MAY 7 1968

This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

UCRL -70816
PREPRINT

CONF-680508--1

MASTER

Lawrence Radiation Laboratory

UNIVERSITY OF CALIFORNIA

LIVERMORE

OUT-OF-CORE THERMIONIC SPACE POWER

William E. Loewe

March 8, 1968

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

This paper was prepared for presentation at
the Second International Conference on Thermionic Power Generation at
Stresa, Italy, EURATOM, May 27-31, 1968.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

fy

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

OUT-OF-CORE THERMIONIC SPACE POWER⁽¹⁾

William E. Loewe

Lawrence Radiation Laboratory, University of California

Livermore, California

Abstract

A survey of conceptual out-of-core thermionic systems using heat pipes has been made to identify critical technology areas, investigate feasibility for space application, locate parameter regimes of interest, and estimate specific mass values. The survey included preliminary comparisons of required, current, and projected state-of-the-art in these critical areas of technology. Temperatures and powers were surveyed in the ranges from 1400°K to 2200°K and from 10 kWe to 10MWe, respectively. A cylindrically symmetric geometry with a linear display of system components was studied.

In general, out-of-core thermionic systems with heat pipes appear to be attractive candidates for use in space over a broad range of electric power levels, meeting the requirements of both advanced auxiliary power and nuclear (electric) propulsion.

I. Introduction

The advantages of thermionic conversion for space power generation have been discussed frequently, and need little discussion at this conference. A convenient reference is an article by B. G. Voorhees.⁽²⁾ A heat source that can be easily matched with thermionic conversion over a range of powers from a few tens of kWe to many MWe, is the nuclear reactor. A sizable body of literature has grown that discusses such a union, with convenient references being again Voorhees⁽²⁾ and also Schreiber and Salmi.⁽³⁾ The major activity has been centered on in-pile concepts. Intrinsic difficulties with this concept, 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 (1) causes swelling of fuel that distorts the sensitive diode gap, (2) causes release of fission products into the similarly sensitive diode plasma, and (3) causes radiation degradation of in-core electrical insulation. Furthermore, the investigation of these problems is extremely costly, requiring 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.⁽⁴⁾ Furthermore, the heat flux transformer properties of heat pipes refine the match between source and convertor, 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 6-9 kg/kWe.⁽⁵⁾ This system showed the compatibility of heat pipes, nuclear reactors, and thermionic conversion in the context of space power generation. Subsequently, Heath and Lantz studied the conceptual feasibility of an 1800°K emitter, 36 kWe system having a specific mass of 8.3 kg/kWe using U²³³ and based on technology available relatively early.⁽⁶⁾ E. S. Pedersen has also studied this general concept, apparently independently. Pedersen studied a 2100°K emitter, 1 MWe system and obtained 5.3 kg/kWe.⁽⁷⁾

During this same period, the performance of heat pipes in a zero-gravity (space) environment has been demonstrated,⁽⁸⁾ and many laboratories have successfully tested a variety of heat pipe sizes, materials, temperatures, and internal and external configurations.⁽⁹⁾ Limitations on heat pipe performance appear, within the approximate bounds set forth originally by Cotter,⁽¹⁰⁾ to be previously caused by incautious preparation (undue contamination), and presently to the availability of laboratory environmental equipment that can function at the desired temperatures and heat fluxes. Also, anticipated problems with start-up and catastrophic burnout seem to have been conquered, and even higher axial fluxes than predicted originally by Cotter may be possible if special precautions are taken.⁽¹¹⁾

Continuing effort at Lawrence Radiation Laboratory on out-of-core thermionic space power has been to elucidate more realistic conceptual system designs and to develop 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 both 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.

This paper is a progress report on a survey of out-of-core systems in which the primary variables are reactor temperatures between 1400°K and 2200°K and electric power levels between 10 kWe and 10 MWe, and in which a variety of property specifications or component models are available for individual investigation in terms of their effect on system performance. The results of this survey will permit, with increasing confidence as models are improved, 1) assessing the feasibility and competitive performance of these systems, 2) selection of power and temperature ranges, 3) identification of vital technologies for emphasized activity, and 4) credibility that comes from spanning a set of conditions that is wide enough to identify trends, in a manner detailed enough to permit comparisons with component specifications from other systems without undue extrapolation.

This survey is accomplished by a computerized optimization 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.

II. Discussion of Models and Property Values

A plan view of the system is shown in Figure 1. The three lengths, R_1 , R_2 , and R_3 , have been arbitrarily held fixed at values of 15 cm, 5 cm, 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.

A. Geometry

The geometric description of the system model shown in Fig 1, although greatly simplified, permits a realistic treatment of all important interactions characteristic of a shadow-shielded system. Enveloping (4π) shields, obviously much more massive, are excluded from the present study although their feasibility is not questioned.

A fixed payload distance of 50 m is assumed, and systems having a shield flare angle adequate to cover any desired shadow diameter at this distance can be selected.

B. Heat Pipes

Heat pipes throughout the system are 1-cm (ID) cylindrical tubes made of tungsten alloy that contain the customary grooves plus screen capillary structures. The wall thickness is determined by vapor pressure of the heat pipe fluid and 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 Figure 2, but a tungsten alloy is supposed to be the material actually used. For several reasons lithium is the heat pipe fluid except in the radiator, where lower temperatures may make sodium desirable for its higher vapor pressure. First, lithium is compatible with the tungsten and UN materials technology being developed for reactors, within this survey's temperature range, under a current LRL program. Second, above perhaps 1200°K, it is a superior heat pipe fluid to any other until its vapor pressure becomes so high, at very high temperatures, that the weight penalty for tungsten creep resistance (also a function of temperature—see Figure 2) is prohibitive. Third, the only other apparent candidate, silver, is inferior in this application for all temperatures of interest, because its improved heat pipe capabilities compared to lithium appear only at temperatures too high to be of practical interest (at the end of the survey range, around 2000°K).

Axial heat fluxes for these heat pipes are first computed according to optimized internal dimensions derived at LRL and elsewhere using Cotter's equations⁽¹⁰⁾ for the case where screen and channel characteristic dimensions are equal. These are shown in Figure 3 for a 100-cm-long pipe. In the radiator, a pressure drop appropriate to an adiabatic transport section is introduced. As remarked in the introductory section to this paper, J. Kemme⁽¹¹⁾ is decoupling groove and mesh dimensions to obtain still higher axial fluxes. Deserving emphasis is the fact that the axial heat fluxes actually used in this survey are constrained to be no more than 50% of the values shown in Figure 3 (cf Table 1). Since Cotter's equations⁽¹⁰⁾ have shown reasonable agreement with experiment for sodium except at very low temperatures⁽¹²⁾ (i.e., low vapor pressure), the axial heat fluxes used seem comfortably realizable. (As also remarked earlier, limitation on experimental demonstration of lithium heat pipes presently stems from equipment, not heat pipe

capability or fabrication.) 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 very similar to those achieved in heat pipes, regardless of mechanism identification, and correlations of burnout data show that lithium should permit almost 10^3 W/cm^2 . Deverall and Kemme⁽¹³⁾ 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 are rarely or never as high as 400, because other limitations are more stringent than heat pipe capability. This is particularly true of lower power systems of earliest interest, where very modest ($< 10^2 \text{ W/cm}^2$) radial fluxes appear in the reactor.

C. Reactor

The reactor consists of a core plus a weightless, unspecified region surrounding it that is described by the dimensions R_1 , R_2 , and R_3 , mentioned earlier. 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 a combination of these, possibly time dependent. Although this bond-swelling-density volume can be varied parametrically, it has not proven to be a strongly influential parameter in the range of zero to 25% of the fuel volume fraction for the systems studied most carefully to date. Therefore, in the data reported here, this volume is set at a representative value of 15% of the fuel volume.

A constraint is placed on the stress in the fuel that results from 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 in detail, 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 a 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, 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, 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 non-criticality-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 have been based on U^{235} fuel, radial power flattening by the use of U^{233} is an available method to achieve 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 enough so that the burnup does not exceed a preset maximum, 2) the heat pipe flux limit in the core must not be exceeded, 3) the (bare) core must have a multiplication factor, $k_{\text{eff}} = 0.9$. To date, a 20,000-hour 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 convertor. The effect of neutron streaming through these heat pipes is not explicitly included in the calculations, which are otherwise based on simple one-group removal theory. The adequacy of this approximation was tested in one instance by comparison against a multiregion, one-group neutron and 6-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, even though the length-to-diameter ratio of these holes is quite small, curved or bent

heat pipes are believed possible. Furthermore, although the highest power systems have quite high heat-pipe (i.e. streaming path) volume fractions, these systems lie well in the future in terms of need, and the low power systems of early interest have streaming path volume fractions that are 5% to 10% or less. That is, neutron streaming, which is ignored in these calculations, may present no problems of significance, and, if it does, solutions appear to be either at hand or realizable by the time a solution becomes necessary for distant future needs.

Shield attenuation is fixed by the following requirements. For manned payloads a 20,000-hour dose of about 17 rem is allowed, leaving a margin for additional natural dose (e.g. solar flares). This implies a shield dose attenuation requirement which then determines the shield thickness. Unmanned shields are set to provide only a shield dose attenuation 10^{-3} less than man rated shields.

E. Insulator Heat Exchanger

Both this heat exchanger and the reactor heat exchanger (see Figure 1) are regions where heat flows from one set of heat pipes to another. In both cases, the heat flux is 400 W/cm², and the flow path is as implied by the left-most portion of Figure 4a. The difference between the two cases is that no BeO spacer-insulator intervenes in the case of the reactor heat exchanger. This re-entrant heat pipe joint is also a characteristic of the thermionic diode (see below), as Figure 4a shows. The mass of both heat exchanger regions is invariably a small proportion of the system mass. It is calculated according to the heat-pipe wall thickness, times the density of W, times the area implied by the thermal power transported divided by the preset heat flux, 400 W/cm². (The weight of the very thin layer of BeO is ignored.)

No temperature drop is accounted for in the reactor heat exchanger. In the insulator heat exchanger, the temperature drop across the BeO is one of the four independent variables. 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 been arbitrarily fixed at 400 volt. The BeO electrical resistivity used is LRL data on ultra-pure material,⁽¹⁴⁾ and is shown in Figure 5. The BeO thermal conductivity is assumed to be 0.15 W/cm-°C at all temperatures, and is obtained from work reported by M. T. Simnad, et al.⁽¹⁵⁾ Earlier system survey calculations 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. On the other hand, the increase in specific mass can be regarded as an upper limit on any penalty caused by difficulties that might not be resolved in connection with thermal contact between W and BeO. For example, this upper limit is less than 25%, at 1800°K for powers of 100 kWe and less.

F. Thermionic Converter

The converter is assumed to be an array of diodes formed by concentric cylindrical surfaces in a manner illustrated in Figure 4. Concentric cylindrical heat pipe/diode configurations have been 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, with two alternatives each [thus, yielding four possible ways to obtain a value for the array efficiency, $\eta(T_E, T_C)$]. This assumption is suggested by Leonard's work (see below), and is not inconsistent with experimental data. In all cases, 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 by Leonard,⁽¹⁷⁾ or that value less a fixed decrement of 0.05. The justification for the use of Leonard's data (shown in Figure 6) is that controlled introduction of electronegative or electropositive additives might result once again in the better values obtained before 1965, when trace quantities of impurities spoiled reproducibility, but occasionally produced the efficiencies quoted by Leonard from the literature available at that time. The justification for the much more pessimistic but reproducible efficiencies, obtained by subtracting 0.05 (5%) from Leonard's data, is that they compare satisfactorily with data obtained by Lieb and Ruteh,⁽¹⁸⁾ by Wilson and Lawrence,⁽¹⁹⁾ and computed by Wilkins using the SIMCON semi-empirical computer code.⁽²⁰⁾ Leonard's data include losses caused by thermal

conduction along interconnections in arrays, but not resulting from I^2R losses. Since the diode weight is a relatively small proportion of the system weight in most cases of interest, a simplifying but not significant assumption can be made. This is, that when the diode array is optimized as constrained by its inclusion in an entire system, so that efficiency is more important than specific mass, small losses in efficiency will result in going from diode to diode array. This assumption has been implied as a first approximation by Busse.⁽¹⁶⁾

Information on the influence of collector temperature on maximum diode efficiency is not well-established. *A priori*, it may be supposed that a factor, depending on T_C relative to T_E and multiplying $\eta_1(T_E)$ as discussed above, would be unity (at temperatures above the Cs reservoir temperature) until back emission becomes significant, and then fall monotonically until $T_E = T_C$, where a zero efficiency might be expected to occur. Such an over-simplified model has been used in the survey to date, with the efficiency 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 Ingold⁽²¹⁾ and Wilson and Lawrence,⁽²²⁾ as approximated by straight lines, and the latter value is similarly implied by Leonard's data.⁽¹⁷⁾ As these data mature, they can be readily introduced into the survey results.

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 and collector thicknesses are set at 2 mm and 1 mm, respectively.) The emitter surface power density used was obtained by adjusting the data of Lieb and Ruffe⁽¹⁸⁾ to the conditions where maximum efficiency is expected to occur, namely around 0.8 volt and a gap of about six mils. The result of a fit to this adjusted data is shown in Figure 7. The specific mass of the diode array actually 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 to the system axis, is constrained to be less than 250 W/cm². This is a reasonable although somewhat optimistic value presently undergoing further investigation at LRL. 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 possible configuration is the truncated cone suggested by Salmi,⁽²³⁾ although the achievement of sufficiently low temperature drops between heat pipes may be problematical. Flat heat pipe radiators that are redundant except for an armored central feed and return line are being designed at LRL, and appear attractive. 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/cm². In order that unreasonably long radiators 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 Figure 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 that 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 system mass, inasmuch as the radiator proportionality factor typically turns out to be 2.5 g/cm² or more for the systems investigated, compared to the geometry-independent value of 1.8 g/cm². When the total system is recomputed without the inclusion of this modifier, but having preset flare angles as determined by earlier calculations using this modifier, total specific masses are indeed reduced somewhat (at 1800°K for example, by roughly 1 kg/kWe).

III. Results

Figure 8 shows the total system specific mass for a system with a man-rated shield and Figure 9 shows corresponding data resulting from shielding requirements for unmanned payloads. There is a heavy incentive for exceeding temperatures in the reactor core of 1400°K, while 1800°K is both attractive and reasonable. 2000°K yields a small improvement, and 2200°K, omitted for purposes of clarity, is actually harmful to specific mass (due to the need for thicker-walled heat pipes).

Figure 10 shows the incentive to obtain the more optimistic conversion efficiencies (see discussion of models). The ordinate in Figure 10 is the ratio of data obtained with the pessimistic conversion efficiencies (Figure 6 less 5% and an efficiency break point at $T_C/T_E = 0.55$) to the data shown in Figure 6 with an efficiency break point at $T_C/T_E = 2/3$. In the power range of early interest, penalties of the order of 1.5 are seen to be assessed in system specific mass (at 1800°K).

Figure 11 is a cross plot at 100 kWe of the data shown in Figure 9. It shows explicitly the typical rapid rise in specific mass below 1800-1900°K, the temperature-independent region around 2000-2200°K, and the upswing beginning at 2200°K.

Characteristic parameters typical of the systems described by this study are illustrated in Table 1. The system described there would supply 100 kilowatts of auxiliary power for a manned mission. Its 10° shield flare angle would shadow a circle more than 17 m in diameter at the crew vehicle distance assumed (50 m), providing substantial room for extravehicular activity.

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 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. Therefore, it is believed justifiable to draw certain general conclusions from the foregoing results.

IV. Conclusions

Thermionic converters can be linked with nuclear reactor power sources and heat pipe thermal transport, to produce conceptually sound and reasonable electric power generators for space applications. Such generators are competitive in specific mass at reasonable temperatures, have a high degree of performance improvement potential, and great power up-rating potential from low levels. The advantages of such a generator that were anticipated in the Introduction section appear realizable. Conservatism in expected heat pipe performance is not a heavy penalty. It needs to be shown that thermionic converters, when freed from the rigors of a nuclear core, can yield reliably the high efficiencies obtainable in the laboratory, over lifetimes of 20,000 hours and more. For this purpose, an emitter temperature of 1800°K seems to be satisfactory, and significantly lower temperatures are acceptable initially if necessary to achieve the required lifetimes.

A place in the space program awaits reliable, long-life thermionic conversion systems. The course of their development and their application no longer appears to require diode placement in the extremely high intensity nuclear radiation fields found in compact power reactors.

V. 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 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 M. Jester, who gave his advice and time unstintingly at critical times.

REFERENCES

- (1) Work performed under the auspices of the U. S. Atomic Energy Commission.
- (2) VOORHEES, B. G., "Thermionic Conversion for Space Auxiliary Power Generation," Chemical Engineering Progress Symposium Series No. 75, 63, pp. 110 et seq.
- (3) SCHREIBER, R. E., and SALMI, E. W., A Look at Nuclear Thermionic Systems, *Astrodynamics and Aeronautics*, (1968) pp. 50 et seq.
- (4) GROVER, G. M., et al., EUR 2229, e
- (5) BARNETT, C. S., *Trans. Am. Nuc. Soc.* (1966) No. 9, 2, pp. 338, 339.
- (6) HEATH, C. A., and LANTZ, E., "A Reactor Concept for Space Power Employing Thermionic Diodes and Heat Pipes," National Aeronautics and Space Administration Report NASA TM X-52370, 1967.
- (7) PEDERSEN, E. S., "Heat Pipe Thermionic Reactor Concept," RISO-M-514, Atomenergi-kommissionens, 1967.
- (8) DEVERALL, J., and SALMI, E., "Heat Pipe Performance in a Space Environment," Thermionic Conversion Specialist Conference (Palo Alto, California) pp. 359 et seq., 1967.
- (9) WALL, R. B., "Heat Pipe Experiments," Thermionics Specialists Conference (AIAA), 1965. BUSSE, C. A., GEIGER, E., PATZSCHKE, M., and QUATAERT, D., "Heat Pipe Life Tests at 1000°C and 1600°C," Thermionic Conversion Specialist Conference, 1966. KEMME, J. K., "Heat Pipe Capability Experiments," Thermionic Conversion Specialist Conference, 1966.
- (10) COTTER, T. P., Theory of Heat Pipes, Los Alamos Scientific Laboratory Report LA-3246-MS, 1965.
- (11) KEMME, J., "High Performance Heat Pipes," Thermionic Conversion Specialist Conference (Palo Alto, California) pp. 355 et seq., 1967.
- (12) KEMME, J. E., Heat Pipe Capability Experiments, Los Alamos Scientific Laboratory Report LA-3585-MS, 1966.
- (13) DEVERALL, J. E., and KEMME, J. E., "High Thermal Conductance Devices Utilizing Boiling of Lithium and Silver," Los Alamos Scientific Laboratory Report LA-3211, 1964.
- (14) NEWKIRK, H. W., and CLINE, C., "Electronic and Ionic Conductivity in Polycrystalline BeO," Lawrence Radiation Laboratory Report UCRL-6513-T, 1961.
- (15) SIMNAD, M. T., et al., "BeO, Review of Properties for Nuclear Reactor Applications," Proceedings of the Conference on Nuclear Applications of Non-Fissionable Ceramics, Washington, D.C., pp. 169-228, 1966.
- (16) BUSSE, C. A., "Optimization of Heat Pipe Thermionic Converters for Space Power Supplies," Joint Nuclear Research Center Ispra Establishment, Italy, EUR 2534, e, 1965.
- (17) LEONARD, A., "Out of Pile Thermionic Space Power Systems Using a Gaseous Heat Transfer Fluid," Rand Corporation, Santa Monica, RM 4469-PR, 1965.
- (18) LIEB and RUFEB, "Performance and Potential Capabilities of Thermionic Conversion Devices," presented at Electron Devices Meeting, Washington, D.C., 1966.
- (19) WILSON and LAWRENCE, *Advanced Energy Conversion*, 4, pp. 195, 1964.
- (20) WILKINS, D. R., "Theoretical Description of Thermionic Converter Output Performance Characteristics," Thermionic Conversion Specialists Conference, Houston, 1966.
- (21) SUTTON, G. W., *Direct Energy Conversion*, McGraw-Hill Book Company, 1966.
- (22) WILSON and LAWRENCE, *Advanced Energy Conversion*, 4, pp. 195 et seq., 1964.
- (23) SALMI, E. W., A Study of a Nuclear Thermionic Propulsion System, AIAA Paper No. 67-229, New York, 1967.

Table 1. 100 kWe Electric Power Generated at 1800°K Reactor Temperature System Configuration, Manned Payload.

Values of Geometrical Parameters in Figure 1.		Core Data	
$R_1 = 15 \text{ cm}$	$\theta = 10.0^\circ$	Volume fractions	
$R_2 = 5 \text{ cm}$	$S_1 = 26.8 \text{ cm}$	Heat Pipes (ID)	0.18
$R_3 = 5 \text{ cm}$	$S_2 = 41.1 \text{ cm}$	Heat Pipe Wall (W)	0.04
$R_C = 10.1 \text{ cm}$	$L_S = 31.3 \text{ cm}$	Fuel	0.679
$L_C = 46.1 \text{ cm}$	Payload diameter - 17.6 meters	Bond/Swell	0.101
			<u>1.000</u>
		Number of	
		Heat Pipes - 75	
		Axial Heat Pipe	
		Flux - 14.4 kW/cm ²	
		Radial Heat Pipe	
		Flux - 78 W/cm ²	
		Thermal Stress	
		in Fuel - 10,000 psi	
		Fuel Centerline	
		Temp - ~1850°K	
		Burnup in	
		20,000 hrs - 0.63%	
		U ²³⁵ Fuel	
Shield Data.		System Data	
Heat Pipe Axial Flux - 8.6 kW/cm ²		Electric Power - 100 kWe	
Heat Pipe Volume Fraction - 5.3%		Electric Voltage - 400 volts	
Converter Data:		Thermal Power - 850 kW _{th}	
Emitter Temperature - 1790°K		Specific Masses, kg/kWe	
Collector Temperature - 1330°K		Reactor	- 1.48
Diode Efficiency - 12.5%		Reactor Heat Exchanger	- 0.02
Array Efficiency - 11.8%		Shield	- 9.00
Array end-on Power		Insulator Heat Exchanger	- 0.04
Density - 18.8 W/cm ²		Converter	- 1.67
Radiator Data:		Radiator	- 1.27
Radiating Area - 5.3 m ²		TOTAL	13.48
Length of Flat Radiator, L_F - 2.2 m			
Figure of Merit, $L_F/2S_2$ - 2.7

Figure 1. System Geometry.

STRENGTH DATA FOR TUNGSTEN

Figure 2. Strength Data for Tungsten.

Figure 3. Axial Fluxes for 100-cm Heat Pipes.

Figure 5. Electrical Conductivity of BeO .

Figure 6. Diode Efficiency vs. Emitter Temperature.

Figure 7. Converter Power Density vs. Emitter Temperature.

Figure 8. System Specific Mass vs. Electric Power — Man-Rated Shields.

Figure 9. System Specific Mass vs. Electric Power — Unmanned Payloads.

Figure 10. Ratio of System Specific Mass, Pessimistic to Optimistic Converter Performance, vs. Electric Power.

Figure 11. System Specific Mass vs. Temperature for 100-kWe Generator — Unmanned Payload.

DISTRIBUTION

LRL Internal Distribution

Michael M May

TID Berkeley

TID File 30

External Distribution

D. S. Beard 8
Space Nuclear Systems Division
U. S. Atomic Energy Commission
Washington, D. C.

H. Neu 300
Direct Conversion Division
Ispra, Italy

Division of Technical Information Extension, Oak Ridge

LEGAL NOTICE

This report was prepared at an account of Government sponsored work
within the United States, nor the Commission nor any person acting on behalf
of the Commission

A. Makes any warranty or representation, expressed or implied, with
respect to the accuracy, completeness, or usefulness of the information con-
tained in this report, or that the use of any information, apparatus, method, or
process disclosed in this report may not infringe privately owned rights, or

B. Assumes any liabilities with respect to the use of, or for damage
resulting from the use of any information, apparatus, method, or process, as
disclosed in this report

As used in the above "person acting on behalf of the Commission"
includes any employee or contractor of the Commission or employee of such
contractor, to the extent that such employee or contractor of the Commission
or employee of such contractor prepares, disseminates, or provides access to
any information pursuant to his employment or contract with the Commission
or his employment with such contractor

JB:dh