/kW$_e$ at a q_v of 0.5 W/cc. Figure 7(a) shows that the fins account for 90 of the 210 lb/kW$_e$ of generator weight.

As the emitter temperature increases, the fin weight becomes less important, the minimum weights shift back toward an L/D of 1.0, and the weight level decreases. At an emitter temperature of 2000° K, for example, the minimum weight in all cases occurs at L/D's of 3.0 or less, and generator weights as low as 40 lb/kW$_e$ are achieved at a q_v of 10 W/cc and a power output of 1000 W_e.

Specific weights for generators in which the thermionic converters are mounted around the flat ends of the fuel block are presented for an emitter temperature of 1600° K in figure 8(b) as a function of the fuel-block length-to-diameter ratio.

For cases in which relatively long fuel blocks are allowable, the weight trends are identical to those shown for the side-mounted configurations; the weight decreases from an L/D of 0.5 to a minimum value and then rises again as L/D increases. As shown, at a q_v of 0.5 W/cc and a power output of 100 W_e, the weight reaches a minimum at an L/D near 1.0 and increases steadily with increasing L/D. At a power output of 1000 W_e, no minimum is observed, and the generator weight decreases steadily with



(c) Emitter temperature, 2000° K.

Figure 9. - Minimum generator specific weight as function of fuel-block effective-volume power density for side-mounted configurations.

increasing L/D until the limiting value of 3.5 is reached. In this case, the lowest achievable specific weights range from 900 to 1030 lb/kW$_e$ in the range from 1000 to 100 W$_e$, respectively.

When the emitter temperature is increased to 2000° K, the weights also reach minimums for end-mounted systems at L/D's of 3.0 or less, and generator specific weights as low as 46 lb/kW$_e$ are achieved at a q_v of 10.0 W/cc.

In optimizing the design of a radioisotope thermionic generator, therefore, the performance tradeoff that exists between fin weight (which decreases with increasing L/D) and generator efficiency (which is a maximum at an L/D of 1.0) must be considered. This tradeoff is best illustrated by referring to figures 4 and 8(a) and taking as an example the 1000-W$_e$ system and a q_v of 0.5 W/cc. As shown in figure 4, a maximum generator efficiency of 0.065 is achieved at an L/D of 1.0, and as shown in figure 8(a), the generator specific weight at an L/D of 1.0 is 1200 lb/kW$_e$. The minimum generator specific weight, 900 lb/kW$_e$, occurs at an L/D of 3.0, and the generator efficiency at an L/D of 3.0 is 0.062 (fig. 4). Therefore, by incorporating a fuel block with a length-to-diameter ratio of 3.0 instead of 1.0, the generator weight is decreased by one-fourth (300 lb/kW$_e$), while the efficiency penalty is only 5 percent. For all cases in which radiator fins are required, the same trend is observed; that is, large weight savings and small efficiency penalties are realized by designing for minimum weight. Therefore, selecting the fuel-block length-to-diameter ratio that yields minimum generator weight is advantageous.

Specific weight summary curves for the side-mounted configurations are presented in figures 9 and 10. In these figures, the minimum achievable

TABLE I. - FUEL-BLOCK LENGTH-TO-DIAMETER RATIO AND FRACTIONAL SYSTEM EFFICIENCY CORRESPONDING TO MINIMUM SYSTEM SPECIFIC WEIGHTS FOR TWO CONFIGURATIONS

(a) Side-mounted

Fuel-block effective-volume power density, q_v, W/cc	Emitter temperature, T_E, ^oK					
	1600		1800		2000	
	Length-to-diameter ratio, L/D	Generator efficiency, η_g	Length-to-diameter ratio, L/D	Generator efficiency, η_g	Length-to-diameter ratio, L/D	Generator efficiency, η_g
Generator output power, P_g, 100 W_e						
0.5	1.0	0.051	1.0	0.045	1.0	0.048
1.0	1.0	.058	1.0	.068	1.0	.078
3.0	3.0	.066	1.0	.094	1.0	.114
5.0	3.0	.068	1.0	.102	1.0	.126
10.0	3.0	.070	1.0	.108	1.0	.132
Generator output power, P_g, 250 W_e						
0.5	1.0	0.055	1.0	0.061	1.0	0.066
1.0	3.0	.061	1.0	.080	1.0	.092
3.0	3.0	.069	1.0	.103	1.0	.124
5.0	5.0	.069	1.0	.108	1.0	.133
10.0	10.0	.068	3.0	.109	1.0	.139
Generator output power, P_g, 500 W_e						
0.5	3.0	0.058	1.0	0.074	1.0	0.081
1.0	3.0	.064	1.0	.090	1.0	.107
3.0	10.0	.068	3.0	.104	1.0	.134
5.0	10.0	.069	3.0	.109	1.0	.140
10.0	10.0	.070	5.0	.115	3.0	.143
Generator output power, P_g, 1000 W_e						
0.5	3.0	0.062	1.0	0.081	1.0	0.094
1.0	5.0	.066	3.0	.093	1.0	.116
3.0	10.0	.069	3.0	.109	3.0	.133
5.0	10.0	.071	5.0	.112	3.0	.138
10.0	10.0	.073	10.0	.115	3.0	.146

TABLE I. - Concluded. FUEL-BLOCK LENGTH-TO-DIAMETER RATIO AND FRACTIONAL SYSTEM EFFICIENCY CORRESPONDING TO MINIMUM SYSTEM SPECIFIC WEIGHTS FOR TWO CONFIGURATIONS

(b) End-mounted

Fuel-block effective-volume power density, q_v, W/cc	Emitter temperature, T_E, ^oK					
	1600		1800		2000	
	Length-to-diameter ratio, L/D	Generator efficiency, η_g	Length-to-diameter ratio, L/D	Generator efficiency, η_g	Length-to-diameter ratio, L/D	Generator efficiency, η_g
Generator output power, P_g, 100 W_e						
0.5	1.0	0.051	1.0	0.047	1.0	0.048
1.0	1.0	.059	1.0	.068	1.0	.078
3.0	1.0	.067	1.0	.093	1.0	.114
5.0	.5	.068	1.0	.102	1.0	.124
10.0	(a)	-----	1.0	.108	1.0	.131
Generator output power, P_g, 250 W_e						
0.5	3.0	0.055	1.0	0.061	1.0	0.068
1.0	3.0	.061	1.0	.081	1.0	.094
3.0	.5	.069	3.0	.090	1.0	.124
5.0	.5	.070	3.0	.103	1.0	.134
10.0	(a)	-----	1.0	.116	5.0	.134
Generator output power, P_g, 500 W_e						
0.5	3.0	0.058	1.0	0.725	1.0	0.083
1.0	1.0	.066	3.0	.086	1.0	.106
3.0	.5	.070	3.0	.104	3.0	.128
5.0	(a)	-----	1.0	.113	3.0	.135
10.0	(a)	-----	1.0	.116	1.0	.145
Generator output power, P_g, 1000 W_e						
0.5	3.0	0.062	3.0	0.078	1.0	0.095
1.0	1.0	.068	3.0	.093	1.0	.116
3.0	(a)	-----	3.0	.1093	3.0	.133
5.0	(a)	-----	1.0	.116	3.0	.138
10.0	(a)	-----	.5	.119	1.0	.149

[a]Systems limited to ratios less than 0.5.

weights obtained from the plots of specific weight against fuel-block length-to-diameter ratio are shown as functions of the primary design variables. The corresponding generator efficiencies and the fuel-block length-to-diameter ratio (to the nearest integer) at which the minimum weight occurs are listed in table I(a) (p. 18).

The significance of both fuel-block effective-volume power density and output power level is illustrated in figure 9. At an emitter temperature of 1600° K (fig. 9(a)) the generator weight decreases sharply as the volume power density increases from 0.5 to 5.0 W/cc; the decrease is of the order of 700 to 1000 lb/kW$_e$ over the range of output power. A further increase in q_v from 5.0 to 10.0 W/cc results in slight specific weight improvements, of the order of 50 lb/kW$_e$ at power levels to 500 W$_e$, while at the 1000-W$_e$ level, a slight increase in specific weight occurs. This increase is due to the fact that, as the generator becomes more compact (e.g., by increasing output power and volume power density), the fin weight becomes significant at this emitter temperature.

With the exception of the 1000-W$_e$ generator, which actually weighs more than the 100-W$_e$ generator at a q_v of 10.0 W/cc, a specific weight advantage is realized by operating at the higher power levels. As shown in figure 9(a), at a q_v of 5.0 W/cc, increasing the power output from 100 to 250 W$_e$ results in a weight reduction of about 40 lb/kW$_e$, while further increases result in very slight improvements. At all power levels, specific weights of the order of 200 lb/kW$_e$ are achieved at volume power densities of 5.0 W/cc or greater.

Increasing the emitter temperature from 1600° to 1800° K (fig. 9(b)) also results in weight improvements. Over the q_v range from 0.5 to 5.0 W/cc, the decrease in weight ranges from 1100 lb/kW$_e$ at a power level of 100 W$_e$ to 570 lb/kW$_e$ at a power level of 1000 W$_e$. In this case, the radiator fin weight is not significant at the higher q_v, and the performance of each of the four systems improves slightly (of the order of 25 lb/kW$_e$) when q_v is increased from 5.0 to 10.0 W/cc. When the power output is increased from 100 to 250 W$_e$, the specific weight decreases by about 40 lb/kW$_e$ over the q_v range from 5.0 to 10.0 W/cc. An additional reduction of 15 lb/kW$_e$ is achieved in going from 250 to 500 W$_e$, and a 10-lb/kW$_e$ reduction is achieved in going from 500 to 1000 W$_e$. Specific weights on the order of 200 lb/kW$_e$ are now realized at all power levels at a q_v of about 2.0 to 3.0 W/cc.

The same trends are evident at an emitter temperature of 2000° K (fig. 9(c)), where again, because fin weights are not significant, the weight decreases with increasing q_v at all power levels. The performance improvement ranges from about 1100 lb/kW$_e$ at a power level of 100 W$_e$ to about 500 lb/kW$_e$ at 1000 W$_e$ over the range of volume power density, and the weight reduction as power level increases is about the same at a given q_v as for the case of 1800° K emitter temperature. At 2000° K, specific weights of the order of 200 lb/kW$_e$ are realized at a q_v of less than 2.0 W/cc, while at 10.0 W/cc, the specific weights are less than 100 lb/kW$_e$ at all power levels.

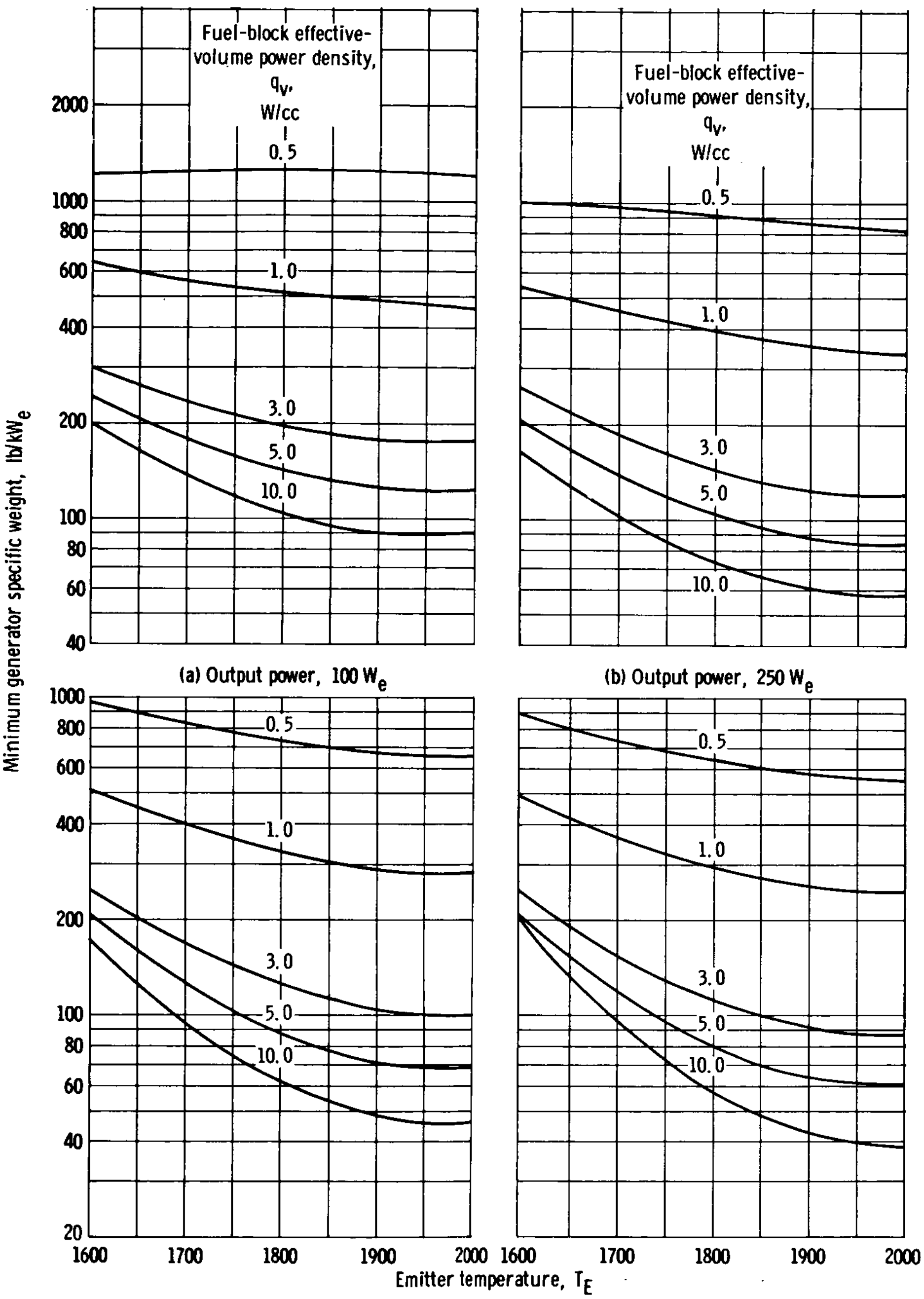


Figure 10. - Minimum generator specific weight as function of emitter temperature; side-mounted configurations.

The importance of emitter temperature in establishing system weight is shown in figure 10, where specific weight is plotted against emitter temperature with q_v as a parameter for each of four output power levels. At the 100-W_e power output (fig. 10(a)), and a q_v of 0.5 W/cc, the generator specific weight reaches a maximum at an emitting temperature of 1800° K and identical weights at 1600° and 2000° K. In this case, operating at the lower emitter temperature would be an advantage although the specific weight level of 1200 lb/kW_e might be excessive. As q_v is increased, the specific weight decreases with increasing emitter temperature with (in all cases) the greater decrease occurring over the first 200° K. For example, at a q_v of 1.0 W/cc, the weight is reduced by 100 lb/kW_e in going from 1600° to 1800° K, while a weight reduction of about 20 lb/kW_e is realized in going from 1800° to 2000° K. At a q_v of 10.0 W/cc, the initial reduction (1600° to 1800° K) in weight is 95 lb/kW_e, while the second 200° K increase results in a weight decrease of about 10 lb/kW_e.

When the power output is increased to 250 W_e (fig. 10(b)), the specific weight decreases continually with increasing emitter temperature at a q_v of 0.5 W/cc, the decrease being almost linear with a slope of 50 lb/kW_e/100° K. At higher q_v's, the trends are identical to those observed at the 100-W_e level, a significant weight reduction in going from an emitter temperature of 1600° to 1800° K (85 lb/kW_e at a q_v of 10.0 W/cc) and a minor weight reduction in going from 1800° to 2000° K (15 lb/kW_e at a q_v of 10.0 W/cc).

Specific weights for a power output of 500 W_e are presented in figure 10(c). The trends are identical at all q_v's to those shown for the 250 W_e at the higher volume power densities. At a q_v of 0.5 W/cc, for example, the decrease in specific weight is about 250 lb/kW_e in going from 1600° to 1800° K and about 70 lb/kW_e in going from 1800° to 2000° K. The corresponding reductions at a q_v of 10.0 W/cc are 110 lb/kW_e, which is slightly higher than for the 250 W_e case, and 15 lb/kW_e, which is the same as for the 250 W_e case.

At the 1000-W_e power level (fig. 10(d)), the curves behave in exactly the same fashion as for the 500-W_e case with the reduction in specific weight being slightly greater when the emitter temperature is increased from 1600° to 1800° K than the reduction achieved in going from 1800° to 2000° K.

For the side-mounted configurations, therefore, at each of the three emitter temperatures, a significant advantage is gained if a fuel-block effective-volume power density of the order of 5.0 W/cc is achieved with reductions in system specific weight ranging from 500 to 100 lb/kW_e realized by increasing the volume power density from 0.5 to 5.0 W/cc. Further increases in power density to as high as 10.0 W/cc result in slight weight improvements. An advantage can also be gained by operating at power levels in the range 250 to 500 W_e, but little additional gain is realized by increasing the power output to 1000 W_e. With the exception of the 100-W_e case at a q_v of 0.5 W/cc, which exhibits a minimum weight at an emitter temperature of 1600° K, significant weight savings are

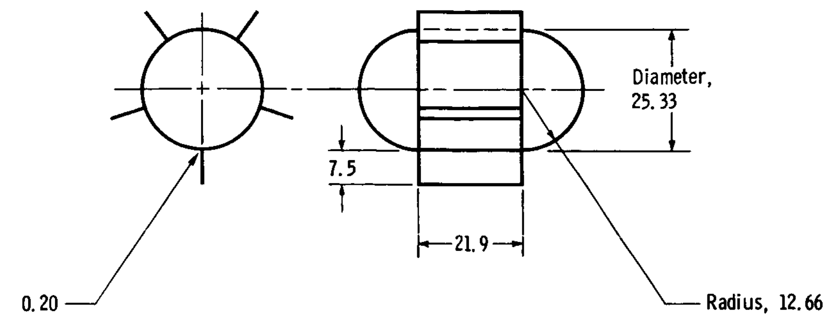


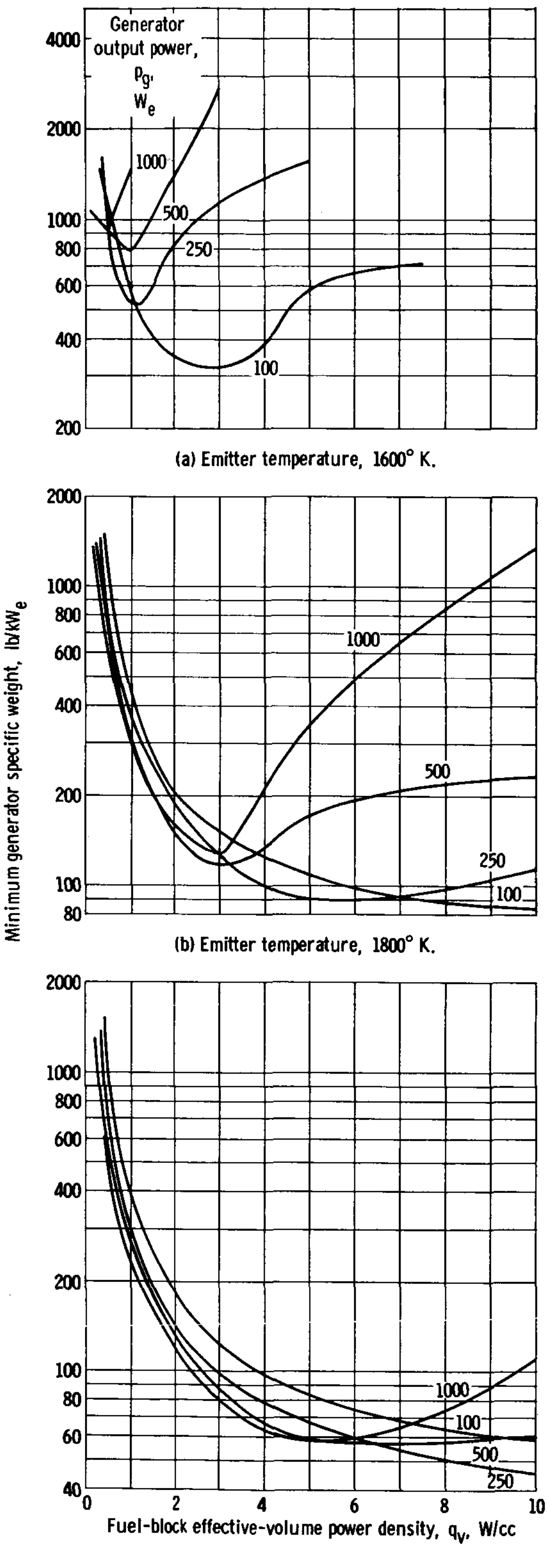
Figure 11. - Minimum weight, 500-W_e side-mounted generator. Fuel-block effective-volume power density, 5.0 W/cc; diode emitter temperature, 1800° K. (All dimensions are in centimeters.)

realized by operating at an emitter temperature of 1800° K, and slight additional weight reductions result from a further increase to 2000° K. At a q_v of 5.0 W/cc, the specific weight is reduced by 100 lb/kW_e at the 100-W_e power level and by 130 lb/kW_e at the 1000-W_e power level when the emitter temperature is increased from 1600° to 2000° K. For a generator in which the volume power density is 5.0 W/cc and the output power is 500 W_e, specific weights are 200, 90, and 70 lb/kW_e at emitter temperatures of 1600°, 1800°, and 2000° K, respectively. The minimum achievable weights for the 500-W_e system at the above emitter temperatures (occurring in all cases at a q_v of 10.0 W/cc) are 170, 62, and 46 lb/kW_e.

A schematic diagram of a 500-W_e side-mounted generator in which the fuel-block effective-volume power density is 5.0 W/cc and the diode emitter temperature is 1800° K is presented in figure 11. The generator weight minimizes at a fuel-block length-to-diameter ratio of 3.0. The generator body diameter is 25.33 centimeters, and the overall generator length (including end caps) is 47.23 centimeters. The tapered fins have a root thickness of 0.20 centimeter, and are 7.50 centimeters long. These dimensions result in an overall generator diameter of 40.33 centimeters.

The minimum specific weights for the end-mounted configurations are presented as a function of the fuel-block volume-power density in figure 12, and the corresponding generator efficiencies and the fuel-block length-to-diameter ratio at which the minimum weight occurs are listed in table I(b) (p. 19).

The effect of converter area coverage in limiting the fuel-block length-to-diameter ratio and subsequently increasing the radiator fin weight as either q_v or output power increases is clearly illustrated in figure 12(a) for an emitter temperature of 1600° K. At a power output of 100 W_e the minimum weight decreases with increasing q_v until a q_v of 3.0 W/cc is reached; then the fin weight increases rapidly and the generator weight begins to rise. The curve is terminated when the coverage of the fuel-block ends is complete. As the power output increases, the fin weight becomes even more significant, and the curves minimize at lower values of q_v until at 1000 W_e, the minimum specific weight



(c) Emitter temperature, 2000° K.

Figure 12. - Minimum generator specific weight as function of fuel-block effective-volume power density for end-mounted configurations.

occurs at a q_V of 0.5 W/cc. At the minimum, the specific weights range from 320 lb/kW$_e$ at a power output of 100 W$_e$ to over 900 lb/kW$_e$ at a power output of 1000 W$_e$.

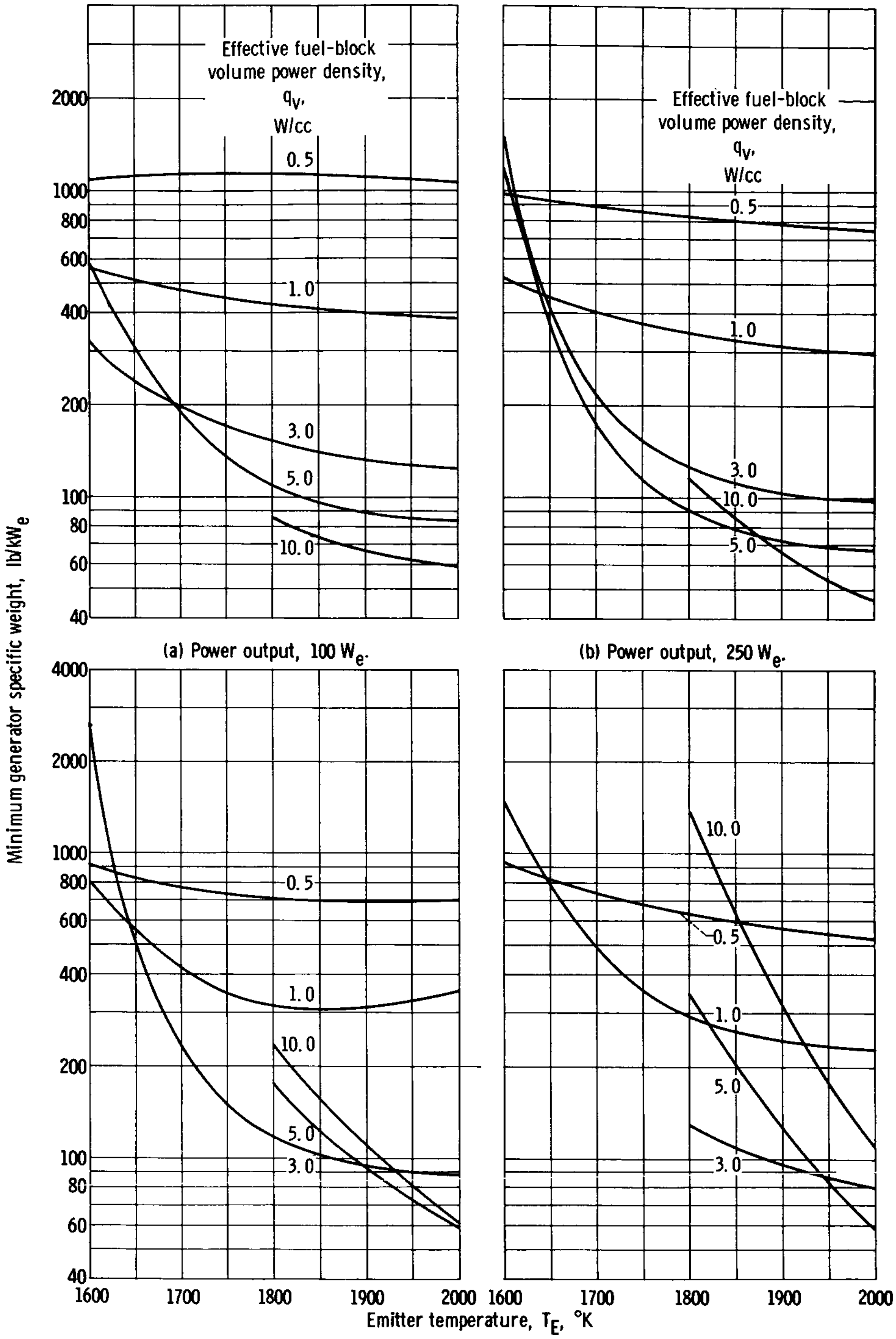
Increasing the emitter temperature to 1800^o K (fig. 12(b)) increases the useful q_V range, but the curves still minimize at values of q_V less than 10.0 W/cc for power levels above 100 W$_e$. At a power output of 100 W$_e$, the minimum specific weight decreases continuously as q_V increases, and the decrease is much more significant from 0.5 to 5.0 W/cc than from 5.0 to 10.0 W/cc. As the power output increases to 250 W$_e$, a minimum is observed at a q_V of 5.0 W/cc. The minimum then shifts toward lower values of q_V as the power output is further increased; for example, the minimum occurs at a q_V of 3.0 W/cc at the 1000-W$_e$ level. Again, the lower power output generators have lower specific weights than the higher output power generators, with the minimum ranging from 85 lb/kW$_e$ (power output of 100 W$_e$ at a q_V of 10.0 W/cc) to 130 lb/kW$_e$ (power output of 1000 W$_e$ at a q_V of 3.0 W/cc).

At 2000^o K, because of higher diode efficiency and higher heat-rejection temperature, radiator fins are either not required or their weight can be neglected except for the most compact generators. As shown in figure 12(c), the specific weight decreases steadily with increasing q_V for the 100- and 250-W$_e$ systems. At the 500-W$_e$ level, a broad minimum is observed between q_V's of about 6.0 and 8.0 W/cc, while at the 1000-W$_e$ level, a sharper minimum is observed at a q_V of 5.0 W/cc. In regard to the specific weight against output power behavior, the 250-W$_e$ generator exhibits the lowest specific weight (46 lb/kW$_e$), while the 100-, 500-, and 1000-W_e generators exhibit a minimum weight of the order of 60 lb/kW_e.

Minimum specific weights are presented as functions of emitter temperature for the end-mounted configurations in figure 13. At a power output of 100 W_e (fig. 13(a)), the minimum weight occurs at an emitter temperature of 1600° K for a q_v of 0.5 W/cc. As the volume power density increases, the weight decreases with increasing temperature, with the most significant decreases occurring when the emitter temperature is increased from 1600° to 1800° K. For example, at a q_v of 5.0 W/cc, the weight decreases from 600 lb/kW_e at an emitter temperature of 1600° K to 110 lb/kW_e at an emitter temperature of 1800° K. In going from an 1800° to a 2000° K emitter temperature, the weight decreases from 110 to about 85 lb/kW_e. It is noteworthy that the converter fractional area coverage does not permit generator operation for the q_v of 10.0 W/cc and an emitter temperature of 1600° K.

At the 250-W_e level (fig. 13(b)), the specific weight decreases with increasing emitter temperature at all q_v's, with the most significant decrease again occurring between emitter temperatures of 1600° and 1800° K for a q_v of 5.0 W/cc. In this case, the weight decreases from over 1500 to 90 lb/kW_e for a 200° K increase in emitter temperature. The same pattern is evident at a power output of 500 W_e (fig. 13(c)) with an even more sizable decrease in weight occurring for a q_v of 5.0 W/cc than at the lower power levels. When the power output reaches 1000 W_e (fig. 13(d)), a significant decrease in specific weight with increasing emitter temperature in the range from 1600° to 1800° K is evident at volume power densities of 0.5 and 1.0 W/cc, where the weight reductions are 300 and 1200 lb/kW_e, respectively. However, at q_v's of 3.0 W/cc and above, operation at an emitter temperature of 1600° K is not possible and substantial weight savings are made by operating at the highest emitter temperature. For example, between an emitter temperature of 1800° K and an emitter temperature of 2000° K at a q_v of 5.0 W/cc, the weight decreases from 350 to 60 lb/kW_e, while at a q_v of 10.0 W/cc, the weight decreases from about 1400 to 110 lb/kW_e.

In end-mounted configurations, the weight of radiator fins plays a more important part in establishing generator specific weight than in the side-mounted configurations, and this, coupled with the severe L/D restrictions that occur in some cases, leads to less predictable generator performance. At an emitter temperature of 1600° K, specific weights minimize at volume power densities of 3.0 or less, while at an emitter temperature of 1800° K, the specific weight decreases steadily with increasing q_v at the 100-W_e level, but at power levels of 250 W_e, the curves minimize at q_v's of 5.0 W/cc and below. Even at a 2000° K emitter temperature, the specific weight minimizes at a q_v of 7.0 W/cc or below for power levels of 500 W_e and above. Therefore, it is not possible to state a general conclusion regarding volume power density for these configurations without specifying emitter temperature and power level.



(c) Power output, 500 W_e. (d) Power output, 1000 W_e.

Figure 13. - Minimum of generator specific weight as function of emitter temperature for end-mounted configuration.

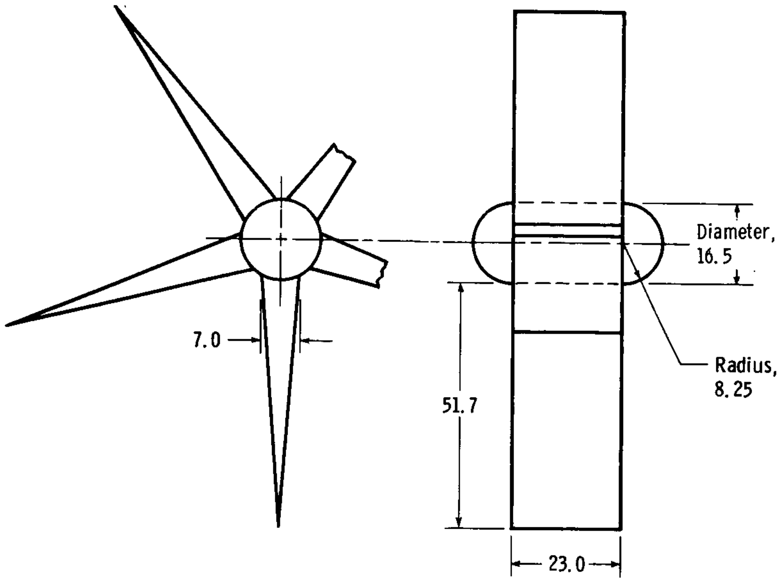


Figure 14. - Minimum weight, 500 W_e end-mounted generator. Fuel-block effective-volume power density, 5.0 W/cc; diode emitter temperature, 1800° F. (All dimensions are in centimeters.)

The same statement holds true for power level. At the lower emitter temperatures, the lower power generators weigh less than the higher power generators. As the emitter temperature increases, the trend begins to reverse, but even at an emitter temperature of 2000° K, the 250-W_e generators exhibit a lower minimum weight than either the 500- or 1000-W_e generators.

For the side-mounted configurations, the conclusion is reached that the weight reduction realized by increasing the emitter temperature from 1600° to 1800° K is much more significant than the reduction realized by an additional 200° K increase (with the exception of the 100-W_e system at a q_v of 0.5 W/cc). This is also generally true for the end-mounted configurations (with the same exception). At the higher power levels (500 W_e and above) and at the higher q_v's (5.0 W/cc and above), however, large weight savings are realized by increasing the emitter temperature from 1800° to 2000° K.

For a 500-W_e generator, the minimum achievable specific weights for an end-mounted configuration at emitter temperatures of 1600°, 1800°, and 2000° K are 800 lb/kW_e (q_v of 1.0 W/cc), 120 lb/kW_e (q_v of 3.0 W/cc), and 60 lb/kW_e (q_v of 5.0 W/cc).

A schematic diagram of a 500-W_e end-mounted generator in which the fuel-block effective-volume power density is 5.0 W/cc and the diode emitter temperature is 1800° K is presented in figure 14. The minimum generator specific weight occurs at a fuel-block length-to-diameter ratio of 1.0 in this case.

The generator body diameter is 16.50 centimeters and the generator overall length (including end caps) is 39.50 centimeters. The radiator fins are much larger than in the corresponding side-mounted configuration (fig. 11); the required root thickness is

7.00 centimeters, the length 51.70 centimeters, and the overall generator diameter 119.90 centimeters, compared with an overall diameter of 40.33 centimeters for the minimum weight 500-W_e side-mounted generator.

SUMMARY OF RESULTS

The following results were obtained from a parametric analysis in which the effects of heat-source volume power density, electrical output power, and emitter temperature on the performance of a radioisotope thermionic generator were investigated:

1. For configurations in which thermionic converters were located either around the lateral surface area of the fuel block (side-mounted) or around the flat ends of the fuel block (end-mounted), there was a significant advantage on the basis of both system efficiency and specific weight in increasing the emitter temperature from 1600° to 1800° K, generally followed by slight improvements when the emitter temperature was increased from 1800° to 2000° K.

2. For both configurations, at emitter temperatures of 1800° and 2000° K, significant improvements in performance were realized when the fuel-block effective-volume power density was increased from 0.5 watt per cubic centimeter (W/cc) (the lowest value considered in the study) to values of the order of 3.0 to 5.0 W/cc, with slight additional improvements resulting when the volume power density was increased from 5.0 to 10.0 W/cc.

At an emitter temperature of 1600° K, the same trend was observed for the side-mounted configurations, while for end-mounted configurations, minimum generator specific weights were realized at values of power density ranging from 3.0 W/cc at an output power level of 100 electric watts (W_e) to 0.5 W/cc at an output power level of 1000 W_e.

3. Over the emitter temperature range considered for the side-mounted configurations, a significant reduction in generator specific weight was realized when the electrical power output was increased from 100 W_e to the order of 250 to 500 W_e, and a slight additional reduction was achieved when the power output was increased from 500 to 1000 W_e. For end-mounted configurations at emitter temperatures of 1600° and 1800° K, the minimum specific weight increased with increasing power level, while at an emitter temperature of 2000° K, the 250-W_e system exhibited the lowest weight.

4. The side-mounted configurations, at a given emitter temperature, volume power density, and output power, generally exhibited lower specific weights than the end-mounted configurations. For comparison, at 500-W_e output power, the minimum specific weights (excluding nuclear shielding and ablative material for reentry protection) for the side-mounted and end-mounted configurations are presented in the following table:

Emitter temperature, ^{o}K	Configuration	
	Side-mounted	End-mounted
	Minimum specific weight, lb/kW_e	
1600	170	800
1800	62	120
2000	46	60

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, July 8, 1966,
120-27-06-06-22.

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