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THERMIONIC REACTORS FOR ELECTRIC PROPULSION — PARAMETRIC STUDIES

by

W. G. Homeyer, C. A. Heath, and A. J. Gietzen

May 20, 1968

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ABSTRACT

In-core nuclear thermionic power plants consist of a reactor containing thermionic cells, a nuclear radiation shield, a heat rejection system, and electrical transmission lines and power conditioning equipment. The influence of design parameters on size, mass, and reliability is evaluated over a range in power output from tens of kilowatts to several megawatts. Methods of achieving high reliability with a minimum sacrifice in size and mass are described. The importance of the multiplicity of components and their manner of connection is evaluated.

Major parameters of the reactor include the emitter and collector temperatures and electrical power density, the emitter size, the nuclear fuel fraction, and the fissile nuclide. The parameters affecting the shadow-shield mass include the cone angle, the dose rate allowable, and the distance between the reactor and the region to be shielded. For the heat rejection system, the coolant composition, the temperature, and the multiplicity of components (pumped loops and heat pipes) are important factors. Transmission lines are characterized by their composition, temperature and length, and by the voltage output of the reactor. Power conditioning design is based on voltage input and component ratings.

INTRODUCTION

In-core nuclear thermionic power plants consist of a nuclear reactor containing fueled thermionic converters, a nuclear radiation shield, a heat rejection system, and electrical transmission lines and power conditioning equipment. The arrangement of three of these components, the reactor, shield, and heat rejection system is shown in Fig. 1. The radiation shield is a "shadow" shield which protects only the region occupied by the crew from radiation. Located within the shield is a heat exchanger within which heat is transferred from the activated reactor coolant to a secondary coolant which carries heat to the radiator panels. The radiator panels are made up of many heat pipes (Ref. 1) which serve as fins for radiation of heat from the secondary coolant loops. The radiator is located within the shadow of the shield where it cannot scatter nuclear radiation toward the crew. The power conditioning equipment may be either a compact unit located within the radiator and cooled by separate low temperature cooling loops connected to a radiator or may be distributed so as to radiate waste heat directly to space. In the latter case, it would be located to the right of the radiator shown in Fig. 1.

REACTOR

The arrangement assumed for the reactor is shown in Fig. 2, and the dimensions assumed are given in Table 1. The core contains cylindrical thermionic fuel elements and is surrounded by a 10 cm thick BeO neutron reflector. In the radial direction, the fuel elements are characterized by an emitter diameter, by an emitter clad thickness, and by a center-to-center (pitch) spacing. The pitch spacing has been assumed to be 0.5 cm greater than the emitter diameter to allow space for the plasma gap, collector, insulator, sheath, and coolant. In the axial direction the diodes consist of a fueled emitter region and an unfueled region in which no power is generated and where electrical connections between diodes are made. The average density of UO_2 fuel within the emitter cavity was assumed to be no more than 80% of theoretical to allow for fuel zoning to flatten the fission power distribution in the reactor. The electrical power density of 5 W/cm^2 assumed is the average over the core and includes allowances for electrical losses in electrodes and inter-diode connectors.

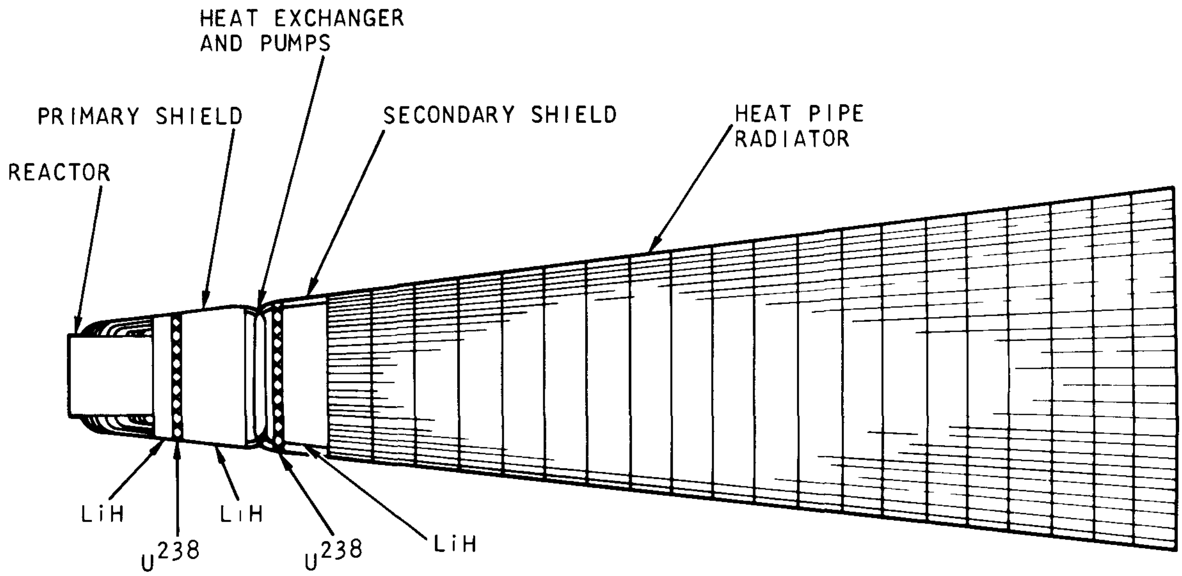

Fig. 1. Schematic of reactor, shield, and radiator

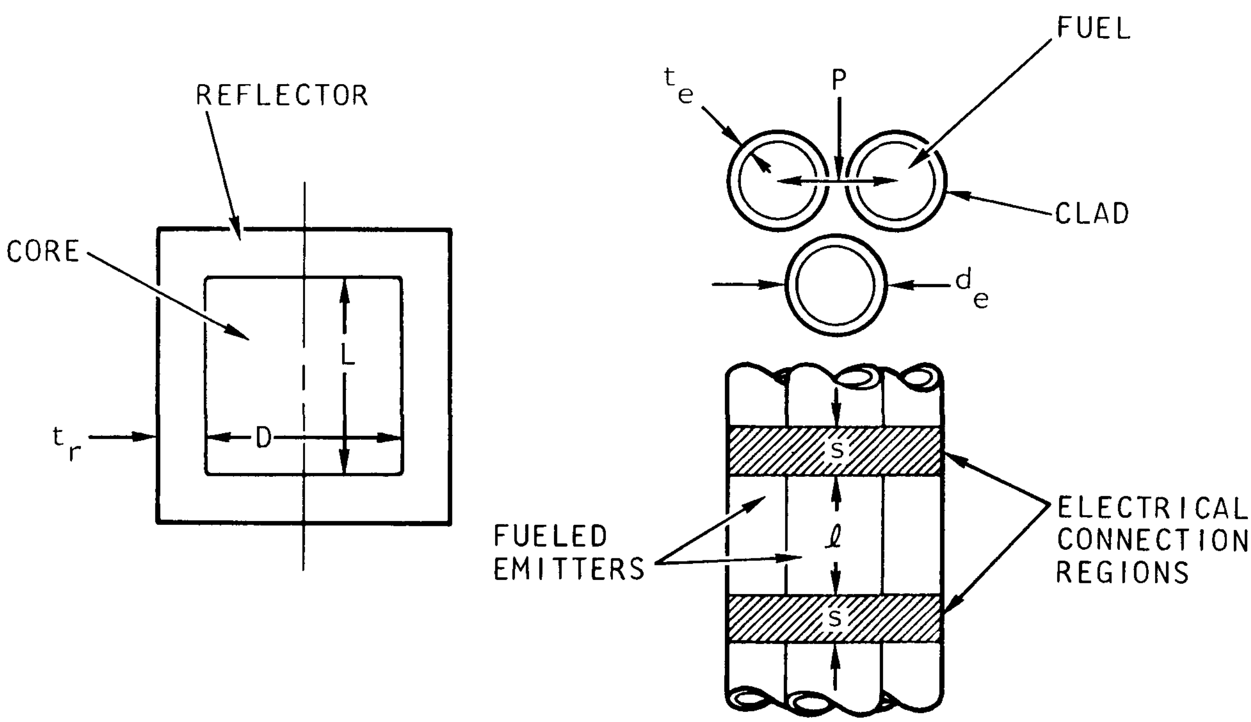

Fig. 2. Reactor and cell schematics

TABLE 1

REACTOR AND CELL DIMENSIONS

Reflector thickness	t_r	10 cm
Core length-to-diameter ratio	L/D	1
Emitter diameter	d_e	1, 2, 3 cm
Pitch spacing of cells	P	1.5, 2.5, 3.5 cm
Emitter clad thickness	t_e	0.1 cm
Length of fueled emitter	ℓ	5 cm
Length of connection region between fueled emitters	s	2 cm
Density of UO_2 fuel		≤ 80%
Average thermionic electrical power density (net)		5 W/cm^2

The variation in the diameter of the thermionic reactor with reactor output power and with emitter diameter is shown in Fig. 3. The UO_2 is assumed to be 93% enriched in U-235. As shown in the figure, the diameter of the reactor can be reduced if lower power output is required, but only to a point at which the criticality limit is reached. At this point, which is indicated by the sharp knee in the curves in Fig. 3, the reactor diameter can no longer be reduced. Lower power levels are reached by lowering the electrical output of the diodes. It is apparent from Fig. 3 that emitters of smaller diameter are advantageous at higher power levels where the size of the reactor is fixed by requirements for electrical output. For lower reactor power levels, where nuclear criticality is a limitation, emitters of larger diameter which have more space for fuel produce a smaller reactor.

The specific mass of the reactor in kg/kWe (kilograms per kilowatt of electrical output) is shown in Fig. 4 as a function of the reactor output power and the emitter diameter. Smaller emitters are shown to produce a lighter reactor at high power levels, but at low power levels, where criticality limits are reached, they result in a much heavier reactor. As in

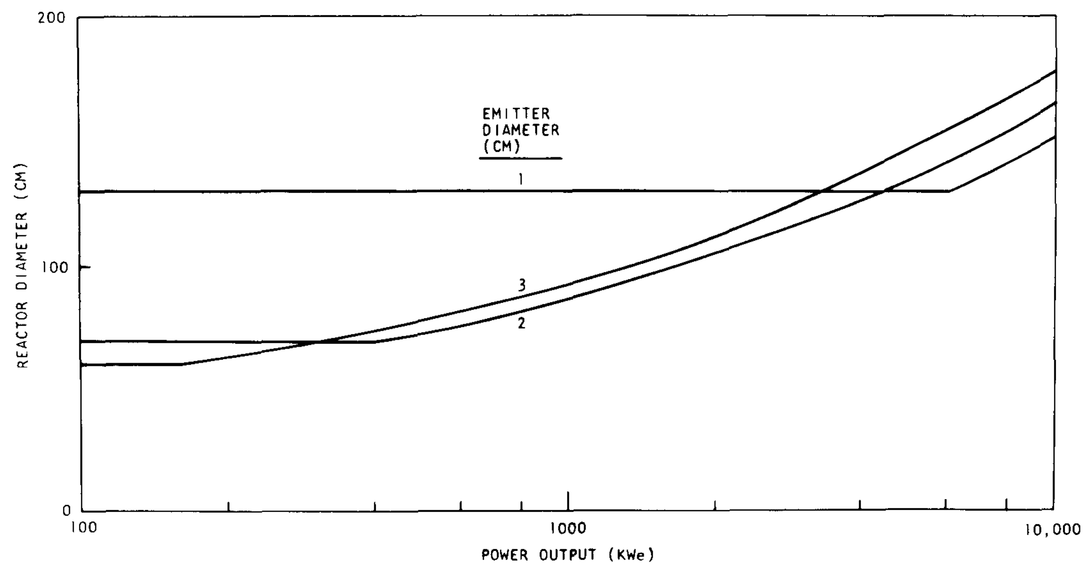

Fig. 3. Reactor diameter and emitter diameter

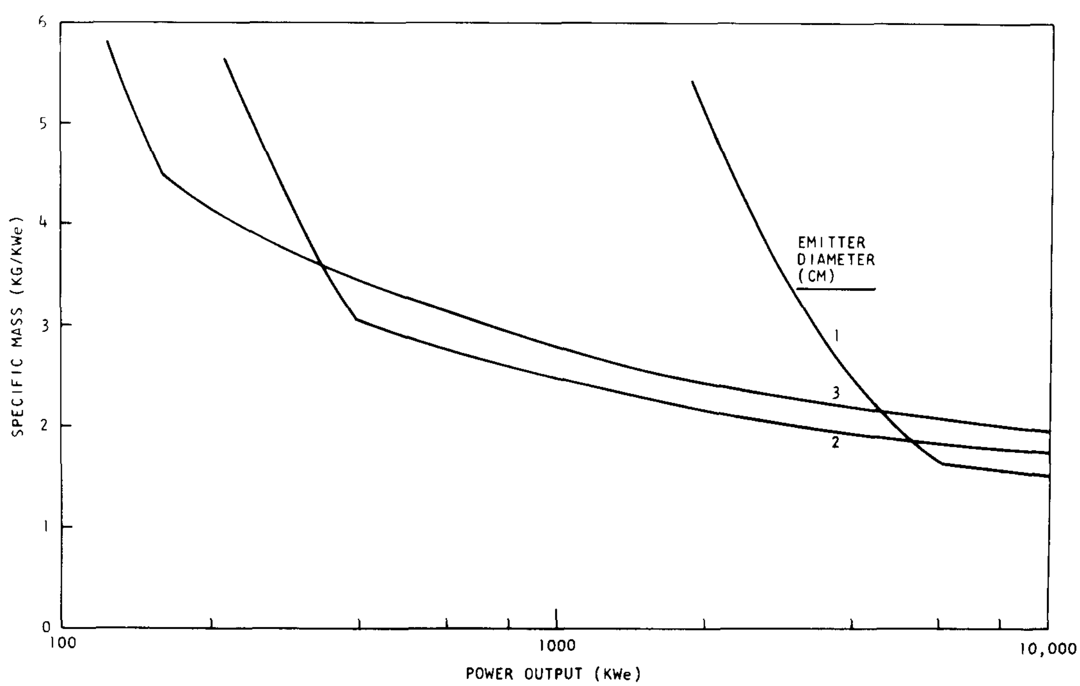

Fig. 4. Specific mass and emitter diameter

the previous figure, the portions of the curves to the left of the knee are criticality limited reactors with electrical output from the diodes reduced below 5 W/cm^2. Also shown in Fig. 4 is the tendency for large reactors with high power output to have a lower specific mass than low power reactors. This trend results from the mass of the reflector becoming a smaller fraction of the total mass as the size of the reactor is increased.

The specific mass of the reactor is shown in Fig. 5 as a function of the power level of the reactor, and the thermionic electrical power density. The emitter diameter is 2 cm.

Two families of curves are shown, one for $U^{233}O_2$ fuel, and one for $U^{235}O_2$ fuel. At the left of each family of curves is the criticality limit for an average fuel density of 80%. As shown here, $U^{233}O_2$ permits much lighter reactors to be produced for low power levels than does $U^{235}O_2$. For higher power levels, above the criticality limit for $U^{235}O_2$, the difference in reactor mass between the two fuels at any given thermionic power density is much smaller. This small difference results from the difference in fuel density required for criticality, and does not reflect a difference in size of the reactor. Figure 5 also illustrates the point that very low thermionic electrical power densities may be adequate with certain combinations of emitter diameter, nuclear fuel, and power output requirement from the reactor. If lower thermionic power densities are required, lower emitter temperatures may be employed and conversion efficiencies will be reduced as shown in Table 2.

The number of thermionic cells in the reactor is given in Table 3 for several power levels and emitter diameters. The number of cells in the reactor has an important influence on the reliability of the reactor and on the mass of the electrical transmission lines.

RELIABILITY

The connection of thermionic cells in series-parallel networks to enhance the reliability of electrical power generation has been the subject of considerable study. The effects of open and short circuit failures of cells in an electrical network on the output of the network were

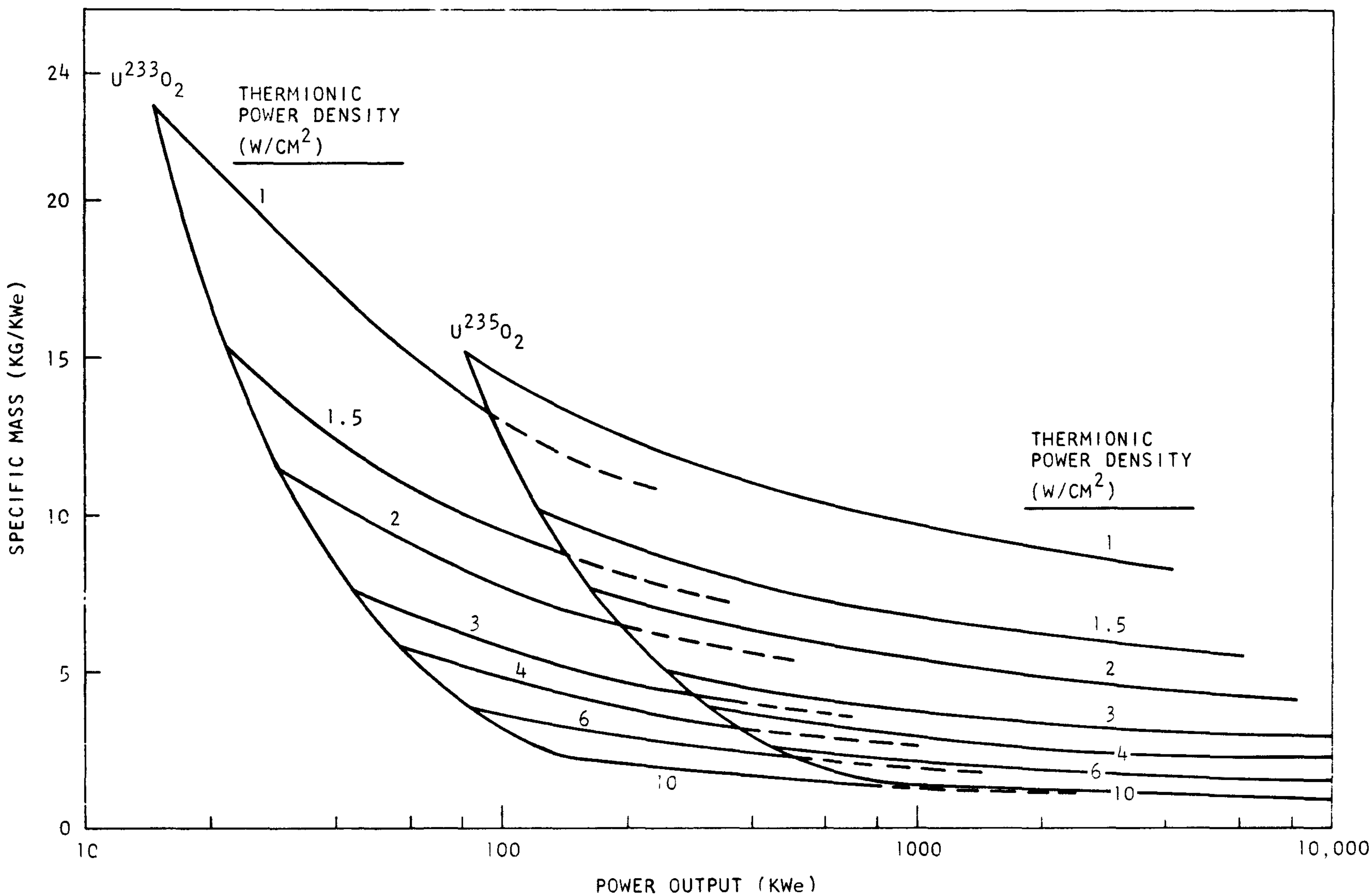

Fig. 5. Specific mass and thermionic power density

TABLE 2

EMITTER TEMPERATURE, POWER DENSITY, AND EFFICIENCY

Thermionic Power Density (W/cm^2)	Emitter Temperature ($^\circ K$)	Conversion Efficiency (%)
1.0	1550	5.4
1.5	1610	6.4
2.0	1650	7.4
3.0	1720	8.9
4.0	1790	10.0
6.0	1930	11.7
10.0	2180	13.9

TABLE 3

NUMBER OF CELLS IN THE REACTOR

Power Level (kWe)	Number of Cells for Emitter Diameter of		
	1 cm	2 cm	3 cm
100	76,657	2,542	684
200	76,657	2,542	849
500	76,657	3,184	2,123
1,000	76,657	6,367	4,245
2,000	76,657	12,733	8,489
5,000	76,675	31,833	21,222
10,000	127,329	63,665	42,443

studied by Holland (Ref. 2) who concluded that the fraction of power lost was independent of the size and shape of the network and was approximately twice the fraction of cells which failed. This work was extended by Yates (Ref. 3) to the case of short circuits through the coolant system. Here we will discuss only one aspect of this question, the influence of the number of cells on the reliability of an electrical network.

If several cells in an electrical network suffer open circuit failure, the possibility arises that the failures will be so located as to cause an open circuit of the entire network. The reliability of a network to escape this type of failure is shown in Fig. 6 as a function of the number of diodes in series and the number in parallel. In this case the probability of open circuit failure of a cell was assumed to be 0.05. As shown here, the open circuit reliability is extremely sensitive to the number of cells in parallel but relatively insensitive to the number in series. Increasing the number of cells in parallel from 3 to 4, for example, reduces the probability of an open circuit failure of the network by more than a factor of 10.

A second type of network failure which may occur results from failure of a sufficient number of cells to cause the power output of the network to drop below the minimum allowable level. This type of failure can be prevented by designing the network with an initial power capacity which includes excess or redundant power to offset losses resulting from cell failures. The addition of a large quantity of redundant power, however, increases the size and weight of the power plant. The quantity of excess power required depends upon the reliability of the individual diodes, upon the number of diodes, and upon the reliability required for the network. The relationship between power redundancy, network reliability, and the number of diodes is shown in Fig. 7 for the case where the diode reliability is 0.9. This reliability, which was selected arbitrarily, might correspond, for example, to an open circuit probability of 0.05 and a short circuit probability of 0.05. As shown in the figure, the reliability of the network to maintain minimum power can always be increased by increasing the quantity of redundant power, regardless of the number of cells. The additional power required to produce a given increment in reliability is

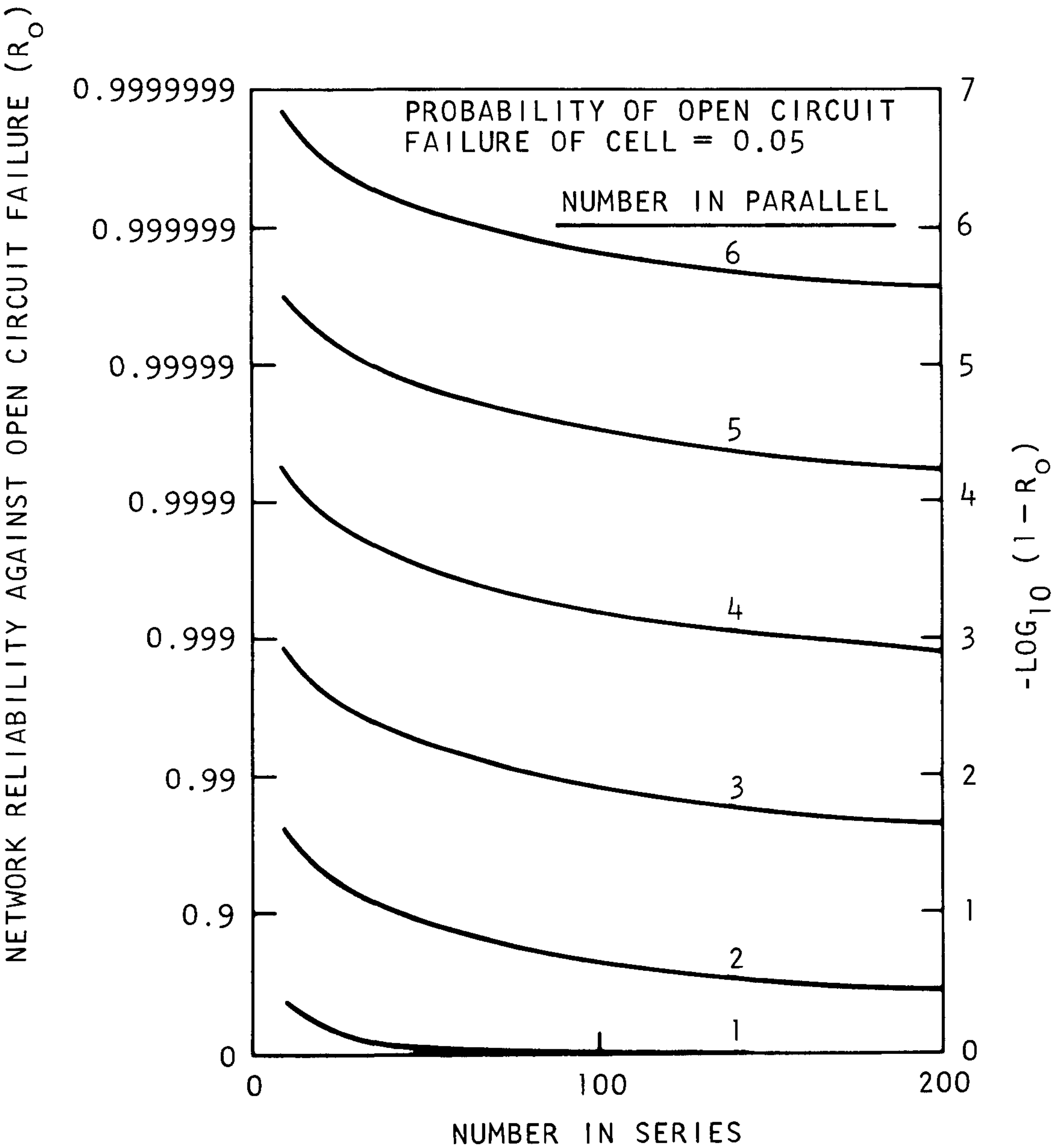

Fig. 6. Reliability against open circuit for various network sizes and shapes

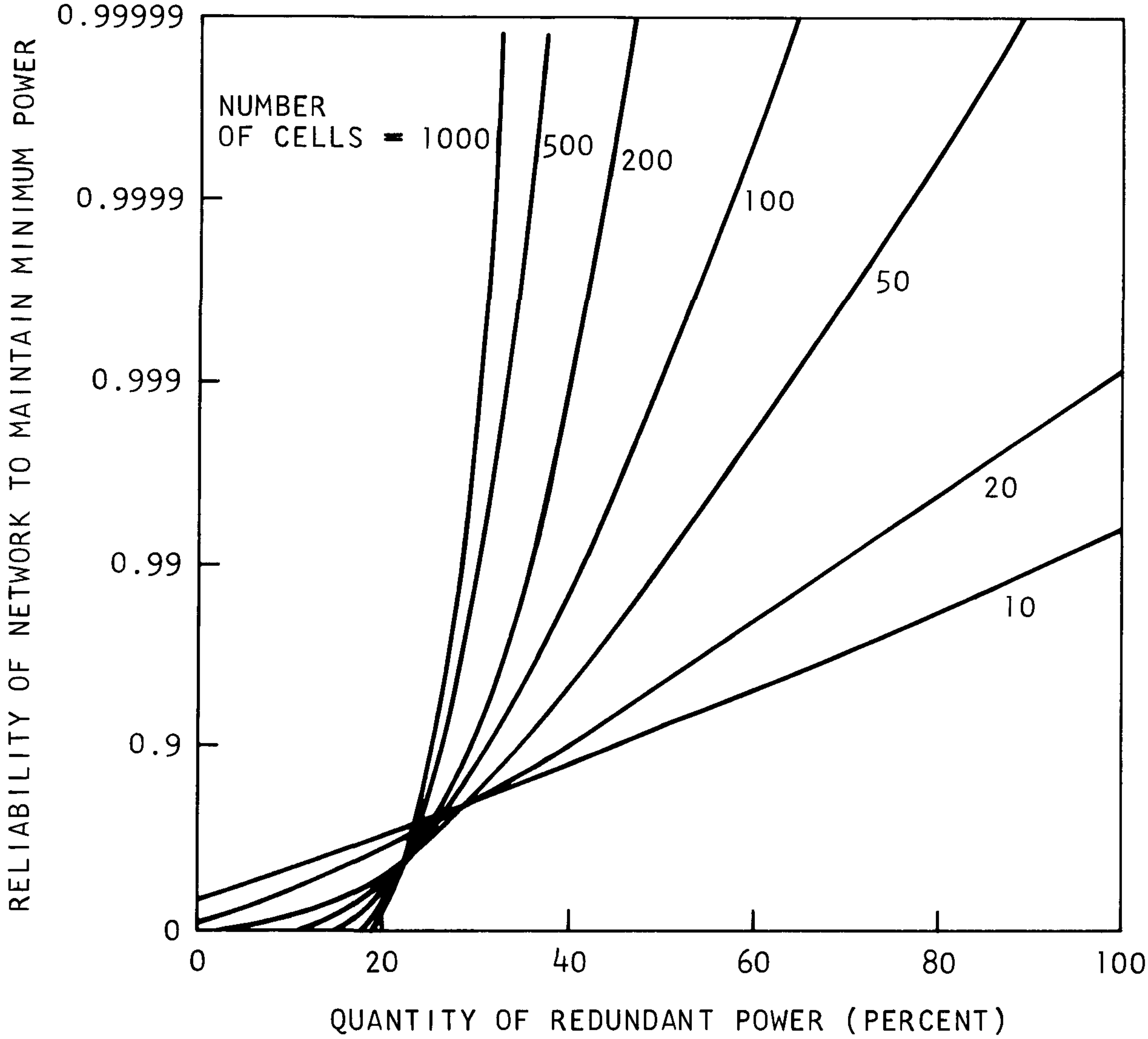

Fig. 7. Network reliability as a function of number of cells and quantity of redundant power

much greater, however, for networks with fewer cells. A network reliability of 0.99, for example, can be obtained with less than 30% redundant power if there are 1000 cells, but requires nearly 100% redundant power if there are only 10 cells. This difference results from the increased statistical predictability of larger numbers. All of the curves are observed to cross between 20 and 25% redundant power. This is near the most probable power loss for 90% reliable cells in a network where fractional power losses are about twice the fraction of cells which fail. Figure 7 shows that very high network reliabilities can be achieved with a small quantity of redundant power if the networks are large. Comparison of Table 3 with Fig. 7 indicates that the number of cells is sufficiently large, even at 100 kWe, for the redundancy requirement to be small.

RADIATION SHIELDING

The radiation shields consist of layers of lithium hydride to attenuate neutrons and depleted uranium to attenuate gamma rays as shown in Fig. 1. The primary shield attenuates radiation from the reactor and protects the secondary coolant from activation. The secondary shield attenuates gamma radiation from the activated primary coolant in the heat exchanger and further attenuates radiation emitted from the reactor.

The mass of the radiation shield is influenced by the size of the reactor, the angle of the cone protected by the shield, and the dose rate to which radiation levels are to be reduced at a given distance from the reactor. Figure 8 shows the variation in specific mass of the shield with the electrical power output of the reactor and the central angle or half angle of the shielded cone. Also shown here in tabular form are the influences of the distance from the reactor and the dose rate to which radiation levels at this distance are to be reduced. The curves show a rapid decrease in the specific mass of the reactor as the electrical power level is increased. The sensitivity of the shield mass to cone angle is also shown. Increasing the half angle of the shadow cone from 5 to 15 degrees more than doubles the mass of the shield. The dose rate and separation distance have much less influence on the mass of the radiation shield.

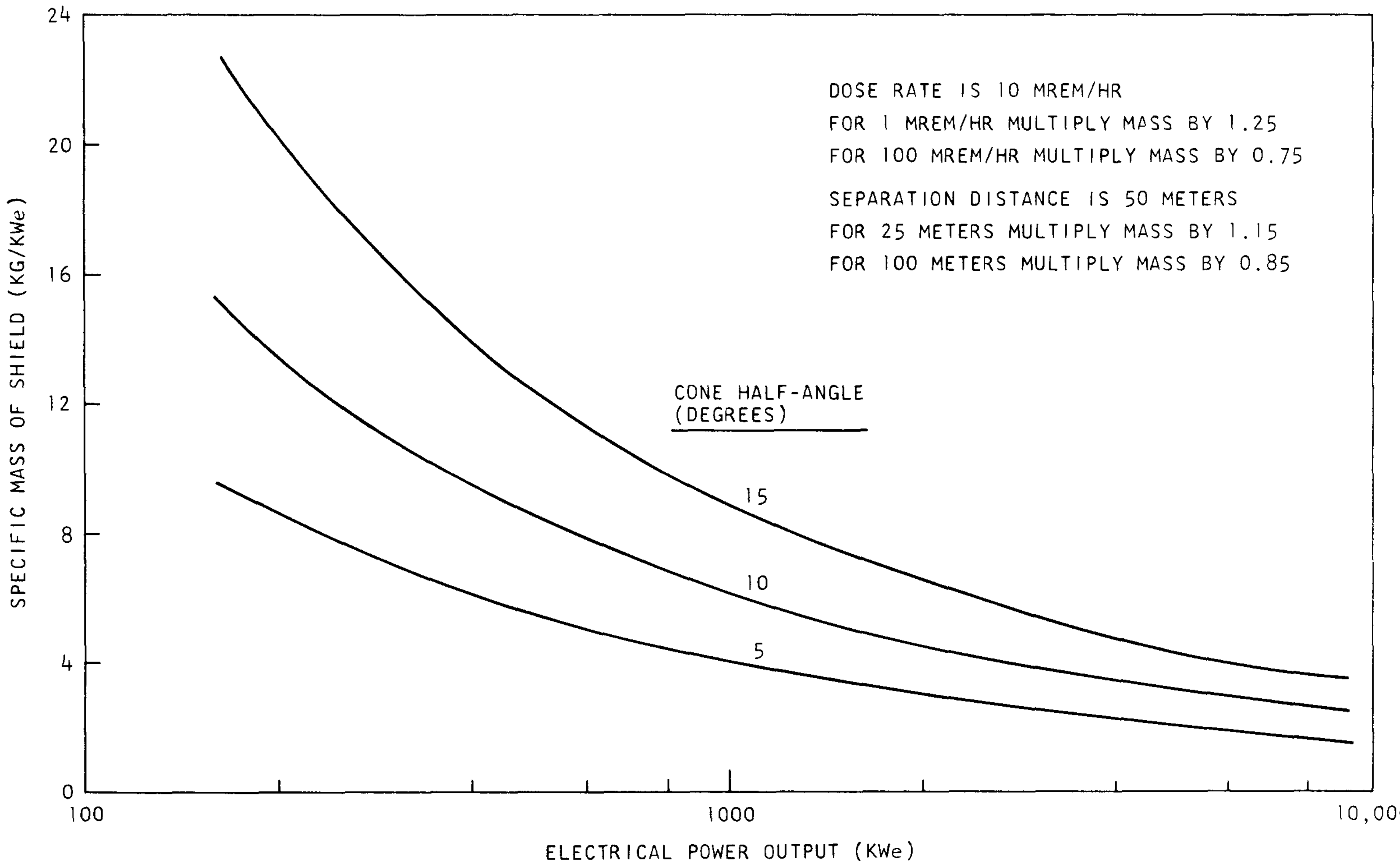

Fig. 8. Shield mass

HEAT REJECTION

The arrangement of the heat rejection system is illustrated in Fig. 1. A compact heat exchanger is used to transfer heat from the primary coolant to the secondary coolant. The secondary loops distribute the heat to the radiator panels which make up the surface of the radiator. These panels are composed of many heat pipes which serve as highly efficient fins to increase the effective radiating surface area.

One question of particular interest is the influence of the collector or coolant temperature on the mass of the heat rejection system. Higher temperatures increase the radiant heat flux and reduce the radiator area, but increase the wall thicknesses required due to the loss in strength of structural materials and the increase in fluid pressure within the heat pipes. In addition, the efficiency of thermionic energy conversion varies with collector temperature, passing through a maximum in the vicinity of $1000^{\circ}K$. The net effect of these factors is shown in Fig. 9. The specific mass of the heat rejection system is shown to pass through a broad minimum at a collector temperature of about $1080^{\circ}K$. The mass of the reactor, shield, and heat rejection system combined is minimum at a lower collector temperature, $1050^{\circ}K$, and remains within 10% of the minimum over the interval between 950 and $1150^{\circ}K$. Results shown in Fig. 9 are for a 300 kWe power plant, but the location of the minimum is relatively insensitive to the power level.

The heat pipe fins in the radiator make up more than half of the mass of the heat rejection system. The multiplicity of these heat pipes was varied to determine if there was an optimum. As shown in Fig. 10, the mass of the heat rejection system decreases continuously as the multiplicity of heat pipes increases. This advantage of smaller, more multiple heat pipes results from structural factors and meteoroid survival requirements. The lengths of the walls of smaller heat pipes are shorter, and the area they expose to meteoroids in space is less. Both factors allow the walls of small heat pipes to be made thinner with equivalent material stresses and meteoroid survival probabilities.

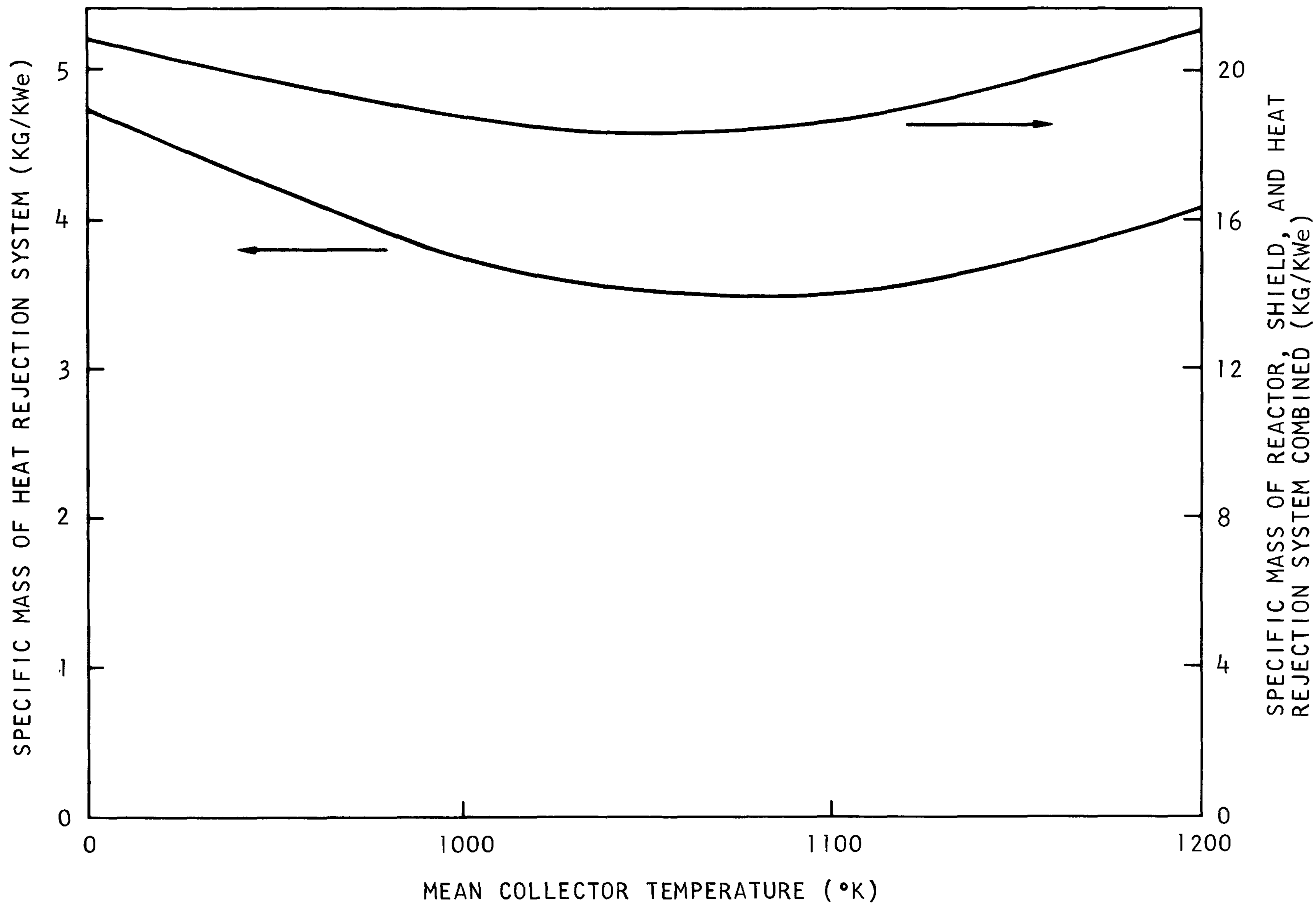

Fig. 9. Heat rejection system mass and collector temperature

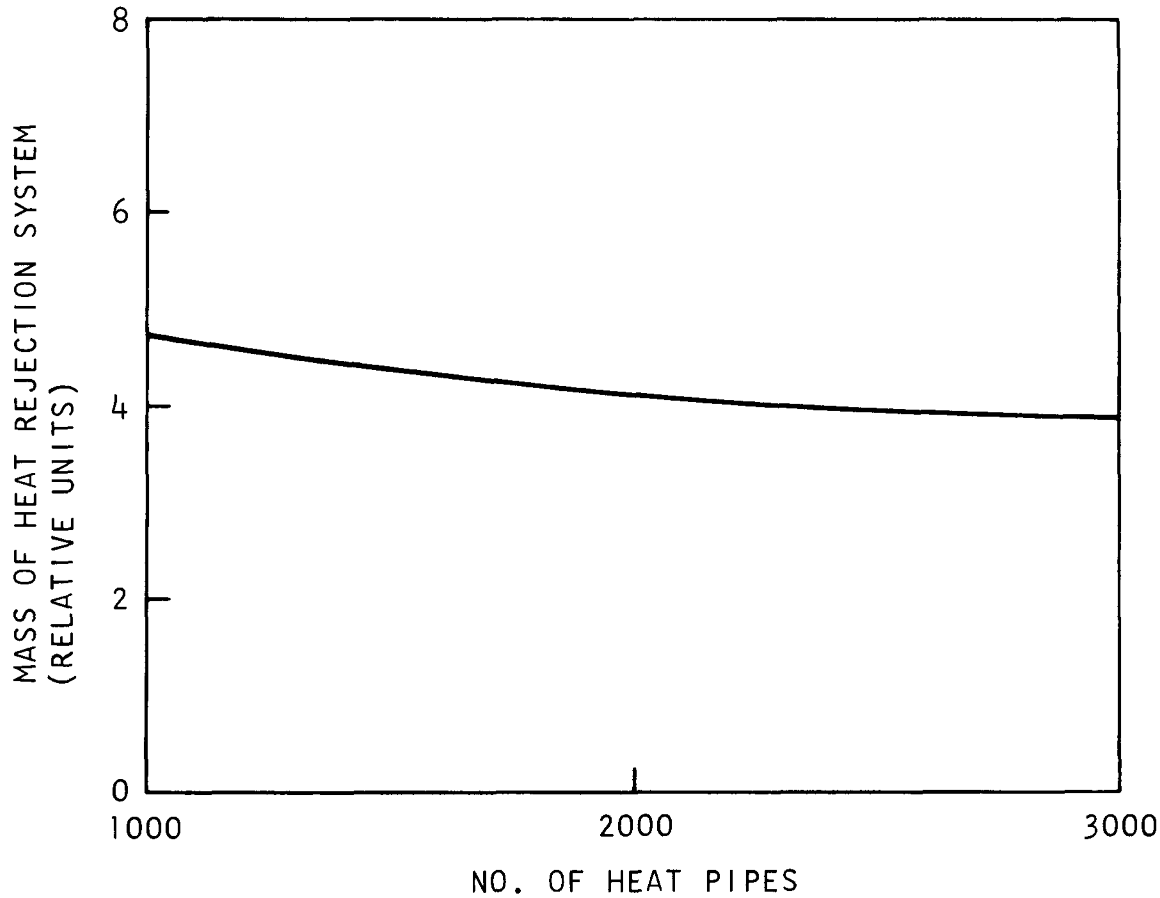

Fig. 10. Variation of mass of heat rejection system with heat pipe multiplicity

TRANSMISSION LINES

Transmission lines are required to carry the current output from the reactor to the power conditioning equipment and back to the reactor. The mass of these lines is proportional to their length, cross sectional area, and density, while the electrical losses in the lines are proportional to their length and resistivity and depend also on their cross sectional area and current. If the additional mass of reactor, shield, and heat rejection system necessary to produce an increment of power is known, the cross sectional area of the transmission lines can be optimized for minimum total mass of the power plant. Characteristics of such optimized transmission lines are given in Table 4 for an incremental mass-to-power ratio of 10 kg/kWe. The specific mass of the lines is given as a function of the output voltage of the reactor and the total length (to and from the reactor) of the lines. Also shown here is the variation in the mass of an optimized transmission line with operating temperature (due to differences in resistivity) and the variation with material at the same operating temperature (due to differences in density and resistivity). As indicated in the table, the specific mass of the transmission lines varies directly with their length and inversely with the voltage output of the reactor. Low transmission line temperatures are advantageous if the lines can be readily cooled below the reactor and radiator temperatures. Lithium, aluminum, and beryllium can provide lighter transmission lines than copper because their high resistivity is more than offset by their low density. Only the specific mass of the lines is given in Table 4, but other quantities of interest can be derived from these numbers easily. The percentage of the reactor output power lost in the lines is ten times the numbers in Table 4; e.g., 4% of the power output of a reactor with a 50 volt output is lost in optimized transmission lines 10 meters long. The additional mass of power plant required to produce the power dissipated in the lines is equal to the mass of the lines, so the total mass penalty for power transmission is approximately twice the numbers given in Table 4.

TABLE 4

TRANSMISSION LINE PENALTIES

Length (meters)	Specific Mass of Transmission Lines* (kg/kWe)		
	50 Volts	100 Volts	200 Volts
10	0.4	0.2	0.1
20	0.9	0.4	0.2
50	2.1	1.1	0.5
100	4.3	2.1	1.0

*Copper at 873°K

Variation with Temperature

T (°K)	Relative Mass
673	0.88
873	1
1073	1.13

Variation with Material at 873°K

Material	Relative Mass
Lithium	0.63
Aluminum (673°K)	0.66
Beryllium	0.88
Copper	1

POWER CONDITIONING EQUIPMENT

Power conditioning equipment for electric propulsion by ion engines transforms most of the reactor output power from low voltage dc to high voltage (3 to 4 kilovolts) dc. Design studies of power conditioning equipment employing present day solid state components have indicated that modules with 90% efficiency radiating their waste heat directly to space from their chassis can be constructed with a specific mass of 2 kg/kWe. These modules employ highly multiple components and include redundant components to provide high reliability.

SUMMARY

As shown in the previous sections, the masses of the power plant components depend on a number of parameters. An arbitrary but consistent set of assumptions was made to permit an overall comparison to be made. This is given in Table 5. The specific mass of the power plant is shown to vary from 35.1 kg/kWe at 100 kWe to 10.7 kg/kWe at 10,000 kWe. This variation in specific mass is due primarily to the radiation shield and reactor. The specific masses of the other components are relatively constant over this power range, with the specific mass of the heat rejection system actually increasing with power level. At 100 kWe the shield is 64% of the total mass of the power plant and the reactor 21%, while at 10,000 kWe the heat rejection system has become the dominant factor, contributing 35% to the total mass.

Comparison of Table 3 with Fig. 7 shows that a network reliability of 0.999 or higher can be achieved with a small quantity of redundant power (~ 30% for 0.9 reliable cells). Comparison of Table 3 with Fig. 6 indicates that a voltage output of 100 volts or more can be obtained from the reactor even at 100 kWe without compromising the reliability of the network.* Figure 10 indicates that a large number of heat pipes can be used in the radiator to increase reliability with no sacrifice in mass of the heat rejection system.

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*There are more than 680 cells in the 100 kWe reactor (Table 3) and 4 cells in parallel are adequate for an open circuit reliability of 0.999 (Fig. 6). Thus the number of cells in series is 170, which results in an output of 102 volts at 0.6 volts per cell.

TABLE 5

SUMMARY

Component	Specific Mass (kg/kWe) at a Power Level of						
	100 kWe	200 kWe	500 kWe	1000 kWe	2000 kWe	5000 kWe	10,000 kWe
Reactor	7.3	4.2	2.9	2.5	2.2	1.9	1.6
Shield	22.5	15.0	9.5	6.5	4.5	3.5	2.5
Heat rejection system	3.1	3.2	3.3	3.4	3.5	3.6	3.8
Transmission lines	0.2	0.2	0.2	0.2	0.3	0.6	0.8
Power conditioning	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Total power plant	35.1	24.6	17.9	14.6	12.5	11.6	10.7

Assumptions

Emitter diameter of 1, 2, or 3 cm chosen to produce smallest reactor with U-235 and a power density of 5 W/cm^2.

Shield cone half angle of 10°, dose rate of 10 mrem/hr, separation distance of 50 meters.

Collector temperature optimized.

Voltage output as large as possible but ≤ 400 volts.

Power conditioning located on far side of radiator from reactor.

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