NASA TECHNICAL MEMORANDUM

NASA TM X-52122

NASA TM X-52122

FACILITY FORM 602

N65-34909 (ACCESSION NUMBER) (THRU)

21 (PAGES) 1 (CODE)

TM-X-52122 (NASA CR OR TMX OR AD NUMBER) 03 (CATEGORY)

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GPO PRICE $ ________

CFSTI PRICE(S) $ ________

Hard copy (HC) 1.00

Microfiche (MF) .50

ff 653 July 65

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TECHNICAL PREPRINT prepared for International Conference on Energetics sponsored by the American Society of Mechanical Engineers
Rochester, New York, August 18-20, 1965

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION · WASHINGTON, D.C. · 1965

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SYMBOLS

A	fuel-block surface area covered by diodes, sq cm
A_c/A_s	fraction of fuel block surface area covered by diodes
A_s	total fuel-block surface area, sq cm
D	fuel block diameter, cm
L/D	length-to-diameter ratio of fuel block
P_o	electrical output power, W
p_c	diode electrical-output power density, W/cm^2
Q_{in}	heat generated by fuel block, W
Q_{loss}	heat lost through thermal insulation, W
q_{loss}	heat lost through thermal insulation per unit area, W/cm^2
q_v	effective fuel-block-volume power density (thermal power of fuel block/total fuel block volume), W/cc
η_d	diode efficiency
η_g	generator efficiency

Introduction

The radioisotope thermionic power generation system appears to be very attractive for many space power applications because of its potentially high efficiency, high heat-rejection temperatures, and compact size. In the design of such a system ther are a number of parameters which must be considered. For example, the type of radioisotope used, the diode operating temperatures, the fuel block geometry, and the manner in which the diodes are positioned around the fuel block are all design variables within, of course, certain physical constraints. The results of a parametric analysis are presented in which the effects of these design variables on system performance, particularly efficiency, are pointed out. Cooling the system by direct radiation to space is then discussed. Finally, system specific weight calculations are presented for a range of design variables.

Parametric Analysis

A schematic diagram of the type of power system analyzed is shown in Fig. 1. The system is internally fueled with the radioisotopic fuel encapsulated in a cylindrical block. In the figure, planar diodes are shown facing the lateral surfaces of the fuel block. However, depending on the system electrical output power and the effective volume power density of the fuel block, the diodes might be mounted facing the flat ends of the fuel block or perhaps a single cylindrical diode might be used. In multi-diode configurations it was assumed that the heat would be transferred from the fuel block to the thermionic converters by radiation, thus allowing series and parallel electrical connections. Stacked foil-type insulation is used to thermally shield the fuel-block surface area not radiating directly to the diodes. Waste heat is conducted through the diode support structure to the generator shell where it is radiated directly to space. In some cases, fins are required to augment the heat-rejection capability of the shell.

The system heat flow is shown in Fig. 2. The thermal input to the system, which was fixed at 5000 W for the parametric analysis, is provided by the decay of the radioisotope fuel. Heat is transferred from the fuel block to the thermionic diodes where a portion of it is converted into electrical energy. The waste heat from the converters, as well as the heat lost through the thermal insulation, must then be rejected from the system.

Pertinent equations used in the analysis are presented below. In the first equation, the heat flux available to the thermionic converters is presented as a function of the fuel block thermal power Q_{in}, heat lost through the insulation Q_{loss}, and the surface area of the fuel block covered by converters A_c.

$$\text{Available heat flux} = (Q_{in} - Q_{loss})/A_c \tag{1}$$

The heat flux required by the converters is then presented as a function of the electrical power density p_c and the diode efficiency η_d.

$$\text{Required heat flux} = p_c/\eta_d \tag{2}$$

These heat fluxes must then be matched by varying the amount of fuel block area covered by the diodes. The allowable diode fractional area coverage A_c/A_s is determined from the following equation.

$$A_c/A_s = \left[(Q_{in}/A_s) - q_{loss}\right] \Big/ \left[(p_c/\eta_d) - q_{loss}\right] \tag{3}$$

The electrical output power of the system P_o is then given in terms of electrical power density, diode fractional area coverage, fuel block diameter D, and the fuel block length-to-diameter ratio L/D.

$$P_o = p_c(A_c/A_s)A_s = p_c(A_c/A_s)\pi D^2\left[(L/D) + (1/2)\right] \tag{4}$$

In the last equation, the system efficiency is presented as the ratio of electrical output power to thermal input power.

$$\eta_g = P_o/Q_{in} \tag{5}$$

The design variables considered in the analysis were the effective volume power density of the fuel block (defined as the ratio of fuel block thermal power to the total fuel block volume), the length to diameter ratio of the fuel block, and the diode performance. The effect of these variables on fractional area coverage, output power, and generator efficiency was investigated.

The range of the design variables considered in the parametric analysis is as follows. The effective volume-power density of the fuel block was varied up to 10 W/cc. This would include all of the isotopes that appear promising for long-time missions. The addition of cladding and internal void volume (to allow for helium accumulation from the alpha-emitting isotopes) results in a packaged power density much lower than the original isotope power density. For example, the power density of an isotopic fuel form such as curium-244 oxide can be lowered by a factor of as much as 5 to 7 in the packaged form[1]. The length-to-diameter ratio of the fuel block was varied from 0.25 to 10, the limits being fixed mainly by practical considerations. The diode emitter temperature was varied between 1600 and 2000 deg K.

As pointed out earlier, stacked-foil type thermal insulation was used in the study. Heat-loss calculations were based on radiative heat transfer between 25 tantalum foils having an emissivity of 0.3. The diode performance data used in the analysis is shown in Fig. 3. These data, generated by the Thermo Electron Engineering Corporation for the Office of Naval Research[2] are considered to be representative diode performance. The curves represent maximum efficiency data obtained by optimizing the interelectrode spacing at each emitter temperature. As shown on the figure, the diode power density varies from 1 to 10 W/sq cm, and the efficiency varies from 8 to 16 percent over the range of emitter temperatures considered.

Pertinent results of the parametric analysis are presented in Figs. 4 and 5. In Fig. 4, the system efficiency is shown as a function of fuel block length to diameter ratio with both the emitter temperature and fuel block effective volume power density included as parameters. At an emitter temperature of 1600 deg K and a volume power density of 0.5 W/cc, the system efficiency exhibits a broad maximum peaking at 6 percent at a length-to-diameter ratio of 1.0. In this case, the maximum electrical power output of the system is 300 W.

Increasing either the emitter temperature or the volume power density results in improved efficiency and also makes the performance less dependent on the length-to-diameter ratio. As shown in Fig. 4, at an emitter temperature of 1600 deg K, a volume power density of 10 W/cc results in a maximum efficiency of 7.5 percent (power output of 375 W(e)). Increasing the emitter temperature from 1600 to 1800 deg K at a volume power density of 10 W/cc yields a maximum efficiency of 12.0 percent and a power output of 500 W(e). A further increase in emitter temperature to 2000 deg K would result in system efficiencies on the order of 15 percent.

Another factor that is dependent on diode performance, fuel block volume power density, and fuel block geometry is the fraction of the fuel block surface area which is covered by diodes. The diode fractional-area coverage is presented as a function of fuel block length to diameter ratio in Fig. 5(a) for an emitter temperature of 1600 deg K and a volume power density of 0.5 W/cc. The curve labeled "Total" represents the fraction of the total fuel block surface area covered by converters. The total coverage reaches a maximum of about 10 percent at a length-to-diameter ratio of 1.0. If the diodes were mounted only on the lateral surface of the fuel block, the curve labeled "Lateral" would represent the fraction of lateral surface area covered by converters, which, as shown, remains relatively low over the range of length-to-diameter ratios considered. If, on the other hand, diodes were mounted only on the ends of the fuel block, as in the SNAP-13 system, the curves labeled "End" would represent the fraction of the fuel-block end area covered by converters. The end coverage increases rapidly with increasing length-to-diameter ratio; complete coverage being reached at a length-to-diameter ratio of 7.5. In this case an end-mounted configuration having a length-to-diameter ratio greater than 7.5 could not be built.

At a fixed emitter temperature, increasing the fuel block effective volume power density results in increased fractional area coverage; however, area coverages become so large, particularly at the lower emitter temperatures, that the fuel block length to diameter ratio range which can be considered is significantly reduced. For example, at an emitter temperature of 1600 deg K and a volume power density of 10 W/cc (fig. 5(a)), the total coverage reaches a maximum of 92 percent. Calculated values for fractional coverage of the fuel block ends exceeded 1.0 over the entire length-to-diameter-ratio range, while the lateral fractional area coverage is complete at a length-to-diameter ratio of 2.2.

If the emitter temperature is increased, the fractional coverages are reduced as seen by comparing Figs. 5(b) and (c). In Fig. 5(c), fractional coverages are presented for a volume power density of 10 W/cc and an emitter temperature of 1800 deg K. In this case, the total coverage maximizes at 32 percent and the lateral coverage reaches 75 percent. Again, however, the length-to-diameter-ratio range for the end mounted configurations is quite restricted with end coverage becoming complete at a length-to-diameter ratio of about 1.0.

The trends displayed in the parametric analysis would be similar regardless of the input power level, but it should be pointed out that the absolute value of system performance is dependent on input power level. In Fig. 6, the system efficiency is presented as a function of thermal input power with the fuel block effective volume power density as a parameter. The system performance is quite dependent on input power at the lower volume power densities, but as the volume power densities increase the dependence is reduced. For example, in covering an input power range of 5000 to 25 000 W, a 20 percent increase in system efficiency is realized at the 0.5 W/cc volume power-density level, while at the 5 W/cc level an increase of less than 10 percent is realized. The trend of increasing efficiency with increasing input power level results from the fact that as input power level increases the ratio of the heat lost to total input power Q_{loss}/Q_{in} decreases.

Heat Rejection Considerations

In the construction of a practical generator there are a number of considerations, in addition to the parametric variables discussed above, that influence the design. One of the more important of these considerations is heat rejection. Even though the heat rejection temperatures of thermionic systems are high, the cooling problem is not necessarily eliminated. The prime radiator area requirements for these systems vary from several square feet per kilowatt (electric) at the higher emitter temperatures to perhaps 20 sq ft/kW(e) at lower emitter temperatures. However, because the generator and heat source are quite compact, in many instances fins, with their associated weight penalties, will be required to cool the systems.

The necessity for fins is illustrated in Fig. 7, where a comparison of the amount of heat which can be radiated from the generator shell Q_{cap} to the total amount of heat that must be rejected from the system Q_{rej} is presented as a function of fuel block length to diameter ratio. The case considered is one in which the emitter temperature is 1600 deg K and the thermal input is 5000 W. Values of less than one for the heat rejection ratio Q_{cap}/Q_{rej} indicate that fins must be added to augment the heat-rejection capability of the generator shell. For the side-mounted configurations (shown by the solid lines) at the lower volume power densities the heat can be rejected solely by the shell; for example, at a volume power density of 0.5 W/cc length-to-diameter ratios of 1.5 or greater will yield systems which can be cooled without the addition of radiator fins. As the volume power density increases, the systems become more compact and the generator shell area is reduced. Consequently, the amount of waste heat which can be rejected from the shell decreases until, at a volume power density of 10 W/cc, finning would be required over the entire range of length-to-diameter ratios considered. For the end mounted configuration (shown by the dashed lines) the trend with the length-to-diameter ratio is reversed; that is, as the length-to-diameter ratio decreases the heat rejection capability of the shell increases. However, length-to-diameter ratios of 0.1 or less are required to yield end-mounted systems which do not require fins.

Specific Weight Calculations

Before discussing the results of the system weight calculations it would be helpful to refer to Fig. 1 again and consider the materials that might be used in a design of this type. At thermionic operating temperatures the fuel block would most probably be constructed from tungsten or one of its high-temperature alloys. The fuel-block weight estimates used in this analysis were based on the results of a previous study conducted at the Lewis Research Center(1). Internal void volumes were included to allow for helium accumulation from alpha-emitting isotopes. The thermal insulation was discussed earlier. Molybdenum was selected for the diode support structure because of its high thermal conductivity to weight ratio at the heat rejection temperatures. In a design of this type the generator shell would be the primary containment vessel; therefore, a high strength, oxidation resistant alloy, such as Haynes 25 or René 41, would be an appropriate construction material. Beryllium was selected as the material for the tapered radiator fins; the choice again being made on the basis of a high thermal conductivity to weight ratio. The surfaces of the fins and generator shell would be treated to provide a high emissivity. The system weight estimates do not include nuclear shielding or ablative heat shielding which would be required to protect the system during reentry. Preliminary calculations for side mounted configurations indicate that the addition of reentry heat shielding could increase the weights presented by a factor of 50 to 100 percent. In Fig. 8, the system specific weight in lbs/kW(e) is presented as a function of volume power density for a configuration in which the diodes are positioned around the lateral surface area of the fuel block. Here fuel block geometry has been considered as a parameter. The emitter temperature in this case is 1600 deg K and the output power is 250 W. Two sets of weights are presented; one set (shown in solid lines) represents the total system specific weight, and the other set (shown by dashed lines) represents the total of all component weights with the exception of the radiator fin weights. Thus, the difference in the level of these two sets of curves is the weight penalty associated with the radiator fins. It can be seen that in many cases penalties of hundreds of pounds per kilowatt are incurred. The weights with fin weight excluded are as expected; the weights decrease with increasing volume power density due to increasing efficiency. In this case, the effect of the length-to-diameter ratio is not pronounced, but when total system weights are considered the length-to-diameter ratio is an important factor. As shown on Fig. 8 a minimum in system weight is attained at a length-to-diameter ratio of 3 and an effective volume power density of approximately 4 W/cc.

The effect of output power on system weight can be seen in Fig. 9 again, for an emitter temperature of 1600 deg K. Here, a case with a length-to-diameter ratio of 1 is considered, and the curves are terminated at a point where the fractional area coverage becomes complete. As mentioned previously, the absolute value of system efficiency increases as the output power increases and one would normally expect the higher powered systems to weigh less than the lower powered ones. However, as the power level increases, the systems become more compact and at this emitter temperature the increasing fin weights cause the curves to cross over. The specific weight for the 250 W system is seen to be several hundred pounds per kilowatt lower than that for the 1000 W system at the higher volume power densities.

The need for heat rejection augmentation decreases with increasing emitter temperature and at emitter temperatures on the order of 1800 deg K and above the higher powered systems exhibit the anticipated weight advantage; that is, at the higher output power levels the increased efficiency becomes the dominant factor and the higher powered systems display lower specific weights.

The effect of emitter temperature on system weight can be seen in Fig. 10 for an output power of 250 W. As shown, substantial weight savings are realized by increasing the emitter temperature from 1600 to 1800 deg K. The weight reduction is due to a combination of improved diode performance at the higher emitter temperature and the fact that finning is no longer required to augment the heat rejection from the generator shell. In comparing system performance at 1800 and 2000 deg K it is seen that once fins are no longer needed, relatively little is gained by further increasing the emitter temperature. In addition, at emitter temperatures of 1800 deg K and above, the system weight does not exhibit a minimum with increasing volume power density; the specific weight decreasing continuously with increasing power density. At the higher emitter temperatures effective fuel block power densities of several watts per cubic centimeter are required to achieve system specific weights of several hundred pounds per kilowatt (electric).

Concluding Remarks

The parametric analysis showed that at the lower fuel block power densities the system efficiency maximizes at a fuel block length-to-diameter ratio of 1, while at the higher volume power densities the performance becomes rather insensitive to length-to-diameter ratio. It was also determined that, in some instances, the required converter fractional-area coverage may impose limitations on the design of radioisotope thermionic systems.

From the heat rejection standpoint, the analysis showed that there is a strong incentive particularly at the lower emitter temperatures to design a side-mounted system for the highest practical length-to-diameter ratio (the reverse is true for the end-mounted system). For a side-mounted configuration, if both system efficiency and heat rejection are considered, a minimum in system specific weight may be expected at some intermediate length-to-diameter ratio (i.e., between 1.0 and 10.0). Such a minimum was observed at an emitter temperature of 1600 deg K. However, as the emitter temperature is increased, the system performance and weight become less dependent on fuel block geometry.

In regard to performance level, emitter temperatures of 1800 deg K or higher and effective fuel-block volume-power densities of several watts per cubic centimeter are required to achieve system specific weights as low as several hundred pounds per kilowatt (electric).

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1. English, R., et al.: Study of Radioisotope Solution for Space Power Systems. (To be published)

2. Kitrilakis, S. S., Meeker, M. E., and Rasor, N. S.: Annual Technical Summary Report for the Thermionic Emitter Materials Research Program. Rept. No. 2-63 (TEE 4015-3), July 1, 1961-June 30, 1962, Thermo Electron Eng. Corp., 1962.

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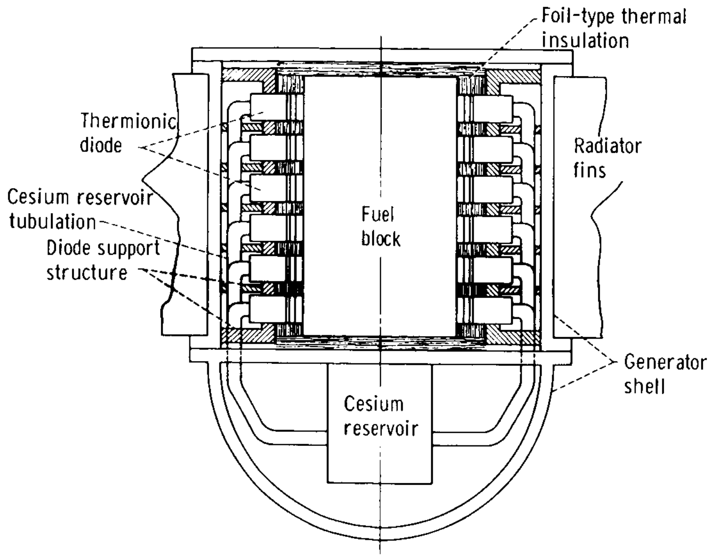

Figure 1. - Conceptual design of radioisotope-thermionic generator (side view).

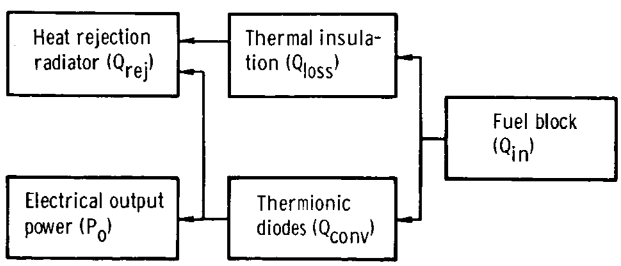

Figure 2. - Energy flow diagram.

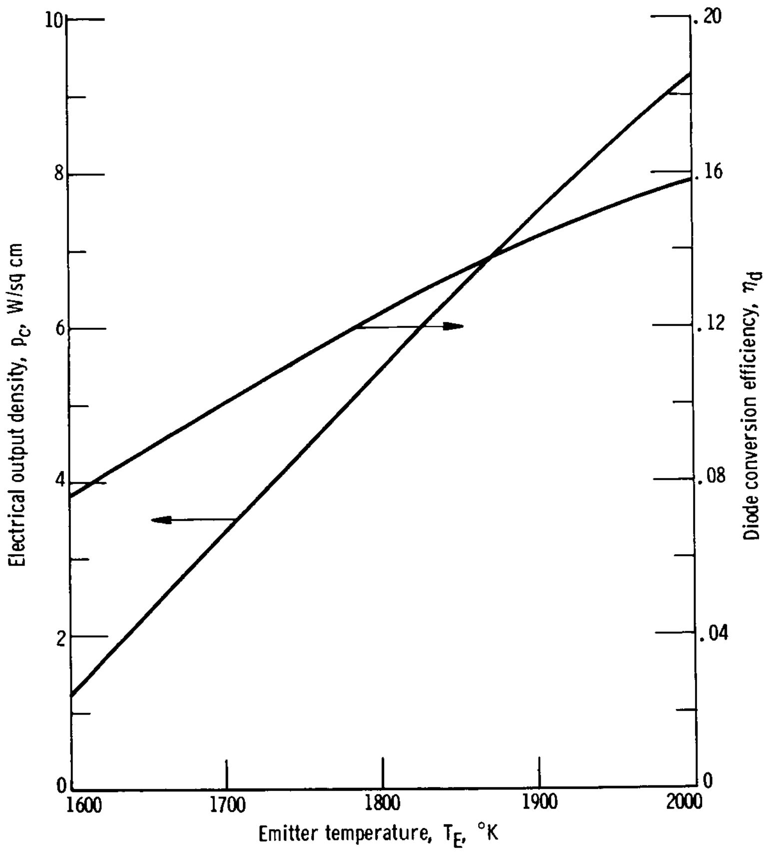

Figure 3. - Diode performance data, variable spacing, maximum efficiency (TEECO report number 2-63).

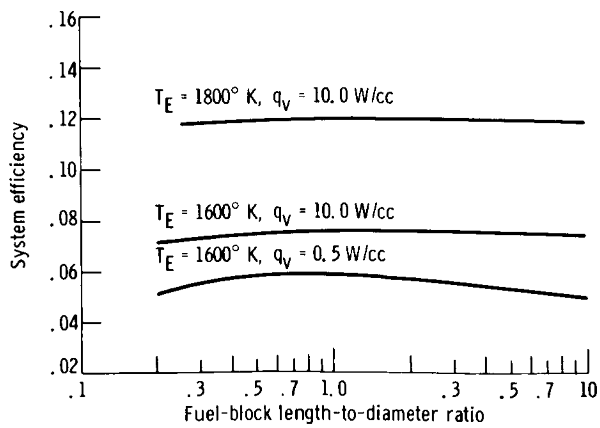

Figure 4. - Generator efficiency as a function of fuel-block length-to-diameter ratio; Q_{in} = 5000 W, side-mounted.

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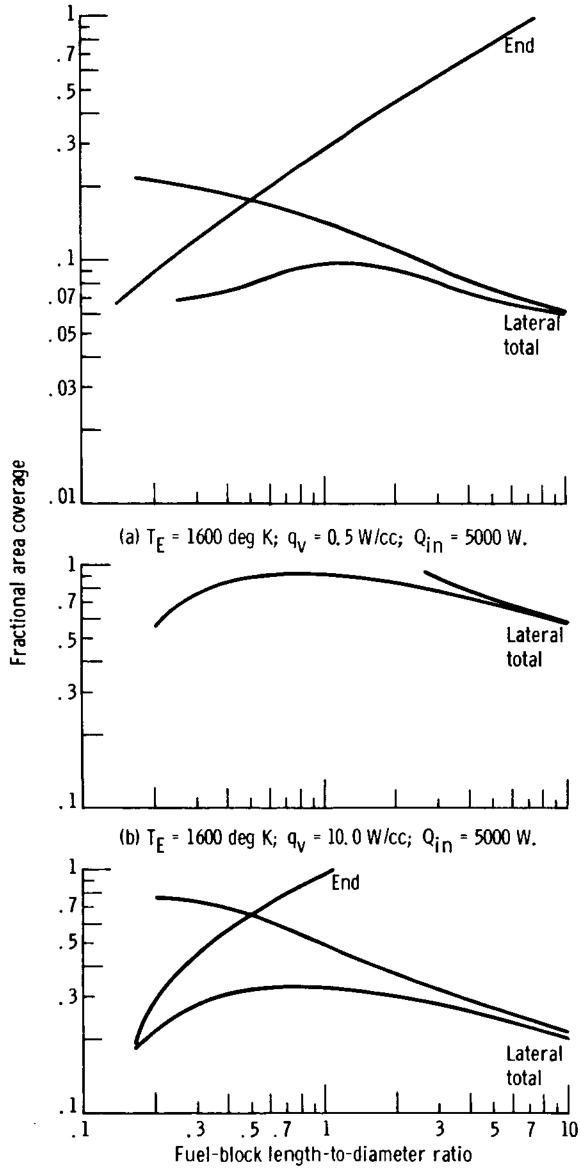

(c) T_E = 1800 deg K; q_v = 10.0 W/cc; Q_{in} = 5000 W.

Figure 5. - Diode fractional area coverages as functions of fuel-block length-to-diameter ratio.

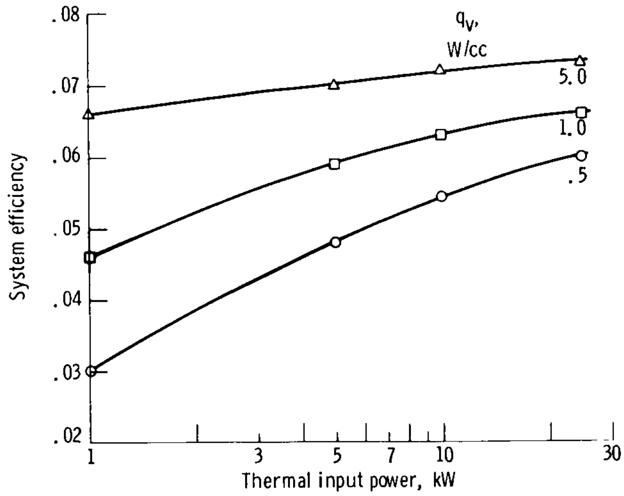

Figure 6. - System efficiency as function of thermal input power, T_E = 1600 deg K, length-to-diameter ratio = 1.0.

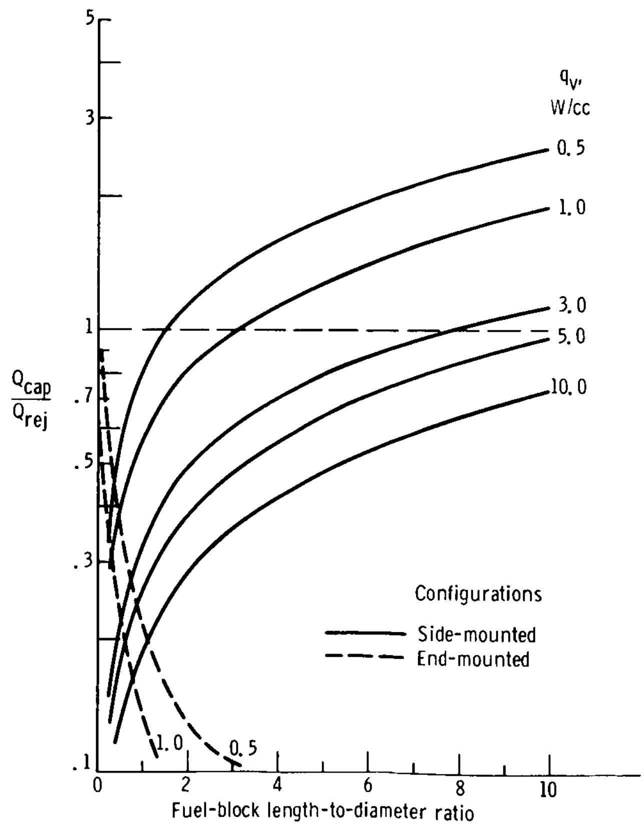

Figure 7. - Ratio of heat that can be radiated from generator shell to total heat which must be rejected from system as function of fuel-block length-to-diameter ratio; T_E = 1600° K, T_R = 700° K, Q_{in} = 5000 W.

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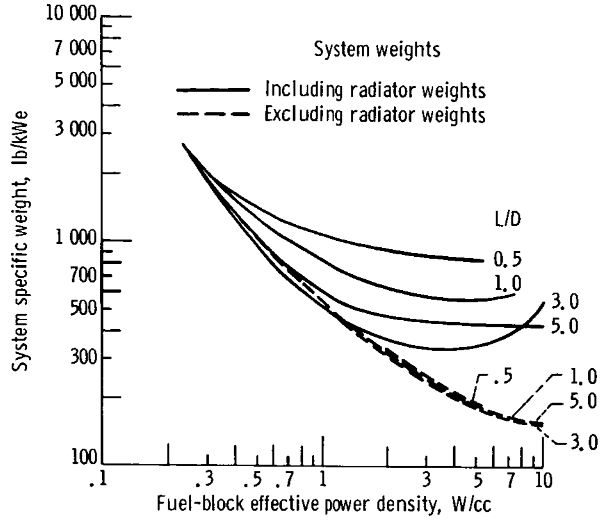

Figure 8. - System specific weight as function of fuel-block effective volume-power density. Side-mounted diodes, $T_E = 1600^\circ$ K, $P_0 = 250$ W.

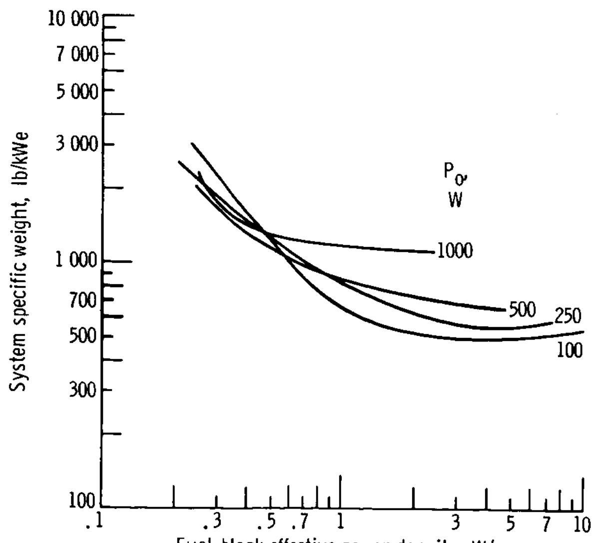

Figure 9. - System specific weight as function of fuel-block effective volume-power density. Side-mounted diodes, $T_E = 1600^\circ$ K, length-to-diameter ratio = 1.0.

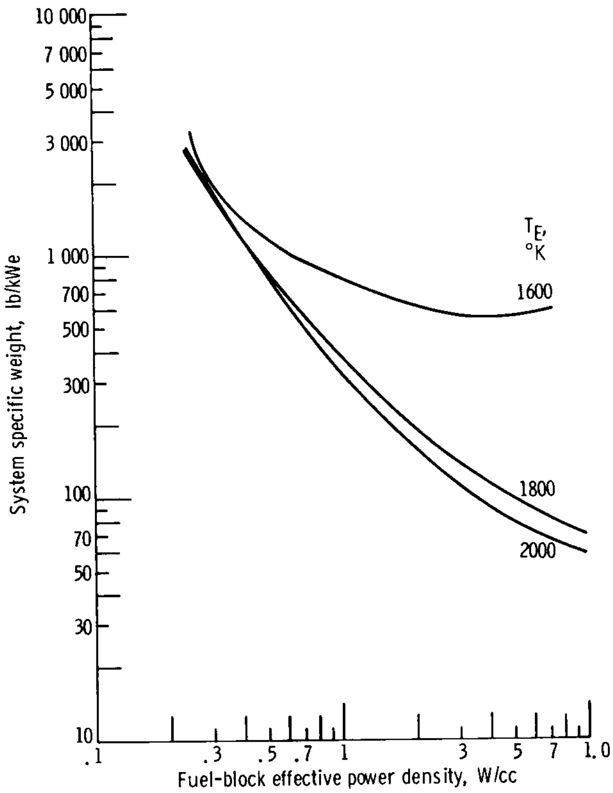

Figure 10. - System specific weight as function of fuel-block effective volume-power density. Side-mounted diodes, P_0 = 250 W, length-to-diameter ratio = 1.0.

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