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# A NUCLEAR THERMIONIC SPACE POWER CONCEPT USING ROD CONTROL AND HEAT PIPES

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## ABSTRACT

A space power system using a fast spectrum nuclear reactor, out-of-pile thermionic diodes, heat pipes, and a dual central absorber rod type of reactivity control has been studied. Emphasis is placed on the neutronic aspects and general feasibility of the concept. Comparison is made between uranium-233 and uranium-235 nitride and plutonium-239 nitride fuels. In this concept heat is transferred from the reactor core to the thermionic diodes by layers of radial heat pipes stacked alternately with slabs of fuel. For this out-of-pile concept, which would supply about 130 kilowatts electric, the reactor can be considerably smaller than the equivalent reactor with in-pile diodes.

# A NUCLEAR THERMIONIC SPACE POWER CONCEPT USING ROD CONTROL AND HEAT PIPES

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## SUMMARY

A nuclear space power system which uses out-of-pile thermionic diodes and is cooled by heat pipes has been studied. The purpose of this study is to examine the general feasibility of the concept with emphasis on the neutronics. The power system uses a cylindrical fast spectrum reactor fueled with uranium-233 nitride ($U^{233}N$) and reflected by molybdenum. The reactor, including the reflector, is 0.355 meter in diameter and 0.51 meter long. Heat is transferred from the reactor core to thermionic diodes by layers of radial heat pipes stacked alternately with slabs of fuel.

Each annular layer of fuel or heat pipes is formed from sector-shaped elements. Outside the radial reflector the diodes are placed concentrically around the heat pipes which lead to radiators.

The reactivity control system consists of a central rod and a concentric tubular sheath of boron-10 carbide located along the cylindrical axis of the reactor. The rod and sheath are separated and cooled by a concentric annular heat pipe.

The axial power is tailored by nonuniform distribution of fuel to provide approximately the same heat flux to each of the 10 axial layers of heat pipes. This power tailoring, to within 5 percent, allows more uniform performance of the thermionic diodes. About 860 diodes convert the thermal output power of 1.74 megawatts to an electric power output of about 130 kilowatts electric, an overall efficiency of 7.5 percent. A comparison is made with systems fueled with uranium-235 nitride ($U^{235}N$) and plutonium-239 nitride ($Pu^{239}N$). Using $U^{235}N$ fuel the reactor is physically larger than the $U^{233}N$ reactor, but the electric power output is also greater (300 kW electric). Use of $Pu^{239}N$ would permit a reactor of about the same physical size as the $U^{233}N$ reactor. The reactor (with either $U^{233}N$ or $Pu^{239}N$) for this out-of-pile concept can be considerably smaller than a reactor which uses in-pile diodes to provide the same electrical output.

## INTRODUCTION

System studies, such as in reference 1, have shown that above a power level of 100 kilowatts electric, a nuclear reactor is the most promising heat source for space power. Several systems to convert the thermal energy of a nuclear reactor to electrical energy while operating in the space environment are currently being examined. However, none of these conversion systems (gas Brayton cycle, liquid metal Rankine cycle, or in-pile thermionic diodes) demonstrates outstanding performance.

This work deals with a thermionic system, but one which has the thermionic diodes outside rather than inside the reactor core. Outside the reactor core the radiation environment is not so harsh and thus the nuclear degradation of the diodes is less than if they were inside the core. The feasibility and potential performance of out-of-pile thermionic diodes is particularly promising when considered in conjunction with the heat pipe, an efficient and simple method of high heat transference. Furthermore, the almost isothermal heat-transfer property of the heat pipe allows the out-of-pile diode emitters to be at about the same temperature as the emitters of in-pile diodes.

Two out-of-pile thermionic space power concepts (refs. 2 and 3), each cooled by heat pipes, have been previously described. Reference 2 describes a concept which uses 120 heat pipes to provide a power output of 36 kilowatts electric. The design in reference 3 is more ambitious in that it would supply 10 megawatts electric, but it also requires a corresponding increase to several thousand heat pipes.

This difference in reactor power levels reflects the wide range of electrical power levels that will be required for the variety of future space missions. In particular, power in the 100 kilowatts electric range will be required for such specific missions as: a satellite in synchronous orbit used for direct broadcast to individual homes, 20 to 40 man orbital space stations, a modest lunar base, and propulsive power for unmanned deep space probes.

The present work examines a thermionic heat pipe space power source similar to that in reference 2. However, this current concept uses a more conventional reactivity control system (absorber rods) and has a higher power output. The emphasis of this study is on the neutronic aspects and general feasibility of the system; thus, the scope is such that there is only a cursory assessment of nonneutronic aspects.

## DESCRIPTION OF THERMIONIC SPACE POWER SYSTEM

The components of a thermionic power system may be categorized into a heat source and its control system, a thermionic conversion system, and cooling systems for the waste heat. The heat source for this power system is a nuclear reactor which is controlled by neutron absorbing control rods. The reactor is cooled by heat pipes which

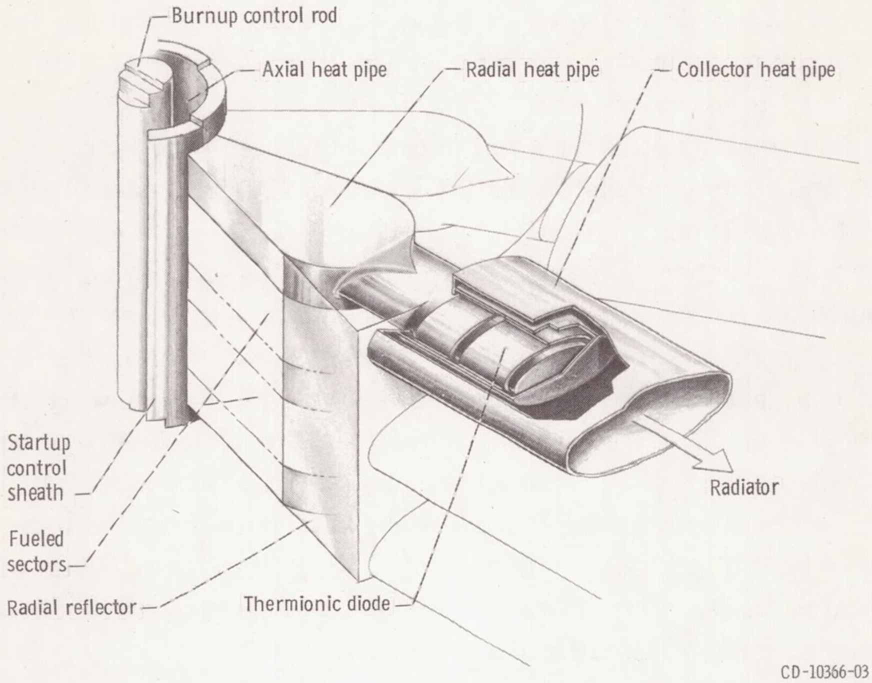



Figure 1. - Cutaway of thermionic space power system using heat pipes.

transfer the heat radially out of the core to the thermionic conversion system. Figure 1 is a cutaway view of the general reactor configuration. Upon emerging from the radial reflector, the heat pipes heat the emitters of the thermionic diodes. The collectors of the diodes are cooled by another set of heat pipes which lead to radiators. Following is a description of these components for this concept.

## Reactor

A cylindrical fast spectrum nuclear reactor is used as the heat source for this concept. Three fuels (uranium-233 nitride ($U^{233}N$), uranium-235 nitride ($U^{235}N$) and plutonium-239 nitride ($Pu^{239}N$)) were considered, and the comparative results are presented in appendix A. However, the concept presented herein is fueled by $U^{233}N$.

The $U^{235}N$ fuel required the largest critical mass which was about 2.5 times the critical mass of $U^{233}N$ or of $Pu^{239}N$. However, the design of this cylindrical reactor is such that the $U^{235}N$ reactor will supply 2.5 times the output thermal power of the $U^{233}N$ or the $Pu^{239}N$ reactor. The $Pu^{239}N$ proved to be a slightly better fuel, from a reactivity standpoint, than $U^{233}N$. But it should be a relatively simple matter to reduce the fuel volume fraction in order for the discussion to be valid for $Pu^{239}N$. The $U^{233}N$ annular reactor core has a length of 31.0 centimeters and a diameter of 23.5 centimeters not including the thickness of the axial and radial molybdenum reflectors. The reactor core consists of alternating fuel and heat pipe slabs or disks. The thickness of each of the fuel disks is limited by the power density and heat-transfer characteristics of the fuel since the centerline temperature must remain below the melting point of $U^{233}N$, 3120 K (ref. 4). The fuel is clad with 0.05 centimeter of tungsten (W). The reactor is reflected axially on each end by 10 centimeters of molybdenum (Mo) and radially by a 6-centimeter-thick annulus of molybdenum.

Each disk of fuel or heat pipes is composed of 24 units, each unit being a $15^{\circ}$ sector (fig. 1). It should be possible to fabricate, inspect, and test these pie-shaped sectors individually prior to putting them together in an assembly. Although it is not the purpose of this work to design a detailed fully compatible system, the following procedure is suggested. A cohesive unit could be formed from the alternating layers of heat pipe sectors and fuel sectors by brazing the layers and perhaps the sectors together. Although the large difference in temperature coefficient of expansion for tungsten (clad) and tantalum (heat pipe) would probably preclude their joint brazing, other materials may be considered. Tungsten and tantalum were chosen only as representative materials that would make the neutronic calculations conservative.

On assembly, each layer of fuel sectors would be oriented with respect to an adjacent heat pipe layer, so that each fuel surface would be cooled by two heat pipes (fig. 2). This staggered orientation would allow the heat load of a failed heat pipe to be carried by the two flanking heat pipes. With such a failure in mind each fuel sector contains some tungsten to improve the thermal conductivity of the fuel elements. By proper distribution of this tungsten into heat conduction paths within a fuel element it should be

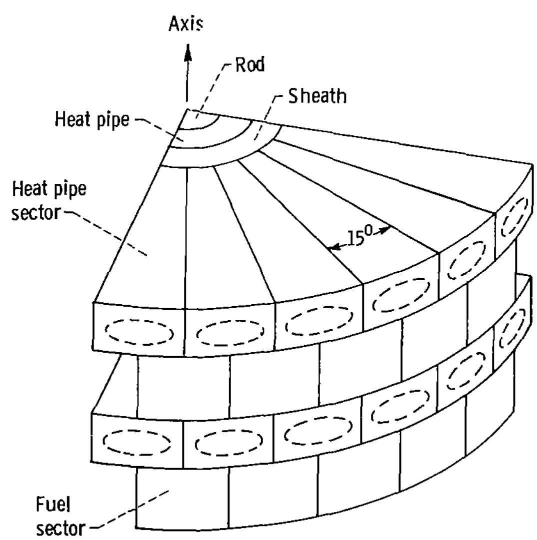



Figure 2. - Portion of one quadrant of reactor showing periphery of reactor core with radial reflector removed.

possible to prevent melting of the fuel except in the event of a failure of adjacent heat pipes.

Furthermore, each fuel sector contains some void volume to allow for fuel expansion and for venting the gaseous fission products. Venting would occur through an orifice to out-of-pile chambers which are radiantly cooled. Such a venting system is described in reference 2.

It is assumed that enough void is present in the central part of the fuel element to allow the fuel to redistribute itself, thus retarding the development of hot spots on the surface of the evaporator. The void zones which would separate each fuel sector into two pieces also contain nitrogen to provide the nitrogen overpressure required to prevent dissociation of the fuel. Reference 4 indicates that an overpressure of 2 to 3 atmospheres (20.3 to 30.4 $N/cm^2$) is sufficient to prevent dissociation.

There is a fuel fabrication method currently being investigated that would allow containment of the gaseous fission products and thus not require venting. The fuel is in the form of small spherical pellets which are coated with ceramic materials. The porosity of the fuel kernels may be regulated, and thus the pores in the fuel supply a void region which can collect and contain the gaseous fission products. This fabrication method has been used successfully for carbide and oxide fuels (ref. 5). Although the fabrication technique may differ, this general method should be applicable to the nitride fuels.

## Heat Pipes

The heat pipe is a simple, highly efficient device capable of transporting several hundred times the heat energy per unit weight as metals such as copper or silver (ref. 6). The almost isothermal operation of the heat pipe is particularly useful in a thermionic conversion system. For example, the thermionic diodes may be placed outside the reactor core in a less severe environment and still operate at about the in-pile diode emitter temperature.

Figure 3 is a schematic drawing of the heat pipe illustrating the basic features and operation. Within the closed shell of a heat pipe a liquid working fluid and some sort of capillary action pump (e.g., wire mesh, porous wick, or longitudinal grooves) comprise the heat-transfer loop. When heat is added to the evaporator end of the heat pipe, the liquid there is vaporized, causing the local pressure to increase. The vapor then flows through the pipe under the pressure gradient. At the colder end of the pipe the vapor condenses and the liquid is returned to the evaporator by capillary action of the wick material.

Heat pipes have been developed at Los Alamos Scientific Laboratory where tests were performed with various combinations of wick geometry and working fluids (ref. 7). Theoretical analysis of heat pipe operation may be found in references 8 and 9. The

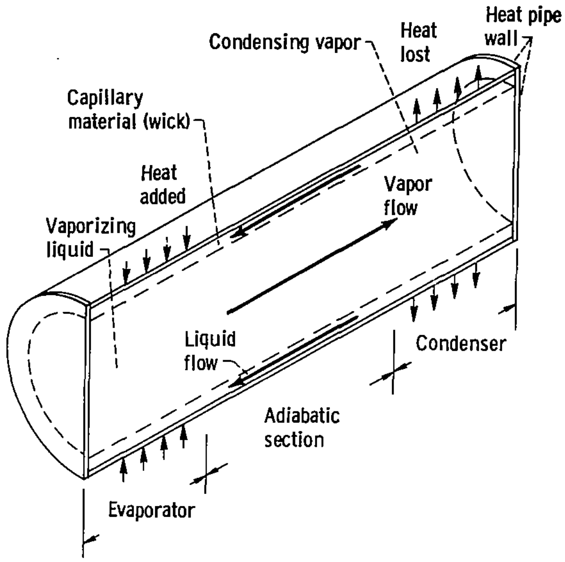



*Figure 3. - Schematic of heat pipe operation.*

TABLE I. - COMPARISON OF ELECTROMAGNETIC COOLANT LOOP WITH HEAT PIPES

| Electromagnetic pumped loop | Heat pipes |
|---|---|
| Fluid loop characteristics | |
| One or more pumps per loop; pressurizer and liquid-metal purifier required; system not permanently sealed; single leak in system catastrophic | No mechanical pumps - many permanently sealed individual loops; system designed so that a single leak can only affect one heat pipe loop |
| Heat transfer | |
| Fluid temperature across core inverse function of pumping power | Isothermal |
| Pumping characteristics | |
| Inefficient and require electricity; allowable magnet temperature limited to below Curie temperature | Use thermal energy directly |
| Afterheat removal | |
| Auxiliary power needed | Afterheat automatically radiated away without core meltdown |
| Restart | |
| Heaters for complete system required to remelt liquid metal | Should be able to restart without use of external heaters |

other conversion systems mentioned previously require electromagnetic pumping. A comparison of a potential heat pipe system with an electromagnetic pumped loop system is given in table I.

In this concept, the heat pipe wall material is tantalum, 0.05 centimeter thick. Tantalum was chosen because it appears to have about the same or greater neutron capture cross section than other refractory alloys. Thus, it represents a conservative assumption with regard to the neutronic properties of the reactor. The merit of a heat pipe working fluid is directly dependent on the boiling point and inversely dependent on the atomic weight of the fluid. Lithium-7, with a high boiling point of 1603 K and a low atomic weight, was chosen as the working fluid. This liquid metal possesses several other desirable characteristics including the highest latent heat of vaporization of all the liquid metals ($19.6\times10^6$ J/kg). Lead, which was used in the experiments of reference 10, could also be used as a working fluid.

Because the vapor density of lithium at ambient temperature is so low, the heat pipe must contain a noncondensable gas, such as helium, to provide for a startup mode (ref. 11). At startup with low heat flux the noncondensable gas will convect heat from the evaporator region to the colder end of the heat pipe. As the vapor pressure of lithium in the evaporator region increases (with temperature) helium is swept from the evaporator region into a zone at the colder end of the pipe. When the pressures in the lithium vapor and helium gas are equal, for example during heat pipe operation, a well-defined interface separates the now passive helium gas and the active lithium vapor.

The evaporator section of each heat pipe is a $15^{\circ}$, pie-shaped sector, about 8 centimeters long, within the core (fig. 1). The heat flux surfaces are those flat sectors in the radial plane which bound the heat pipe. The heat pipe has a rectangular cross section with internal thickness of 1.2 centimeters.

The curve in figure 4 with experimental data taken from references 7, 12, and 13 shows measured evaporator heat flux as a function of lithium-7 temperature. In the current concept, a heat-transfer rate of 250 watts per square centimeter into the evaporator section through the heat pipe wall (at a lithium temperature of 1770 K) is used. Although the heat flux at 1770 K can be larger, the value (250 $W/cm^2$) is considered an average resulting from the radial power variation.

The amount of heat transferred along a heat pipe depends on the cross-sectional area of the pipe. The limit on this heat density or flux axially along the heat pipe can arise from any of several phases of heat pipe operation. In particular, sonic vapor velocity, entrainment of liquid from the wick into the vapor stream, and vapor pressure drop in the evaporator, are the three principal limiting conditions. Using the equations and some of the data in reference 14 the heat density limits introduced by the three conditions mentioned are roughly 300, 50, and 100 kilowatts per square centimeter, respectively. Exceeding the lowest limit could result in burnout of the heat pipe with its associated

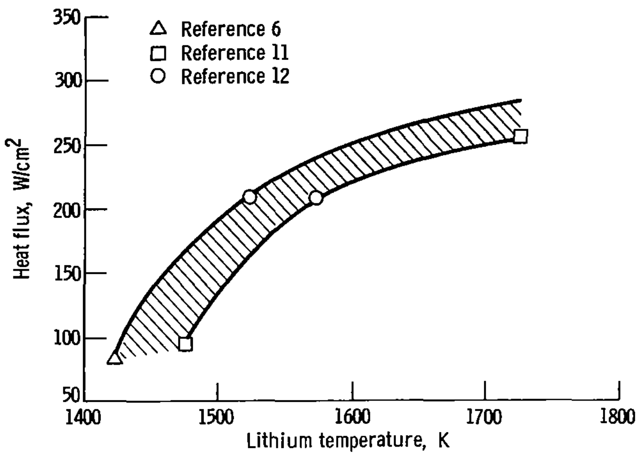



Figure 4. - Measured evaporator heat fluxes in lithium heat pipes. Band allows for dissimilarities in experimental configurations.

failure as a heat-transfer unit. These limits assume the use of lithium (at about 1770 K) as the working fluid.

The emitter heat pipe wedges may have to be rounded at the outer end (periphery of the core) to provide proper vapor and fluid flow within the pipe. Most heat pipes constructed to date have been straight uniform cylinders. However, this proposed heat pipe geometry has some precedence in that heat pipes with rectangular cross sections have been built and designs which bend are being considered. During its passage through and outside the radial reflector, the emitter heat pipe becomes an elliptical cylinder and is assumed to operate adiabatically within the reflector. This adiabatic condition may be approached by surrounding the portion of a heat pipe that is within the radial reflector with a heat insulator, such as alumina ($Al_2O_3$).

The choice of an elliptical rather than a circular cross section is made for two principal reasons. Because each heat pipe, radially outside the reflector, will be surrounded by diodes, a larger perimeter permits the length of heat pipe surrounded by diodes to be shorter, providing a more compact reactor assembly. Furthermore, an ellipse would join more smoothly to the heat pipe sector in the core, an important feature because the heat pipe working fluid must flow across the joint.

Within the reflector the elliptical cross section of the heat pipe (fig. 5) maintains a minor axis which is about equal to the sector thickness (1.2 cm). The length of the major axis may approach the peripheral arc length of the sector, which for a $15^{\circ}$ sector of a radius of about 12 centimeters is about 3 centimeters. With these particular dimensions the heat density in the heat pipe is about 7 kilowatts per square centimeter, well below the smallest calculated limit of 50 kilowatts per square centimeter.

The restriction of the minor axis to the sector thickness limits the amount of unreflected fuel surface; that is, the fuel surface that would allow neutron streaming di-

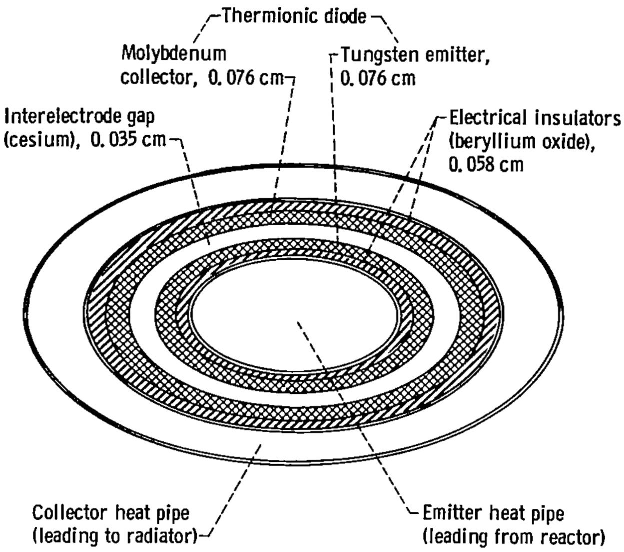



Figure 5. - Cross section of thermionic diode - heat pipe configuration (not to scale).

rectly out of the reactor core. However, once outside the radial reflector, the heat pipes, surrounded concentrically by thermionic diodes, may have a larger cross section.

Each radial heat pipe leading from the reactor must have an inactive zone, beyond the condenser (or diode emitter) region, to provide storage for the gas used in startup but not now participating in the heat-transfer cycle (ref. 11).

The collectors of the diodes are cooled by a separate set of annular heat pipes which lead to radiators. The experiments of Kemme (ref. 7) showed that, because the vapor pressure of lithium is relatively low, a lithium heat pipe would not operate properly below 1070 K. Therefore, since the collector is at about 1000 K, a different working fluid such as cesium will be needed for the collector heat pipes. Also, because of the lower temperature, a heat pipe material such as niobium may be used. Some weight savings would be realized since niobium is about half as dense as tantalum.

## Thermionic Diodes

The thermionic power concept described in this report uses a cylindrical configuration for the diodes. In figure 5, a schematic cross section of the concentric diode - heat pipe configuration is shown. Outside the radial reflector annular tungsten emitters of the out-of-pile diodes encircle each heat pipe but are electrically insulated from it. The annular molybdenum collectors, arranged concentrically around the emitters, are cooled by another heat pipe which extends to a radiator.

A major problem in this or any diode configuration is to allow the emitter to be at a high temperature and simultaneously be electrically insulated from the emitter heat pipe. At present there appear to be few materials which have sufficiently high thermal conductivity and sufficiently low long-term electrical conductivity at the temperature concerned (1770 K).

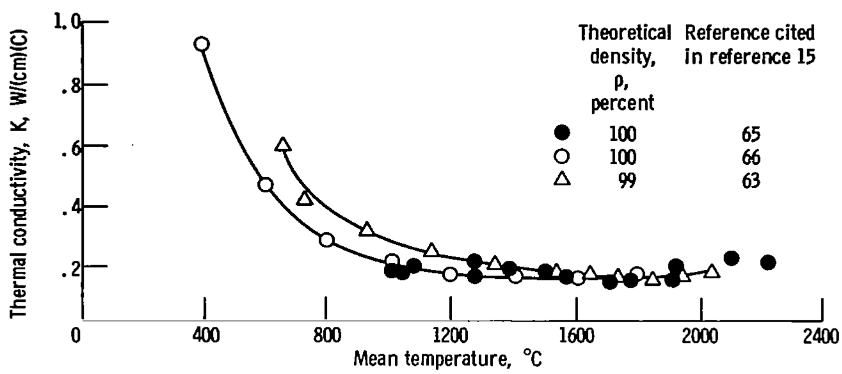
One such material, beryllium oxide (BeO), does have acceptable properties that would permit its use as an insulator between the emitter heat pipe and the emitter (ref. 15). The thermal and electrical conductivity of BeO as a function of temperature are shown in figures 6(a) and (b). These figures are reproduced directly from figures 7 and 20 of reference 15. Another promising insulator consists of small niobium pellets about 50 microns (0.005 cm) in diameter coated with alumina ($Al_2O_3$) and isostatically hot pressed into a cermet (ref. 16). Tests indicate this cermet has thermal conductivity about 60 percent of that for solid niobium, structural integrity to 1700 K, and high electrical resistivity. However, because the beryllium oxide presently seems to have a slightly higher temperature capability it is BeO that is chosen for the current design.

In the proposed concept, the tungsten emitter 0.076 centimeter thick is expected to receive a heat flux of 45 watts per square centimeter at 1757 K. The use of a BeO insulating sheath 0.058 centimeter thick results in the temperature drop (13 K) across the sheath. This drop assumes a thermal conductivity of 0.2 watt per centimeter per K for BeO at 1770 K (fig. 6(a)). The emitter-collector gap (0.035 cm) is filled with cesium at a reservoir temperature of 600 K. The 0.076-centimeter-thick collector is assumed to operate at about 1000 K.

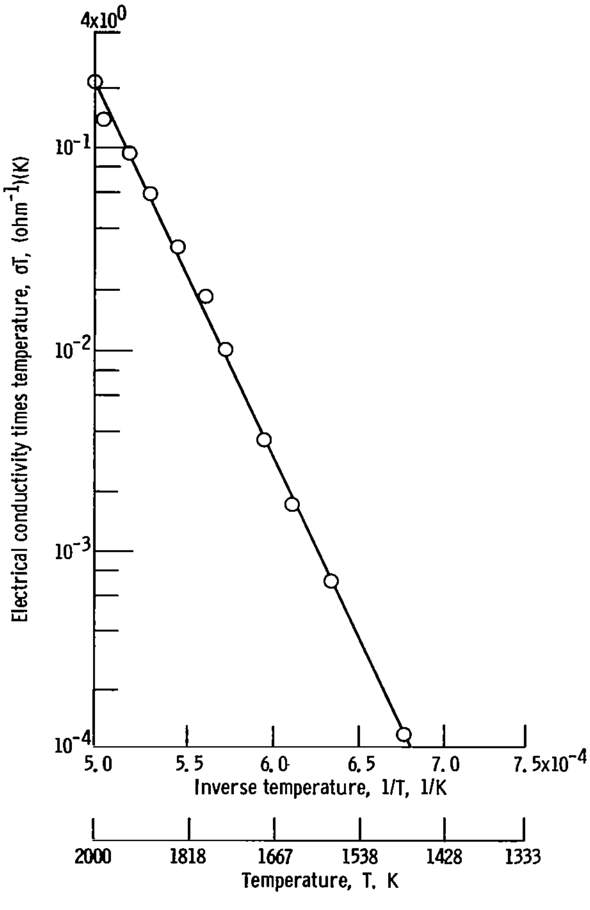
Using the data provided in reference 10 for similar diode operating conditions, an output of 0.5 volt at a current density of 10 amperes per square centimeter of emitter is obtained with a diode efficiency of 11 percent. To provide reliability for the power system it would be desirable to arrange the diodes in some sort of series-parallel circuit. In the region where the diodes are mounted there is room (azimuthally) to place the electrical leads, perhaps from several diodes on each heat pipe.

A prototype diode with its emitter heated by a heat pipe and its collector cooled by a heat pipe has been operated (ref. 10). For this prototype, the tungsten emitter was vapor plated on the outside of a cylindrical tantalum heat pipe. The emitter area was 17.5 square centimeters, and the emitter-collector gap was 0.035 centimeter. The molybdenum collector was sintered to a niobium-zirconium heat pipe. Working fluids of lead and cesium were used, respectively, for the emitter and collector heat pipes. Two alternative diode configurations for this concept are presented in appendix B.

A particular problem for this heat pipe - thermionic diode system could be material compatability at the high temperatures involved (1770 K). In this regard one might consider an all molybdenum thermionic power system comprised of molybdenum (Mo) heat pipes, Mo-$Al_2O_3$-Mo trilayer insulator, and a Mo emitter and collector. A thermionic converter comprised of a Mo emitter and collector has been investigated by RCA (ref. 17).




(a) Thermal conductivity, taken from reference 65 of Simnad, Meyer, and Zumwalt (ref. 15).




(b) Electrical conductivity, taken from reference 70 of Simnad, Meyer, and Zumwalt (ref. 15). Air pressure, 1 atmosphere; BeO oriented along C-axis.

Figure 6. - Thermal and electrical conductivity as a function of temperature for BeO.

## Reactivity Control System

A reactivity control system of the in-pile poison control rod type is examined, in contrast to the moderator-inert gas-thermal absorber arrangement in reference 2. The control mechanism used in the current version of the concept consists of a central rod and a concentric tubular sheath of boron-10 carbide along the cylindrical axis of the reactor. Although boron-10 is primarily known as a thermal absorber, its neutron absorption cross section remains sufficiently high in the keV and MeV regions to enable its use as a fast spectrum reactor control poison. Because of its structural properties boron-10 carbide would have to be canned. The rod and sheath of boron-10 carbide are separated and cooled by a concentric annular heat pipe running the length of the core. The control absorbers may be separately withdrawn to provide two stages of control. The annular heat pipe would not be withdrawn with the outer sheath but would remain in place in the reactor. When the outer sheath is withdrawn, either it or an auxiliary control sheath poised at the opposite end of the reactor may be used as a safety rod. The sheath provides sufficient reactivity control for startup, including the temperature defect. The rod provides for burnup and fine control. A plan view of this control region is shown in figure 7. A radiator for this axial heat pipe must be provided at the end of the reactor, and it may be in the conical form described by Salmi (ref. 18).

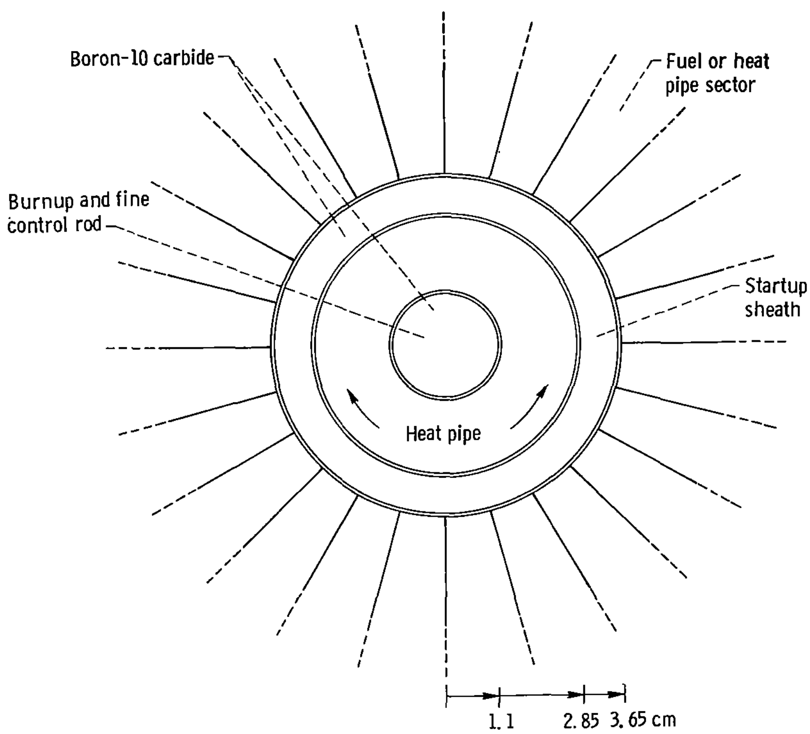



Figure 7. - Plan view of central control region.

# CHARACTERISTICS OF CONCEPT

The calculations performed in this study used the standard computer techniques. The specific computer programs and approximations used are discussed in appendix C.

A symmetric section of the cylindrical reactor is shown in figure 8. The dimensions of the configuration are indicated, and the numbered materials correspond to the composition indicated in table II. The results and performance characteristics of this power concept are now presented in several categories.

## Reactivity Control

The total reactivity control available from the two control absorbers with the dimensions indicated in figure 8 is about 6 percent. The outer sheath (with inner and outer radii of 2.85 and 3.65 cm) provides a reactivity change of about 5 percent for startup.

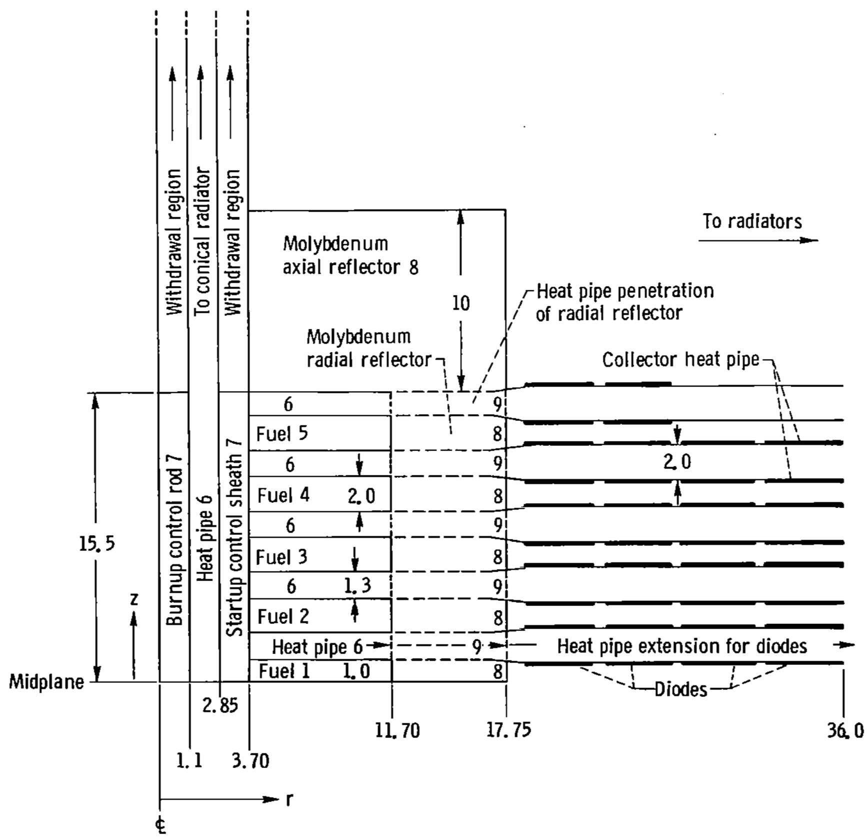



Figure 8. - Reactor configuration including r-z geometry used for two-dimensional calculations. Material numbers refer to compositions listed in table II. Dimensions are in centimeters.

TABLE II. - COMPOSITION OF REACTOR MATERIALS

| Component[a, b] | Composition | Nuclide | Nuclear density, atom/(b)(m) |
|---|---|---|---|
| Fuel 1 | 0.547 $U^{233}N$ | $\{N, U^{233}\}$ | [c]1.908 |
| | .189 Void | ---------- | ------- |
| | .264 W | W | 1.668 |
| Fuel 2 | 0.556 $U^{233}N$ | $\{N, U^{233}\}$ | 1.668 |
| | .188 Void | ---------- | ------- |
| | .256 W | W | 1.618 |
| Fuel 3 | 0.575 $U^{233}N$ | $\{N, U^{233}\}$ | 2.007 |
| | .184 Void | ---------- | ------- |
| | .241 W | W | 1.523 |
| Fuel 4 | 0.631 $U^{233}N$ | $\{N, U^{233}\}$ | 2.204 |
| | .173 Void | ---------- | ------- |
| | .196 W | W | 1.239 |
| Fuel 5 | 0.723 $U^{233}N$ | $\{N, U^{233}\}$ | 2.533 |
| | .156 Void | ---------- | ------- |
| | .121 W | W | .7647 |
| Heat pipe 6 | 0.077 Ta | Natural Ta | 0.4253 |
| | .923 Void | ---------- | ------- |
| Control absorber 7 | [d]$B_4^{10}C$ | $B^{10}$ | 11.64 |
| | | C | 2.91 |
| Axial radial reflector 8 | Mo | Natural Mo | 6.4 |
| Homogenized radial reflector and heat pipe 9 | 0.551 Mo | Natural Mo | 3.526 |
| | .449 Void | ---------- | ------- |

[a]Lithium-7 in heat pipe was neglected.
[b]See fig. 8 for number assignment.
[c]Nuclear density: $U^{233}N$, 3.49; $U^{235}N$, 3.49; $Pu^{239}N$, 3.39.
[d]Boron carbide was assumed to contain 100 percent $B^{10}$.

This is sufficient to bring the reactor from a 2 or 3 percent subcritical state to a hot critical (operating) condition, assuming a temperature defect of 1 to 2 percent reactivity. The inner rod of boron-10 carbide with radius of 1.1 centimeter provides about 1.1 percent reactivity for burnup and fine control of the reactor.

Assuming a 2.2-MeV energy release for each (n, $\alpha$) reaction in boron-10 and a gamma heat deposition rate not greater than 10 watts per gram, the single annular heat pipe is sufficient to cool an inner rod of boron-10 carbide as well as an outer sheath. The maximum heat density in the annular heat pipe would be 0.75 kilowatt per square centimeter. The outer sheath, which is cooled by the annular heat pipe, would not exceed the temperature of the fuel when the sheath is inserted at full reactor power.

Variation of the thickness of the inner and outer sheaths can yield different burnup and startup reactivity margins. In fact, up to 9 percent reactivity can be controlled by this central region. For this maximum control condition the heat pipe would have inner and outer radii of 2.5 and 2.85 centimeters, and the heat density would be about 5 kilowatts per square centimeter.

## Power Tailoring

To achieve uniform thermionic diode operation, each axial layer of diodes should be operated at approximately the same temperature. To perform axial power tailoring, the fuel loading is varied for the fuel disks in order to provide about the same heat flux to each of the 10 axial layers of heat pipes. The effect of radial power variation is nearly eliminated because the heat pipes integrate the heat input over their length.

The heat flux across each heat pipe surface adjacent to a fuel surface is 250 watts per square centimeter at a fuel - heat pipe interface temperature of 1770 K. The highest fuel temperature occurs in the central slabs, where the power peaks occur at the midplane of the fuel slabs. The maximum temperature there is 2250 K, well below the melting point of the $U^{233}N$ (3120 K). The temperatures were determined using the thermal conductivity of $U^{233}N$ (0.26 W/(cm)(K) at 1270 K) from reference 4. Figure 9 shows the axial power profile, with the radial dependence removed, for the unzoned and zoned core. The composition of the fuel disks is given in table II.

The axial power profile at the interior and exterior radii of the zoned core fuel annulus is shown in figure 10. The profiles are qualitatively the same but with the interior profile at a level about 1.1 and the exterior profile at a level about 0.83 times the average power in the core.

With the control sheath withdrawn, simulating the reactor in operation, the axial power profile was obtained for various stages of rod withdrawal. No depletion studies were performed; an undepleted core is assumed at all stages of withdrawal. The axial

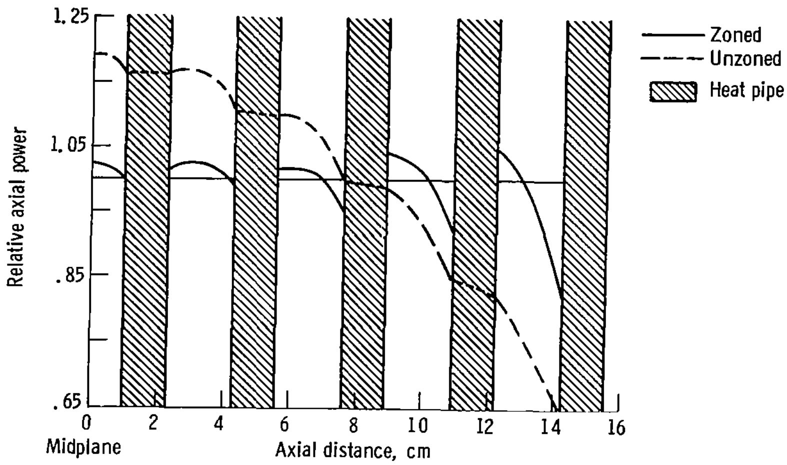



Figure 9. - Axial power profiles for zoned and unzoned configurations. Unzoned concentration is same as zoned concentration in outer slab.

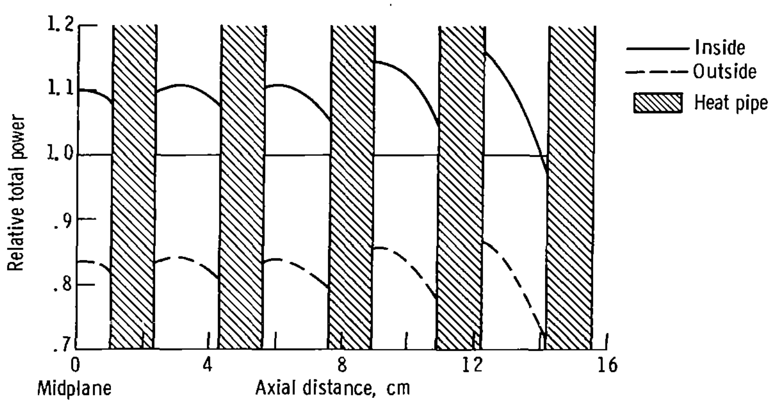



Figure 10. - Axial power profile at interior and exterior radius of fuel annulus. Reactor is axially zoned.

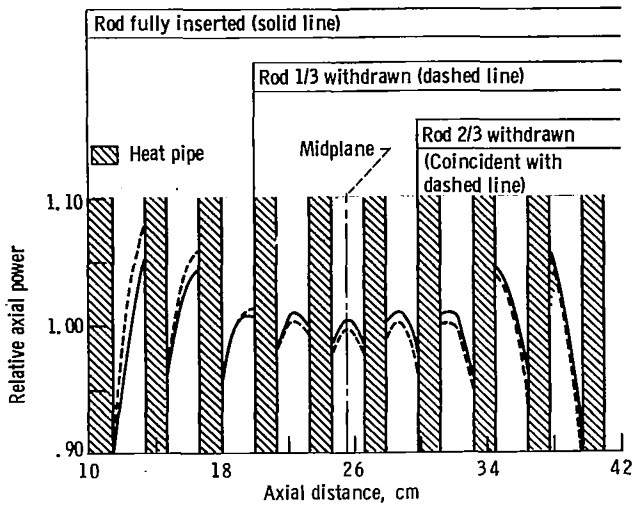



Figure 11. - Axial power profile for various stages of rod withdrawal.

power profiles (radially averaged) for several stages (full, two-third, and one-third insertions) are shown in figure 11. The figure indicates the rod has little perturbing effect on axial power profile. In particular, with the rod withdrawn one-third, the largest power increase in any slab was 2 percent. With the rod withdrawn two-thirds, the profile was essentially the same as for the one-third withdrawn case.

## Heat Pipe Geometry

At a heat flux of 250 watts per square centimeter, the total power deposited into each $15^{\circ}$ sector heat pipe is 8.06 kilowatts. Using an elliptical cross section (fig. 5), with a minor axis of 1.2 centimeters and a major axis of 2.4 centimeters, the heat density in the heat pipe is about 3.6 kilowatts per square centimeter. These dimensions also hold the neutron leakage to an acceptable level.

While external dimensions of 1.3 and 2.5 centimeters for an elliptical cross section are satisfactory for passage through the radial reflector, they are not entirely suitable for a diode mount. It is desirable to make the reactor assembly as compact as possible, and, consequently, the length of the radial extension needed for diode mounting is of concern. Assuming a diode heat flux of 45 watts per square centimeter, each heat pipe needs 179 square centimeters of diode area, and thus the minimum radial extension for diode mounting would be 29 centimeters beyond the radial reflector. Therefore, outside the radial reflector the elliptical cross section is flared out to dimensions of 2.0 and 4.0 centimeters. This provides a larger perimeter for diode mounting (about 9.9 cm), and the diodes thus require an extension of only 18 centimeters.

Since the $15^{o}$ sector was chosen arbitrarily, a $10^{o}$ sector was examined for comparison. If $10^{o}$-sector heat pipes were used, with elliptical dimensions of 2.0 and 2.4 centimeters, the radial extension needed for a diode area of 119 square centimeters would be 17 centimeters. Thus, for a small attendant reduction in radiator and shield weight resulting from their smaller effective radial distance, the use of $10^{o}$, rather than $15^{o}$, sectors would require 50 percent more heat pipes. A larger sector (>$15^{o}$) would depart even more radically from the current uniform-cross-section heat pipes and thus was not investigated.

## Electrical System Output

Each fully heated $15^{o}$ heat pipe requires a total diode area of about 180 square centimeters, and we assume four diodes of 45 square centimeters each are used. Because the heat pipes on each axial end of the reactor receive heat from only one side, only two diodes (90 $cm^2$) will be needed per heat pipe on these levels. Thus, although there are 240 sector heat pipes in the reactor, there are only 216 equivalent full power heat pipes. The total output thermal power from this reactor is 1.74 megawatts.

The diodes on each heat pipe will be electrically insulated and will be joined in a series-parallel circuit with diodes on the other heat pipes. Calculations indicate that a beryllium oxide sheath, 0.058-centimeter thick, could hold the average electrical leakage to 5 percent (current loss) with a voltage of about 50 volts across the diodes. To achieve this 50-volt output, assuming the output voltage and current of each diode are 0.5 volt and 450 amperes, it is necessary to form eight parallel circuits from the 864 diodes. The total system output is then 3600 amperes at 54 volts for 194 kilowatts electric, neglecting losses.

However, there are several losses which must be considered. The calculated electrical leakage of 5 percent is charged as a current loss (in the insulator) with an attendant 5 percent power loss. The series electrical leads are assumed to be optimized, a condition for which the power loss due to lead drop is generally about the same as the diode efficiency (11 percent). Also, each diode has an $I^2R$ power loss of about 16 percent in the tungsten emitter and molybdenum collector combination.

The three loss mechanisms considered constitute a 32 percent power loss. The net system output thus is 131 kilowatts electric at 38.3 volts and 3420 amperes with an overall efficiency of 7.5 percent.

## Radiators

A radiator configuration for this concept is shown in figure 12. In this design each

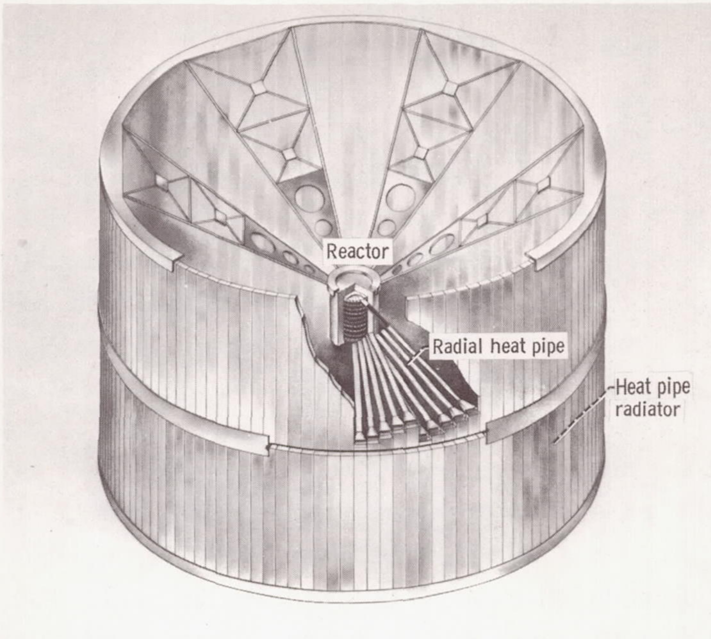



Figure 12. - Thermionic heat pipe space power system with vertical heat pipe radiators.

radial collector heat pipe would lead directly to a separate heat pipe oriented vertically, or at least nearly perpendicular to the radial heat pipe. The vertical or radiator pipe would be completely separate; the condenser end of the radial pipe would butt against the evaporator of the vertical pipe in a L-type joint. There would be 120 separate vertical radiators in a full circle on each side of the midplane of the reactor so that the overall array would resemble a barrel.

The radiator is assumed to have a combination emissivity-surface view factor of 0.77, and a sink temperature of 0 K is assumed for deep space. These assumptions permit an overall diameter of 4.0 meters, and a height of 4.0 meters for this configuration which would tend to be self-supporting. The dimensions of the barrel array would permit the entire configuration to be contained by some of the current launch vehicles (Saturn V or uprated Saturn I).

The cross-sectional width (effective arc length) of each heat pipe radiator would be about 10 centimeters. The annular thickness or cross-sectional height of the radiators would have to be about 5 centimeters in order to accommodate the heat load.

Some further variation on the cylindrical barrel radiator array, such as an hourglass arrangement in which the overall array resembles two opposed truncated cones, might be desirable. Such a configuration would radiate less heat back to the reactor than the barrel array and thus would tend to remove the need for special wicking geometry in order to ensure radiation of heat away from the reactor.

However, it should be noted that the proposed power system does not depend on the niobium heat pipe barrel array explicitly discussed herein. A heat exchanger and standard radiator array could also serve.

## Shielding

There are two types of reactor shielding to be considered: shadow and full ($4\pi$) shields. From a neutron shielding standpoint a shadow shield might be sufficient. However, although the use of a molybdenum reflector somewhat attenuates the primary gamma radiation, the secondary gamma flux from the heat pipe extensions and the radiator might require further shielding at the payload. Thus, feasibility of a shadow shield will probably depend on the mission.

A full ($4\pi$) shield also presents a problem: there are 240 heat pipes protruding radially from the reflector, and the shield must be placed between the reactor and the radiator. One possible $4\pi$ shielded configuration is shown in figure 13. The 10 layers of heat pipe sectors are oriented so that the heat pipe extensions are vertically alined or stacked when leaving the reflector. This allows shield sections to be wedged between the stacks of heat pipe extensions. Once radially outside the shield each heat pipe would then take a separate path to its own radiator pipe in the barrel array. The radiators for the 120 heat pipes on each side of the midplane of the reactor form a complete barrel array.

Furthermore, it may be necessary to make the heat pipes curve in order not to provide a streaming path for neutrons out through the shield. The amount of curvature will

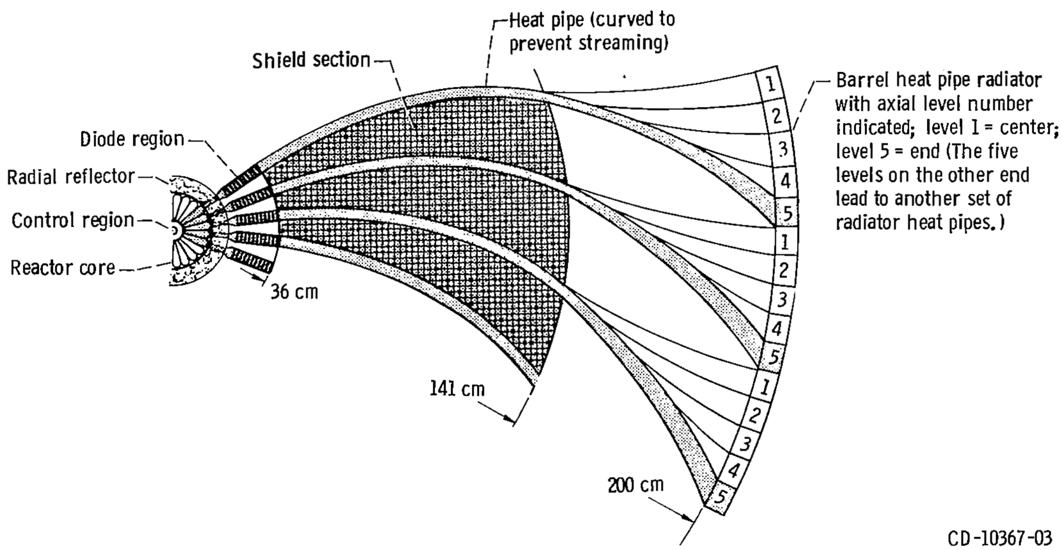



Figure 13. - Top view of reactor power system showing heat removal system. Heat pipes from 10 levels are stacked vertically to simplify shielding configuration.

be determined by scattering characteristics of the heat pipe walls and the operational characteristics of the heat pipe.

A particular advantage of this shield array lies in the curved shield wedges which may run the length of the reactor. These shield sections can be simply inserted between the heat pipe stacks and can be subsequently fastened to the two end shields thus providing considerable structural support. These heat pipes could also cool the shield and thus eliminate the need for a secondary cooling loop.

Reference 19 describes a composite man-rated shield composed of lithium-6 hydride and tungsten. The reference determines that such a shield for a cylindrical reactor and reflector of about the same dimensions as the present concept would weigh roughly 20 000 kilograms.

## Comparison to In-Pile Diodes

In this radial pancake concept, it would be possible to put planar diodes in the core. For this reason, an alternative configuration using planar in-pile thermionic diodes might be considered. In fact, with present methods of in-pile diode construction the in-pile diodes can operate about 300 K hotter, hence more efficiently, than this proposed out-of-pile concept.

In this out-of-pile concept the insulator must be at approximately the same temperature as the emitter, whereas the in-pile configuration allows the insulator to be at a much lower temperature than the emitter. Figure 6(b) shows the penalty in electrical conductivity of a BeO insulator resulting from an increase in operating temperature.

However, a practical limitation exists for thermionic diodes in that their efficiency drops sharply above an input heat flux of 80 to 100 watts per square centimeter. Reference 20 describes an in-pile thermionic conversion system which assumes a representative heat flux of 77 watts per square centimeter. Since the in-pile emitter is limited to 100 watts per square centimeter and the emitter area is about the same as the fuel area, the heat extracted from the fuel is also limited to 100 watts per square centimeter. This contrasts sharply with the 250 to 300 watts per square centimeter heat flux that a Ta-Li heat pipe could accept with the diodes in the out-of-pile configuration. Thus, in order to supply the same electric power with in-pile diodes at the same diode efficiency as the out-of-pile diodes, the core size would have to increase to provide more diode area. If the emitter temperature were increased to permit more efficient operation of the in-pile diodes, then the inclusion of diodes in-pile would decrease the fuel volume fraction and still impose a size penalty for this criticality limited reactor.

Furthermore, with the diodes placed out-of-pile several additional advantages may be realized. For example, (1) the fuel may be able to reach a higher burnup since its swelling is not restricted by the diode emitter-collector gap (of course, the externally fueled in-pile diode concept in ref. 20 is not restricted either); (2) the fast neutron damage to diode insulators should be an order of magnitude less than for an in-pile concept; (3) preliminary testing of each heat pipe and its diodes before assembly may be possible; and (4) each heat pipe allows the integration of heat input over its length and this would allow the out-of-pile diodes to perform more nearly at a common temperature and, hence, near their maximum efficiency.

From a neutron shielding standpoint the penalty in reactor core size incurred by use of the in-pile concept would tend to make the overall weight of a shadow-shielded in-pile assembly greater than for an equivalent out-of-pile assembly. It is not clear what the relative weights of the two assemblies would be when considering total neutron and gamma shielding or in the case of $4\pi$ shielding, since the protrusion of heat pipes through the shield does complicate matters.

## CONCLUDING REMARKS

A summary of reactor, heat pipe, and thermionic diode operating conditions is presented in table III. This shows that a cylindrical fast reactor, using $U^{233}N$ fuel, which is only 23.4 centimeters in diameter and 31.0 centimeters long can produce about 120 kilowatts of electricity at a potential of about 38 volts. Plutonium-239 nitride is found to be a slightly better fuel, from a neutronics standpoint, than $U^{233}N$. On the other hand the use of $U^{235}N$, which requires about 2.5 times as much fuel as the $U^{233}N$ reactor, would provide about 300 kilowatts of electricity. The volume fractions and estimated weights of various materials comprising the power system are listed in table IV. The calculated total weight of the materials for the reactor, the diodes, and the radiator is about 830 kilograms excluding any shielding. A man-rated shield would weigh about 20 000 kilograms.

In order to allow more uniform heat flux to the thermionic diodes, the axial power distribution is tailored, by nonuniform distribution of fuel, to within 5 percent. A boron-10 carbide central control rod and concentric sheath provide respective reactivity changes of about 1.1 percent for burnup and fine control and about 5 percent for startup. However, by increasing the volume fraction of boron-10 carbide in the central region to its maximum, subject to the axial heat pipe requirements, a total of 9 percent reactivity control could be provided. The maximum control (with the same absorber dimensions) available for the $U^{235}N$ reactor is 6.5 percent.

It appears that the heat pipe will be able to carry away about 300 watts of heat from every square centimeter of in-pile heat-transfer surface, which is about the same as the practical heat flux limit on forced convection liquid-metal system. Furthermore, the heat pipe can distribute this heat flux over a much larger heat-transfer surface external to the reactor. This is important since it seems that the thermionic diode, even

TABLE III. - SUMMARY OF OPERATING CHARACTERISTICS

OF POWER SYSTEM

| | |
|---|---|
| Reactor: | |
| Fuel volume fraction | 0.334 |
| Number of fuel layers | 9 |
| Length including 20 cm of axial reflector, m | 0.51 |
| Diameter including 12 cm of radial reflector, m | 0.355 |
| Diameter and height of barrel radiator, m | 4.0 |
| Maximum fuel temperature, K | 2250 |
| Fuel clad temperature, K | 1770 |
| Total thermal power, MW | 1.74 |
| Power density in full core, $W/cm^3$ | 130 |
| Heat pipes: | |
| Number of sectors per axial level | 24 |
| Heat flux into heat pipe, $W/cm^2$ | 250 |
| Total heat per sector at full power, kW | 8.06 |
| Total heat per layer, kW | 193.5 |
| Maximum heat density (in radial reflector), $kW/cm^2$ | 3.56 |
| Radial extension for diodes, m | 0.18 |
| Total number of heat pipes at full power | 192 |
| Total number of heat pipes at half power (layer at ends of core) | 48 |
| Thermionic diodes: | |
| Number of emitters per full power heat pipe | 4 |
| Total number of diodes | 864 |
| Temperature of emitter, K | 1757 |
| Temperature of collector, K | 1000 |
| Emitter and collector thickness, cm | 0.076 |
| Emitter area per diode, $cm^2$ | 45 |
| Current density, $A/cm^2$ | 10 |
| Emitter perimeter, cm | 10 |
| Emitter length, cm | 4.5 |
| Heat flux at diode, $W/cm^2$ | 45 |
| Emitter electrical power density, $W/cm^2$ | 5 |
| Diode efficiency, percent | 11 |
| Electrical power per diode, W | 225 |
| Output diode voltage, V | 0.5 |
| System output: | |
| Total voltage, V | 54 |
| Total output current, A | 3600 |
| Total power output, kW | 194.4 |
| Power lost through leakage, 5 percent, kW | 9.72 |
| Power lost through leads, 11 percent, kW | 21.4 |
| Power lost through $I^2R$ drop, ~16 percent, kW | 32.0 |
| Net output power, kW | 131 |
| Current loss through leakage, 5 percent, A | 180 |
| Net output current, A | 3420 |
| Net output potential, V | 38.3 |
| Overall efficiency, percent | 7.5 |

TABLE IV. - ESTIMATED WEIGHTS OF SYSTEM COMPONENTS

| Component | Material | Volume, $cm^3$ | Weight, kg |
|---|---|---|---|
| Fuel | Uranium-233 nitride | 4 061 | 58.2 |
| | Tungsten | 1 544 | 29.8 |
| Heat pipe | Tantalum (in core) | 713 | 11.8 |
| | Tantalum (extension | 2 650 | 44.0 |
| | Lithium | 5 085 | 2.5 |
| Reflector | Molybdenum | 20 210 | 206.0 |
| Diode | Tungsten (emitter) | 2 950 | 57.0 |
| | Molybdenum (collector) | 2 950 | 30.1 |
| Radiator | Niobium | 46 000 | 387.0 |
| Control system | Boron-10 carbide | 1 167 | 2.9 |
| Reactor subtotal | | | 829 |
| Shield | Lithium-6 hydride, Tungsten | | 20 000 |
| Total | | | 20 829 |

at quite extreme temperatures, will be practically limited to a thermal power input less than 100 watts per square centimeter of emitter area. This limitation presents a considerable disadvantage for an in-pile thermionic concept because a nuclear reactor is capable of producing much higher heat fluxes. Thus, for the same output power, the out-of-pile thermionic reactor can be smaller and lighter than the equivalent in-pile assembly.

An added advantage is that the use of heat pipes extending outside the reactor core directly to radiators eliminates the need for a secondary liquid cooling loop for the shield.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, February 28, 1969,
120-27-06-18-22.

## APPENDIX A

## ALTERNATE FUELS

If uranium-235 nitride ($U^{235}N$) is used as the fuel (with the same volume fraction as for the $U^{233}N$ case) and only the reactor diameter is varied, the core diameter (not including 12 cm of annular reflector) must increase to about 36 centimeters in order to obtain a critical configuration. The volume of $U^{235}N$ needed is thus about 2.5 times the amount of $U^{233}N$ necessary. Since the axial geometry and length were not changed, the power output of the $U^{235}N$ core also increases by about 2.5 times over the $U^{233}N$ output. Thus, a $U^{235}N$ core would have a length of 31 centimeters and a diameter of 36 centimeters; it would supply a power output of 325 kilowatts electric and would require 145 kilograms of $U^{235}N$. By comparison, the $U^{233}N$ core has a length of 31 centimeters and a diameter of 23.4 centimeters; it can provide 130 kilowatts electric of electric power and would use 58 kilograms of $U^{233}N$. Of course, for the $U^{235}N$ core the size and weight of the diode arrays, radiators, and reflectors would be accordingly increased from the $U^{233}N$ case. Although the reactivity worth of the control absorbers is less for the $U^{235}N$ core than for the $U^{233}N$ core, a maximum total control of 6.5 percent is available for the $U^{235}N$ core.

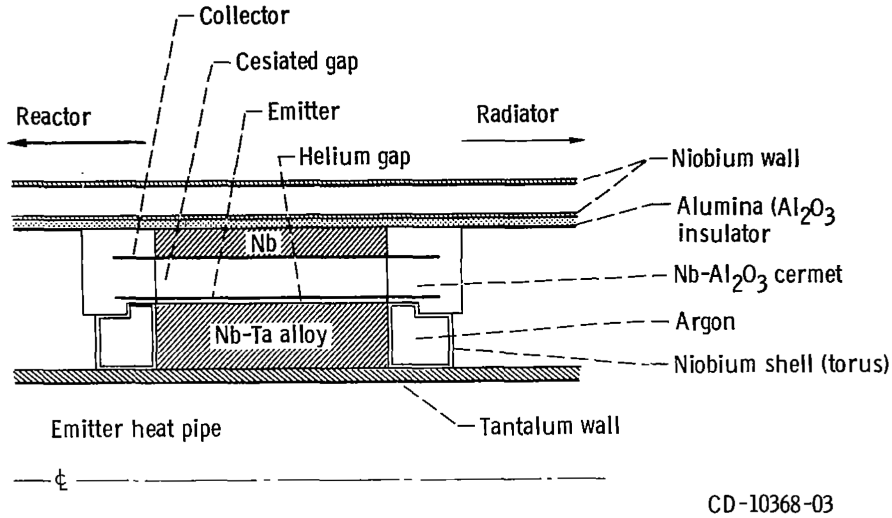
The use of plutonium nitride (composition in percent: 93.37 $Pu^{239}$, 6.0 $Pu^{240}$, 0.63 $Pu^{241}$) fuel at the same volume fraction results in a smaller core with diameter about 22.2 centimeters. The power output and fuel mass are roughly 90 percent of the $U^{233}N$ core. With a nitrogen overpressure of 1 atmosphere (10.13 $N/cm^2$), the melting points of $Pu^{239}N$ and UN are 2870 and 3120 K (compared to a maximum fuel temperature of 2250 K).

# APPENDIX B

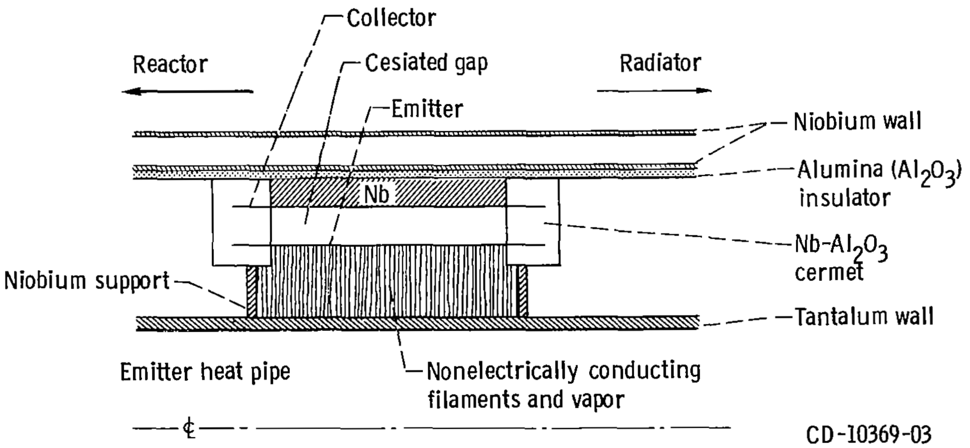
## ALTERNATIVE DIODE CONFIGURATIONS

In order to lessen the demand placed on the insulator when in a simple butting configuration with the heat pipe, two alternative diode configurations are described. The first approach is similar to in-pile diode designs which operate at higher temperatures. Figure 14(a) shows an argon-filled niobium shell which provides support and a substantial temperature drop between the emitter heat pipe and the insulator. The emitter itself is kept at a relatively high temperature by minimizing the necessary gas-filled insulating gap. If argon were used for the gas insulator, a gap of 0.025 centimeter would result in an intolerable temperature drop (>1000 K). Thus, one must consider helium as the insulator with a helium reservoir to replenish this easily lost gas. Even with helium, a temperature drop of about 250 K for a 0.025-centimeter gap must still be accepted. The highest temperature in the insulator will still be that of the emitter, but it will be localized to the relatively small area where the emitter is supported by the insulator.

Another approach (fig. 14(b)) would use a non-electrically-conducting heat pipe similar to that constructed by RCA (ref. 21), although differing considerably in geometry. The nonconducting heat pipe would convey heat from the emitter heat pipe to the emitter. However, the materials for the wicking (some sort of non-electrically-conducting filaments in the emitter - emitter heat pipe gap) and for the working fluid of the heat pipe would have to operate at temperatures around 1770 K, while still remaining sufficiently non-electrically-conductive. Furthermore, the wicking geometry, that is, the orientation of the filaments which would allow heat to be transported from a large area over very short distances, has not been established.




(a) Heat transfer to emitter by radiation.




(b) Heat transfer to emitter by nonelectrically conducting heat pipe.

Figure 14. - Electrically isolated out-of-pipe thermionic diode (not to scale).

# APPENDIX C

## METHOD OF CALCULATIONS

The composition of the materials and their homogenized atom densities are presented in table II. Several fuel slab compositions which are used in performing the axial zoning are shown in this table.

Cross sections for the calculations were obtained from the GAM-II multigroup compilation (ref. 22). Thirteen fast groups were used, the structure of which is shown in table V. Most of the spatial calculations were performed with 13 groups in one dimension in the $S_4 - P_0$ (transport corrected) approximation using the TDSN program (ref. 23). However, two-dimensional r-z calculations were made, using four groups, to provide normalization for the one-dimensional calculations and to determine power profile for control rod withdrawal stages. The two-dimensional geometry is very closely that shown in figure 8 and the reduced group structure used in indicated in table V.

TABLE V. - ENERGY GROUP STRUCTURE

GAM-II (FAST)

| Group | Low energy boundary[a] | Reduced group number |
|---|---|---|
| 1 | 3.6 MeV | 1 |
| 2 | 2.2 MeV | |
| 3 | 1.35 MeV | |
| 4 | 820 keV | |
| 5 | 498 keV | 2 |
| 6 | 302 keV | |
| 7 | 183 keV | |
| 8 | 111 keV | |
| 9 | 41 keV | |
| 10 | 15 keV | |
| 11 | 5531 eV | |
| 12 | 749 eV | 3 |
| 13 | 0.414 eV | 4 |

[a]Upper energy boundary of group 1 is 15 MeV.

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