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**INVESTIGATION OF PERFORMANCE OF AN
OUT-OF-CORE THERMIONIC SPACE POWER SYSTEM**

William E. Loewe

March 18, 1968

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INVESTIGATION OF PERFORMANCE OF AN OUT-OF-CORE THERMIONIC SPACE POWER SYSTEM*

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I. SUMMARY

Conceptual designs of out-of-core thermionic space power generators using heat pipes have been produced for various powers, temperatures, and constraints or parameter values.

Since major impediments to in-pile thermionic systems are alleviated or eliminated in the out-of-core concepts, a competitive degree of feasibility and competitive specific masses are adequate to establish the need for emphasis on these systems in future studies and development activities. Feasibility in the six cases shown here in conceptual detail appears to be limited only by lithium heat pipe feasibility and a favorable outcome of current technology development of UN, W, and Li materials in the temperature range considered. For example, one man-rated system at 300 kWe and 1800°K shows a specific mass of 7.9 kg/kWe and will accommodate an 18 m payload at a 50 m distance.

*Work performed under the auspices of the U.S. Atomic Energy Commission.

II. INTRODUCTION

A considerable literature exists on the use of a nuclear reactor power source with a thermionic converter to obtain electric power in space. Convenient references include Voorhees,¹ and Schreiber and Salmi.² The major activity has been centered on in-pile concepts. Intrinsic difficulties with these concepts, however, result from the fact that use in space implies relatively high temperatures, long lifetimes, and high power densities to provide low specific mass. This combination causes swelling of fuel to distort the sensitive diode gap, release of fission products into the similarly sensitive diode plasma, and radiation degradation of in-core electrical insulation. Furthermore, the investigation of these problems is extremely costly, requiring as it does for meaningful data, long-time irradiation in fast spectrum reactors at very high neutron fluxes and temperatures.

The disadvantages of in-pile systems can be circumvented by the use of nearly isothermal heat pipes to transport the reactor power with a low temperature loss to an externally located thermionic convertor.³

¹B. G. Voorhees, "Thermionic Conversion for Space Auxiliary Power Generation," in Chemical Engineering Progress Symposium Series No. 75, Vol. 63, pp. 110 et. seq.

²R. E. Schreiber and E. W. Salmi, "A Look at Nuclear Thermionic Systems," *Astronautics and Aeronautics*, pp. 50 et. seq. (Jan. 1968).

³G. M. Grover, et al. —EUR 2229, e. Also, *ibid.*, U.S. Patent 3,302, 042 (January 31, 1967).

Furthermore, the heat flux transformer properties of heat pipes refine the match between source and converter, and retain conversion efficiency lost in the in-pile system by axial power flattening problems.

The Lawrence Radiation Laboratory reviewed out-of-core thermionic space power in 1966, and reported an interesting conceptual design for a 2000°K emitter, 10-MWe system intended for use with electric propulsion, with a calculated specific mass of 6-9 kg/kWe.⁴ This system showed the compatibility of heat pipes, nuclear reactors, and thermionic conversion in the context of space and power generation. Subsequently, Heath and Lantz⁵ studied the conceptual feasibility of an 1800°K emitter, 36-kWe system having a specific mass of 8.3 kg/kWe, using U²³³ fuel and based on technology available relatively early. Pedersen⁶ has also studied this general concept, apparently independently. Pedersen studied a 2100°K emitter, 1 MWe system and obtained 5.3 kg/kWe.

The performance of heat pipes in a zero-gravity (space) environment has been demonstrated,⁷ and many laboratories have successfully tested a variety of heat pipe sizes, materials, temperatures, and internal and external configurations.⁸⁻¹⁰

⁴C. S. Barnett, Trans. Am. Nuc. Soc. 9, 2 (338-339) October 1966.

⁵C. A. Heath and E. Lantz, NASA TM X-52370, January 1967.

⁶E. S. Pedersen, RISO-M-514, Atomenergikommissionens, May 1967.

⁷J. Deverall and E. Salmi, Thermionic Conversion Specialist Conference (Palo Alto, California) pp. 35 et. seq., October 1967.

⁸R. B. Wall, "Heat Pipe Experiments," Thermionics Specialist Conference (AIAA) 1965.

⁹C. A. Busse, E. Geiger, M. Patzschke, and D. Quataert, "Heat Pipe Life Tests at 1000°C and 1600°C." Thermionic Conversion Specialist Conference, 1966.

¹⁰J. K. Kemme, "Heat Pipe Capability Experiments," Thermionic Conversion Specialist Conference, 1966.

Continuing effort at Lawrence Radiation Laboratory on out-of-core thermionic space power has had as its primary objective the elucidation of more realistic conceptual system designs, and a consistent and explicit basis for evaluating these systems as space power sources for all reasonable power levels and with reasonable temperatures, for both manned and unmanned applications. A secondary objective is to show the growth potential in power and power-per-unit mass, as needs increase and as available materials improve in temperature capability, respectively. This will ensure that investment in the required development will provide worthwhile long-term returns.

The present paper is a progress report on a survey of out-of-core systems in which the primary variables are reactor temperature and electric power level. This survey is accomplished by a computerized optimization search throughout a phase space made up of four independent variables that describe the system. A trade-off among these variables minimizes specific mass within specified constraints for each system. The system is characterized by reactor temperature, electric power output, and at present, by an imposed geometry that is cylindrically axisymmetric and requires a linear ordering of reactor, heat exchanger, shield, electrical insulator/heat exchanger, thermionic diode array, radiator, and (at a distance in space) payload. Each of these components is described by a model intended to be the simplest that is still adequate to retain the essential features of the component.

III. DISCUSSION OF MODELS AND PROPERTY VALUES

A. Geometry

A plan view of the system is shown in Fig. 1. A fixed payload distance of 50 m has been assumed. The three lengths, R_1 , R_2 , and R_3 , have arbitrarily been held fixed, to date, at values of 15, 5, and 5 cm, respectively (future model improvements will link these to heat fluxes and control requirements that vary from system to system). The flare half-angle θ is one of the four independent variables by which a partially optimized system is obtained. The remaining three independent variables susceptible to variation for minimum specific mass, within the constrained volume of phase space searched, are the volume fraction of fuel in the reactor core, the temperature drop across the electrical insulation in the insulator/heat exchanger, and the temperature of the diode collector.

B. Heat Pipes

Heat pipes throughout the system are 1-cm (i.d.) cylindrical tubes made of tungsten alloy and containing the customary grooves plus screen capillary structures. The wall thickness is determined by vapor pressure of the heat-pipe fluid and the tungsten alloy creep strength, except that a fabricability minimum of 0.5 mm is set. The creep strength used throughout is for pure tungsten, shown in Fig. 2, but a tungsten alloy is supposed to be the material actually used. Except in the radiator, where lower temperatures may make sodium desirable for its higher vapor pressure, lithium is the heat-pipe fluid.

Axial heat fluxes for these heat pipes are first computed according to optimized internal dimensions derived at LRL and elsewhere from Cotter's equations¹¹ for the case where screen and channel characteristic dimensions are equal. (In the radiator, a pressure drop appropriate to an adiabatic transport section is introduced.) The axial heat fluxes actually used in this survey are constrained to be no more than 50% of the values computed in this way (cf. Table 1 for typical values). Since Cotter's equations generally have shown reasonable agreement with experiment for sodium except at very low temperatures¹² (i.e. low vapor pressure), the axial heat fluxes used seem comfortably realizable. Implied groove and screen dimensions are within present fabrication capability.

Radial heat fluxes into the heat pipes are constrained to be less than 400 W/cm^2 . Such a value is reasonable, when compared with customarily observed values in excess of several hundred W/cm^2 into sodium-filled heat pipes. The reasonableness of comparing sodium to lithium in the absence of experimental data follows if it is assumed that heat-pipe limits are set by phenomena (probably incipient boiling) similar, in gross mechanism, to the phenomena operating to produce burnout heat fluxes at solid-liquid interfaces. The latter fluxes are in fact similar to those achieved in heat pipes, regardless of mechanism identification, and correlations of burnout data show that lithium should permit almost

¹¹T. P. Cotter, "Theory of Heat Pipes," LA-3246-MS (1965).

¹²J. E. Kemme, "Heat Pipe Capability Experiments," LA-3585-MS (1966).

10^3 W/cm^2 . Deverall and Kemme¹³ have already run $\sim 200 \text{ W/cm}^2$ Li heat pipes. Actually the point is nearly academic since in the reactor, radial heat fluxes rarely or never approach 400 because other limitations are more stringent than heat-pipe capability.

C. Reactor

The reactor consists of a core plus a massless, unspecified region surrounding it that is described by the dimensions R_1 , R_2 , and R_3 (see Fig. 1). This surrounding region will contain, as necessary, a reflector and/or control system. The bare core itself is required to have a multiplication factor, k_{eff} , of 0.9, thus permitting adequate shutdown margin when unreflected. The fuel is uranium nitride of the necessary enrichment, and all structural material is assumed to be the same tungsten alloy used in heat pipes. The core is composed of UN, W, Li (heat-pipe fluid), and a reserve volume, proportional to the fuel volume, which is assumed in the calculations to date to have the properties of Li but which can represent (1) any other thermal bonding fluid, (2) a space to accommodate fuel swelling, (3) a means for creating an effective fuel density less than theoretical, or (4) a combination of these, possibly time-dependent. This bond-swelling-density volume can be varied parametrically. It has not proved to be a strongly influential parameter in the range of zero to 25% of the fuel volume fraction for the systems studied more carefully to date. Therefore, in the data reported here, this volume is set at a representative value of 15% of the fuel volume.

¹³J. E. Deverall and J. E. Kemme, "High Thermal Conductance Devices Utilizing Boiling of Lithium and Silver," LA-3211 (1964).

A constraint is placed on stress in the fuel due to the thermal gradient between the fuel centerline in a regular array and the associated heat-pipe wall. Although systems limited by three different values of maximum stress have been investigated, the results to be presented here will be based on a limit of 10,000 psi. This stress limit, and the associated temperature drop itself, are interpreted as one limit on radial heat flux into the heat pipe. An acceptable radial heat flux into a reactor heat pipe, therefore, is always less than or equal to the smallest of three values: (1) 400 W/cm^2 set by heat-pipe considerations, (2) the flux derived from a maximum allowable thermal fuel stress, and (3) the flux derived from a maximum allowable temperature drop across the fuel.

A basic variable for a particular system is the reactor temperature, from which all other temperatures are derived. This is a spatially independent, or average temperature. A local maximum (i.e. centerline) fuel temperature is immediately available by adding the fuel ΔT just described. Axial temperature variations are reduced greatly by the properties of heat pipes. Gross radial variations have been ignored, in the belief that radial power flattening can be readily achieved in noncriticality-limited reactors, and that a nonuniform distribution of heat pipes in the core can alleviate the problem in criticality-limited cores. (Nonuniform distribution of heat pipes in the reactor heat exchanger is an additional possibility for obtaining radially uniform thermionic diode array temperatures.) Since all data generated to date have been based on U^{235} fuel, radial power flattening by the use of U^{233} is an available device for achieving uniform radial core temperature profiles.

The reactor core length is established as the largest required by the following three criteria: (1) the total volume of fuel must be such that the burnup does not exceed a preset maximum; (2) the heat pipe flux limit in the core must not be exceeded; and (3) the (bare) core must have a multiplication factor, $k_{\text{eff}} = 0.9$. To date, a 20,000-hr lifetime and a 3% burnup limit have been set for all systems surveyed.

D. Shield

The shield is assumed to be BeO, to tolerate the high temperature heat pipes piercing it in transit from reactor to converter. The effect of neutrons streaming through these heat pipes is not included in the calculations, which are otherwise based on simple one-group removal theory. The adequacy of the latter approximation was tested in one case by comparison against a multiregion, one-group neutron and six-group gamma shielding calculation for the entire system, and was found to agree within 10% in shield mass. If the neutron streaming issue should prove serious, curved or bent heat pipes are believed possible.

Shield attenuation is fixed by requirements for manned payloads 50 m distant from a 60-MWth reactor. A 20,000-hr dose of about 17 rem is allowed in this case, leaving a margin for additional natural dose (e.g. solar flares). This implies a shield dose attenuation requirement of 10^{-7} , which then determines the shield thickness. Unmanned shields are set to provide three orders of magnitude less attenuation, and the shield attenuation required at other powers is scaled from these values simply as the logarithm of the thermal power of the reactor.

E. Insulator Heat Exchanger

Both this heat exchanger and the reactor heat exchanger (see Fig. 1) are regions where heat flows from one set of heat pipes to another.

In both cases, the heat flux is 400 W/cm^2 .

No temperature drop is accounted for in the reactor heat exchanger. In the insulator heat exchanger, the temperature drop across a BeO spacer insulator is one of the four independent variables discussed above. This insulator provides high-temperature electrical insulation along with acceptable thermal conductivity, and is shielded from the nuclear radiations in the core. This insulator makes possible series connection of many diodes to obtain the desired output voltage (see below). A corresponding insulator is required in the in-pile thermionic concepts (which have the electrical insulation within the reactor core).

A power loss in the insulator is calculated from the thermal and electrical conductivities of BeO and the maximum (series string) voltage sustained across the insulation. This voltage has to date been arbitrarily fixed at 400 volts. The BeO electrical resistivity used is LRL data on ultra-pure material,¹⁴ and is shown in Fig. 3. The BeO thermal conductivity is assumed to be $0.15 \text{ W/cm-}^\circ\text{C}$ at all temperatures, and is obtained from work reported by Simnad et al.¹⁵ System calculations

¹⁴H. W. Newkirk and C. Cline, "Electronic and Ionic Conductivity in Polycrystalline BeO," Lawrence Radiation Laboratory, Livermore, UCRL-6513-T, 1961.

¹⁵M. T. Simnad et al., "BeO; Review of Properties for Nuclear Reactor Applications," Proceedings of the Conference on Nuclear Applications of Non-Fissionable Ceramics, Washington, D.C., 1966, pp. 169-228.

have shown that if the BeO is removed and heat transport is accomplished by blackbody radiation, the result is a heavier system at all temperatures of interest. The increase in system specific mass (24% at 1800°K and 100 kWe) can be regarded as an upper limit on any penalty which is due to difficulties not resolved in connection with thermal contact between W and BeO.

F. Thermionic Converter

The converter is assumed to be an array of diodes formed by concentric cylindrical surfaces in a manner suggested by Busse.¹⁶ The properties of the converter are assumed to be determined by emitter and collector temperatures, and are characterized by a conversion efficiency, an emitter power density, and an effective end-on array electrical power density. The conversion efficiency is assumed for simplicity to be a separable product of a function $\eta_1(T_E)$ of the emitter temperature and a function $\eta_2(T_C/T_E)$ of the ratio of the collector temperature to the emitter temperature. It is assumed that electrode spacing, plasma pressure, surface properties, and materials have been held at values yielding maximum efficiency. (Masses of diodes specifically, and properties generally, have been thought of as corresponding to tungsten emitter, molybdenum collector, and cesium plasma.)

The diode efficiency used, as a function of emitter temperature for the case of no back emission (negligible T_C/T_E), is either the value quoted

¹⁶C. A. Busse, "Optimization of Heat Pipe Thermionic Converters for Space Power Supplies," Joint Nuclear Research Center Ispra Establishment, Italy, EUR 2534.e (1965).

by Leonard,¹⁷ shown in Fig. 4, or that value less a fixed decrement of 0.05.

Information on the influence of collector temperature on maximum diode efficiency is not well-established. An over-simplified model has been used in the survey to date, with the efficiency constant above Cs reservoir temperature and then falling linearly to zero at $T_C/T_E = 1$ from either $T_C/T_E = 0.55$ or $T_C/T_E = 0.67$. The former value is consistent with experimental data of Blue and Ingold¹⁸ and Wilson and Lawrence,¹⁹ as approximated by straight lines, and the latter value is similarly implied by Leonard's data.¹⁷

The power density of the emitter surface influences only the converter specific mass, itself a relatively small proportion of the system specific mass. It does so by determining the total emitter area required to produce the demanded system electric power. The emitter surface power density used is shown in Fig. 5. The specific mass of the diode array has an additive term independent of area, intended to account for array structure, amounting to 0.8 kg/kWe.

The overall array power density, defined as the system total electric power output divided by the frontal area presented by the array perpendicular

¹⁷A. Leonard, "Out of Pile Thermionic Space Power Systems Using a Gaseous Heat Transfer Fluid," Rand Corporation, Santa Monica, RM 4469-PR (1965).

¹⁸G. W. Sutton, "Direct Energy Conversion," McGraw-Hill Book Co., (1966).

¹⁹Wilson and Lawrence, "Advanced Energy Conversion," Vol. 4, pp. 195-221 (1964).

to the system axis, is constrained to be less than 250 W/cm^2 . This is a reasonable, although somewhat optimistic, value. This parameter is important at very high system powers, but has no influence at low and intermediate powers.

G. Radiator

The radiator is composed of heat pipes, probably with sodium as working fluid, and arranged to have a high redundancy. A radiator configuration is not specified in this survey, except that the radiator must fit in the shadow cone of the shield and not have an unreasonable ratio of length to width (or diameter). The weight is computed first as proportional to the required radiating area for blackbody radiation, assuming an emissivity of 0.8. The proportionality constant is 1.8 g/cm^2 . So that unreasonably long radiators will not be produced by the optimization process, this proportionality is arbitrarily modified to increase the radiator weight by a factor $[1 + 0.2 (L/D - 1)]$, where L/D is a figure of geometrical merit computed conveniently as the ratio of a flat radiator length to twice the value of S_2 shown in Fig. 1. Very long radiators are undesirable because of temperature drops incurred from heat pipe to heat pipe, and to the mechanical rigidity required to resist flexing. Although this modifying expression produces reasonable system configurations, it is expected that future careful design of actual radiators will yield a realistic modifier which reflects the undesirability of extremely long radiators, and that the modifier used here will be interpretable as a first-order approximation. This procedure is believed to produce a reasonable radiator mass. When the total system is re-computed without this modifier, but with preset flare angles

as determined by prior calculations with this modifier, total specific masses are indeed reduced somewhat (at 1800°K, for example, by roughly 1 kg/kWe).

IV. RESULTS

A variety of systems have been studied to date, reflecting differing assumptions about parameter values and about power needs and temperature capabilities. Of these, a set of six examples is presented here.

These six systems are shown in Table 1. Case 1 is a base case for this table, and is characterized by a reactor temperature of 1800°K, an electric power output of 300 kWe, a man-rated shield, an "optimistic" efficiency, and a flare half-angle that is constrained to be no less than 10°. (An "optimistic" efficiency is one based on Fig. 4 with a break point in T_C/T_E at 2/3.) With reference to the preceding text, the remaining system descriptors and performance specifications shown in Table 1 are self-explanatory. A qualification on the value shown for heat-pipe volume fraction in the shield is needed, however. This value is the maximum value, computed as the heat pipes enter the shield, and is based on an area of πS_1^2 (cf. Fig. 1). This fraction varies through the shield, emerging at the far end with a value only (S_1^2/S_2^2) as large (in Case 1, a value of 5.6%).

The data for Case 1 (in Table 1) describe a reasonable and attractive system. For this case and the others as well, the temperature rise in the reactor fuel is limited by the stress constraint to be well under 50°K. Case 2 shows the same system with an unmanned shield, re-optimized for minimum

specific mass. This can be seen most directly from the specific mass breakdown, with the implied system alterations reflected throughout the data in the Case 2 column. In this case a flare half angle greater than the constraint (10°) yields a minimum specific mass for the system.

Case 3 shows how the Case 1 system is altered when the reactor temperature is only 1500°K . A more conservatively rated system accommodating a larger payload results, but the calculated specific mass rises to 21 kg/kWe . Case 4 shows how the Case 1 system is altered if a "pessimistic" efficiency is assumed. "Pessimistic" here means one based on Fig. 4 less 0.05, with a break point in T_C/T_E at 0.55. Like Case 3, the lowered efficiency boosts thermal power to provide demand electric power, and the appropriate components respond. The net change in specific mass (relative to Case 1) is much less for Case 4 than for Case 3, but nondiode components are not so conservatively rated and the increase in shadowed payload is smaller.

Cases 5 and 6 show two systems that are constrained to have a flare half-angle no less than an arbitrarily pre-set value of 17° . This value seems to have currency when mission logistics involving docking are considered. Case 5 again compares directly to Case 1. The Case 5 system specific mass is almost all shield, as expected at this power and minimum angle. Electric powers of 3-4 MWe are needed before the 17° constraint is no longer a penalty (at which point, system specific mass is about 6.5 kg/kWe). Lower temperatures change this picture somewhat; at 1500°K (as Case 3), systems generating about 500 kWe and above are uninfluenced by the 17° constraint, and have specific masses of about 21 kg/kWe .

Case 6 compares with Case 5 rather than Case 1, since it differs from Case 1 in both electric power generated (50 kWe) and in constrained flare half-angle. In Case 6, the shield completely dominates system specific mass, forcing a total of 39 kg/kWe. Relative to Case 5, re-optimization changes all values in varying degree, but the shield masses reflect the thermal powers and the logarithmic mass variation with thermal power. Only 41 reactor heat pipes are needed for this system, possibly a low (but remediable) value from the point of view of redundancy.

If the practical disadvantages of U^{233} fuel become acceptable, the improved specific masses of the six systems, due to the reduced core mass as mentioned above, will come about primarily through a reduction in the core length shown in Table 1, reducing the core L/D to more customary values.

The data obtained here will doubtless change, as refinements are made in the component models used, and the specific mass will in general increase as realism is improved. For example, some additional tens of degrees in temperature will be lost at various heat-pipe/heat-pipe interfaces, and some small additional weight will be necessary to realize the reflector control system for the reactor. However, relatively little change in the system specific mass is expected after re-optimization, so that it is believed justifiable to draw certain general conclusions from the foregoing results.

V. CONCLUSIONS

In general, the computations carried out support the conceptual feasibility of out-of-core thermionic space power systems, and indicate that competitive specific masses should be realizable. Six cases, representing variations around an 1800°K, 300-kWe system, show reasonable configurations and specifications in enough detail to permit conceptual evaluation and show adaptability of the system type to requirements for various missions in which a shadow shield is acceptable. Therefore, the inherent advantages of an out-of-core thermionic generator for space application, described in the Introduction (Section I), remain strong incentives to emphasize these systems in future studies and development activities.

ACKNOWLEDGMENTS

This paper would not exist without substantial contributions from many staff members who have been part of the Laboratory's reactor project. Although many of these contributions were, in this context, vital and therefore deserving of personal recognition, the number of staff members involved prohibits mention of any except those of M. Janssen, who structured much of the earlier thinking and participated in the original conception of an out-of-core thermionic space power generator using heat pipes, and those of M. Jester, who gave his advice and time unstintingly at critical times.

Table 1. System Configurations and Specifications.

Case	1	2	3	4	5	6
Reactor temperature (°K)	1800	1800	1500	1800	1800	1800
Electric power (kWe)	300	300	300	300	300	50
Shield rating (M, UM)	M	UM	M	M	M	M
Diode efficiency (optimistic, pessimistic)	opt.	opt.	opt.	pessa.	opt.	opt.
Minimum flare half-angle (°)	10°	10°	10°	10°	17°	17°
Geometry (cm)						
R ₁	15	15	15	15	15	15
R ₂	5	5	5	5	5	5
R ₃	5	5	5	5	5	5
R _C	12.8	12.9	19.6	16.1	12.4	9.2
L _c	35.5	35.0	20.5	29.2	36.3	52.0
Flare half-angle, θ (°)	10.0	11.2	13.8	10.0	17.0	17.0
S ₁	27.6	28.8	34.6	29.7	34.6	36.2
S ₂	43.9	37.1	61.6	48.4	61.7	59.3
L _s	93	42	110	106	88	75
Payload diameter (m)	17.6	19.8	24.6	17.6	30.6	30.6
Core data						
Volume fractions						
Heat pipes (i.d.)	0.29	0.29	0.34	0.36	0.28	0.12
Heat pipe wall	0.06	0.06	0.07	0.07	0.05	0.03
Fuel	0.57	0.57	0.51	0.49	0.58	0.74
Bond/swell	0.08	0.08	0.08	0.07	0.09	0.11
Number of heat pipes	187	194	521	368	172	41
Axial H. P. flux (kW/cm ²)	15.3	15.4	10.6	16.0	15.2	13.9
Radial H. P. flux (W/cm ²)	108	110	129	137	105	67
Burnup in 2×10^4 hr (%)	1.6	1.7	2.5	2.95	1.5	0.3
Shield data						
H. P. axial flux (kW/cm ²)	7.93	11.9	3.9	7.3	8.2	8.9
H. P. Vol. fraction (%)	14	9	36	28	8	1.5
Converter data						
Emitter temp (°K)	1791	1790	1498	1788	1793	1798
Collector temp (°K)	1280	1300	1090	1290	1230	1310
Diode efficiency (%)	13.7	13.1	7.0	6.8	15.1	13.1
Array efficiency (%)	13.3	12.8	6.9	6.5	14.6	10.9
Array end-on power density (W/cm ²)	50	69	25	41	25	4.5
Radiator data						
Radiating area (m ²)	16.0	15.8	62.8	34.6	16.9	3.1
Length of flat radiator (m)	4.7	4.7	9.1	7.5	3.6	1.0
Figure of merit (L/D)	5.4	6.4	7.4	7.8	2.9	0.9
System data						
Electric power (kWe)	300	300	300	300	300	50
Thermal power (kWth)	2260	2350	4330	4630	2060	460
Specific masses (kg/kWe)						
Reactor	0.54	0.54	0.70	0.65	0.53	2.92
Reactor HX	0.02	0.02	0.03	0.04	0.02	0.02
Shield	3.82	1.45	8.39	5.28	6.66	33.14
Insulator HX	0.04	0.04	0.07	0.07	0.03	0.05
Converter	1.69	1.69	3.37	1.70	1.67	1.65
Radiator	1.82	1.98	8.64	4.94	1.41	1.07
TOTAL	7.93	5.72	21.20	12.68	10.30	38.85

FIGURE CAPTIONS

Fig. 1. System geometry.

Fig. 2. Strength data for tungsten.

Fig. 3. Electrical Conductivity of BeO.

Fig. 4. Diode efficiency vs emitter temperature.

Fig. 5. Converter power density vs emitter temperature.

Figure 1. System Geometry.

Figure 2. Strength Data for Tungsten.

Figure 3. Electrical Conductivity of BeO.

Figure 4. Diode Efficiency vs. Emitter Temperature.

Figure 5. Converter Power Density vs. Emitter Temperature.

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