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A REACTOR CONCEPT FOR SPACE POWER EMPLOYING THERMIONIC DIODES AND HEAT PIPES

by Colin A. Heath and Edward Lantz

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TECHNICAL PAPER proposed for presentation at Fifth Aerospace Sciences Meeting sponsored by the American Institute of Aeronautics and Astronautics

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Abstract

A thermionic generator power system using a reactor heat source connected to external diodes by heat pipes is investigated. A concept is proposed which appears capable of supplying up to several hundred kilowatts of electrical power. Experimental results from laboratory test of both heat pipes and thermionic diodes have been used to set reasonable performance levels for thermionic diodes which are both heated and cooled by heat pipes. A reactor fueled with slab geometry fuel elements of uranium-233 nitride could provide a minimum power of 36 kwe limited by criticality considerations. Reactor control is effected by a combination of moderator and neutron absorbing material in a central region of the reactor. Neutronic calculations indicate that a 6% swing in reactivity is obtainable with this control system. Total mass of the reactor, thermionic diodes, radiator and reactor shield for an instrumented payload is estimated to be 300 kg.

Introduction

A considerable amount of interest has been created recently in a device for the transfer of heat commonly known as a heat pipe (refs. 1 and 2). Such a device is illustrated in figure 1.

Figure 1 shows a sealed pipe which has been out gassed to vacuum for several hours and then filled with a small quantity of liquid metal. The pipe contains some type of capillary geometry close to the inside wall. This geometry may either be grooves scored lengthwise down the tube or a series of mesh screening that has been pressed against the inside wall (refs. 3 and 4).

When heat is added to the evaporator end of the heat pipe, it heats and vaporizes the liquid metal that is there and the local vapor pressure increases. Vapor then flows down the pipe under the pressure gradient to the cold end where it condenses. The liquid metal then returns to the evaporator due to the capillary pumping in the "wick" material.

The heat pipe operates with very little temperature change down its entire length while conducting large quantities of heat so that it has a very high value of effective thermal conductivity. It becomes possible then, for the high temperature at the fuel clad surface in a nuclear reactor to be transferred to a second surface placed outside the reactor core.

This feature immediately offers promise for use with thermionic diodes. It may now be possible to obtain a diode emitter surface with a temperature close to the temperature of the fuel clad while being placed outside the core.

Then, since the heat pipe is essentially an isothermal heat transfer device, it may be possible to operate many thermionic diode emitters at the same temperature even though the power density generated throughout the reactor is not constant. This should alleviate the amount of power tailoring that needs to be done in the reactor.

Also, if we can place the thermionic diodes outside the reactor core we no longer need be concerned about fuel swelling causing the diode emitter to short out to the diode collector. It then becomes possible to design diodes with smaller spacing between emitter and collector and reap higher values of power level and efficiency. Further, the electrical insulation material can be removed from high radiation regions and thus reduce the damage by fast neutrons.

These advantages have previously been recognized at other laboratories and a design study of an out-of-pile heat pipe thermionic reactor has been performed (ref. 5). However, this previous study was devoted to power levels around 10 mW electric. At such power levels, the heat removal system included thousands of heat pipes and a very complex heat pipe exchanger using liquid silver. Our goals are more modest in scope. Other laboratories are now also investigating small, heat-pipe, thermionic reactors.

This paper deals with a reactor - heat pipe - thermionic diode combination which could supply power for an electrical propulsion system for deep space probes or perhaps for a direct broadcast satellite. Experimental results from laboratory tests of both heat pipes and thermionic diodes have been used to set performance levels that should be obtainable on the basis of present experience. If, as will be discussed, better performance may be expected of these devices in the future, the performance levels of such a system will appear correspondingly better.

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Because of the size and power density requirements that will be expected of future power supply systems, we have allowed an extrapolation to fuel materials that are not presently proven. However, no attempt has been made to design a fuel element in detail. The present proposed arrangement contains only four fuel regions, all of which could be constructed as thick discs. Here again, the development of more sophisticated fuel element configurations with more heat transfer area should improve the performance estimates that are made here.

What is presented in this paper is a conceptual design of a space power system using out-of-pipe thermionic diodes which are both heated and cooled by heat pipes. The design is intended to be as simple as possible and to indicate the performance levels that might be available from future systems of this type. The concept could well be applied to a range of required power levels but the specific design looked at here represents the smallest reactor size possible within reactivity limitations. The values of system power that are available from this reactor are established by the maximum fuel temperature, the heat transfer capabilities of the heat pipes, and the presently obtained efficiencies of thermionic diodes.

Heat Pipe Performance

A theoretical analysis of heat pipe operation has been performed by Cotter (ref. 2) and also by Anand (ref. 6). Both of these analyses predict a maximum value for heat transferred along the heat pipe based upon the pressure rise due to capillary forces being strong enough to override pressure drops in the flowing liquid and vapor phases. These models assume that no other limiting mechanism might occur although Cotter specifically states that no boiling must take place at the evaporator. Cotter's requirement of no boiling means no bubble formation at the evaporating surface. Whether or not there are other mechanisms of interference between vapor flow and liquid flow near the interface surface is not known at this time.

A series of heat pipe capability experiments have been performed at Los Alamos Scientific Laboratory and have been reported by Kemme (ref. 3). Tests were performed with a number of pipes, all of which were 30 centimeters long with a vapor passage diameter of 1.5 centimeter. Tests were run with sodium, potassium and lithium with various configurations of capillary geometry. The results obtained for the upper limit of heat transfer with sodium and potassium working fluids were in fairly good agreement with theoretically predicted values.

Kemme also made a test with lithium as a working fluid in a niobium - 1 w/o zirconium heat pipe. The capillary geometry in this pipe was constructed as 88 channels cut into the inside wall of the pipe; each channel was 0.12 millimeter wide and 0.30 millimeter deep. This geometry had given very low values of heat transfer limit with sodium. At 850° C heat transfer was limited at 2000 watts with lithium compared to 550 watts with sodium. At 1150° C the lithium heat pipe was limited at 4000 watts. No limits could be determined above 1150° C since the heat transfer equipment could remove only 4000 watts.

These data represent the highest heat transfer limits to date. However, Kemme increased the limiting heat flux with sodium at 850° C by a factor of three by changing the channels from 0.12 mm by 0.30 mm to 0.16 mm by 0.40 mm, respectively. Also an addition of a screen inside the heat pipe increased the limiting heat flux of sodium by another factor of 2.5. If a similar increase of the lithium heat transfer limit can be attained by these geometry changes this limit may be as high as 800 watts/cm^2 at 1150° C.

Considerable experimental work has been performed on the combination of thermionic diodes and heat pipes by Harbaugh (ref. 4). At the time of a recent termination of a contract, a TZM (Mo - 0.5 Ti - 0.08 Zr) heat pipe with a molybdenum capillary screen had operated with a lithium working fluid for 3250 hours at 1350° C (ref. 7). This heat pipe had three diodes mounted in series on the condensor end of the pipe insulated from the pipe by a sheath of Al_2O_3. The output from this assembly averaged around 120 watts or 2 watts per square centimeter of diode throughout the operating life (ref. 4). This unit was operated for a short period of time at 1500° C and delivered more than 4 watts per square centimeter.

It appears that present technology does permit the building and operation of a heat pipe using lithium at 1500° C. Although the present life test at 1350° C ran for only 3250 hours, the decision to shutdown was administrative and not due to any failure. It is generally believed that, if sufficient attention is devoted to keeping the purity of materials at the highest levels, the heat pipe should be able to run for extremely long periods of time. Great care must however be taken to avoid any contamination. RCA found it necessary to use only tools and jigs constructed of molybdenum during the manufacture of the heat pipe (ref. 4).

A prototype of a thermionic diode with its emitter heated by a heat pipe and its collector cooled by a heat pipe has been built and operated (ref. 8). A cylindrical converter was constructed with the tungsten emitter vapor-plated on the outside of a tantalum heat pipe with a diameter of 1.77 centimeter. The emitter area was 17.5 square centimeters and the gap between the emitter and collector was 0.035 centimeter. The collector was molybdenum sintered on to a niobium - 1 percent zirconium heat pipe. A schematic diagram of this prototype is shown in figure 2. The emitter heat pipe was constructed of tantalum and contained lead as a working fluid. The collector heat pipe of niobium - 1 zirconium employed cesium as a working fluid. The emitter pipe was heated by radio frequencies, the collector pipe was cooled by radiation.

The voltage-current characteristics of this device are shown in figure 3 for an emitter temperature of 1500° C, a collector temperature of 730° C, and a cesium temperature of 325° C. The maximum power output of 5.2 watts per square centimeter was obtained at 0.4 volts output. The optimum collector temperature is generally at 700° C; a data point not taken in this test.

Figure 4 shows a set of curves compiled by Williams, Ward and Breitwieser of NASA Lewis Research Center which represent an envelope of thermionic data obtained at different laboratories (refs. 9, 10, 11). The data from the heat pipe - thermionic diode combination has been added to the compilation. It is seen that these data compare well with other experimental tests. The lower values of current at a given voltage probably result from the approximately 0.036 cm (0.014 inch) diode spacing compared to the 0.013 cm (0.005 inch) and 0.025 cm (0.010 inch) spacings shown in the figure.

Integration of Thermionic Diodes and Heat Pipes with a Nuclear Power Source

Based upon the experimental data presented in the previous section, a concept has been developed using out-of-pile thermionic diodes and heat pipes for a power source for an unmanned scientific space probe. This particular design does not necessarily represent a final configuration, but merely a first step toward a thermionic reactor system design.

From the heat pipe analyses and experiments previously described it appears that a heat flux of 280 watts/cm^2 of evaporator surface should be obtainable in a lithium heat pipe operating at a temperature of 1565° C; this value was used for the design of the evaporator. For the thermionic emitter, which will be designed for operation at 1500° C, a heat flux of 45.5 watts/cm^2 was selected as being representative of presently obtainable performance. The electrical output of the system will depend primarily upon the efficiency of the operating diode. As was shown in figure 4, a diode efficiency of approximately 10 percent is a reasonable value that has been frequently obtained.

A plan view of the arrangement of heat pipes inside the reactor core is shown in figure 5. The proposed design employs heat pipe evaporator sections shaped as sectors of a circle. The heat flux surfaces are those flat surfaces in the horizontal plane that bound the top and bottom of the sectors. That region of the heat pipe that passes through the heavy metal reflector is a circular region that is assumed to operate as an adiabatic section of the heat pipe.

Outside the heavy metal reflector, the high temperature heat pipe is sheathed with an electrical insulating material upon which are placed the emitters of thermionic diodes. Concentrically around the emitter surfaces is placed the collector heat pipe in a fashion similar to the design of Busse, Caron and Cappelletti (ref. 8). The cesium supply may be connected to the interdiode space, as shown in figure 5, in a region where space is available.

A side view of the reactor concept is shown in figure 6. Neutronic calculations made with the TDSN program (ref. 12) and GAM II (ref. 13) and GATHER II (ref. 14) cross sections show that a core of this size is required to achieve criticality with the 29% void fraction in the core due to the presence of the heat pipes.

The simplicity of this core concept is seen in that only four fuel elements with a simple disc geometry are needed. The thickness of these fuel elements has been established as 2.92 centimeter based upon a heat pipe operating temperature of 1565° C and a centerline temperature fuel that is lower than the melting point. The melting point of uranium nitride with a nitrogen overpressure of 2.5 atmospheres has been reported as 2847° C (ref. 15). The 2.5 atmospheres of nitrogen pressure is sufficient to prevent disassociation. The centerline temperature of the fuel element in this design will be 2555° C with a surface heat flux of 280 watts per square centimeter.

Although this centerline temperature seems rather high, recent experimental evidence indicates that high fuel temperatures permit better operation when the fuel is vented. It has been found in uranium dioxide (ref. 16) that at fuel temperatures below 1400° C the fission product atoms are not sufficiently mobile to conglomerate into bubble regions that cause fuel swelling. At temperatures around 1800° C the fuel swelling problem becomes very troublesome. However, at a temperature of 2200° C, fission product atoms easily migrate and can be released. It appears that if the fuel matrix temperature is sufficiently high ceramic fuels can be successfully vented without serious swelling and cracking problems. Since it is not feasible to contemplate the venting of uranium nitride to space, it is proposed to vent the fuel to a nitrogen gas system maintaining the overpressure on the fuel. Figure 7 indicates the arrangement of this gas system. The fueled regions are to be connected to this system through small orifices or molecular sieves that will prevent $U^{233}N$ movement out of the fuel disk. These uranium flow restrictors would be located in a high temperature region of the core to prevent possible plugging by recondensed fuel or fission product atoms.

Control of a Fast Reactor Using Internal Reflection

Figure 6 also shows a schematic representation of a reactivity control system. Insertion of a material such as lithium 6 in the control regions shown obtains control by absorption of thermalized neutrons. For a reactor of the dimensions shown in figure 6 the effective multiplication factor dropped by 5.5% when nitrogen gas in the control spaces was replaced by lithium 6.

The neutron energy spectrum in this reactor core is shown in figure 8. The solid line histogram represents the flux spectrum in the reactor when only nitrogen is contained in the control space. The dashed line represents the spectrum calculated when lithium 6 has been inserted. It is seen that the reactivity control is in the removal of thermal neutrons produced in the internal reflectors.

A typical operating power distribution with this control system is represented in figures 9 and 10. Lithium 6 has been removed from the two end regions in the core to reach a clean critical condition while lithium 6 remains in the central regions for later burnup compensation and other control requirements. These power profiles represent the fissions per unit volume within the core region. If the axial peak to average values shown in figure 10 causes excessive fuel temperature in higher power density reactors of this type, the thickness of a particular fuel element at the maximum power generation point may be decreased.

One possible mechanism for transfer of control material into the control spaces is shown in figure 11. The nitrogen and lithium could be separated by some form of piston which would be correctly oriented by guide tubes running inside slots in the internal reflector material. The lithium 6 can be introduced into the reactor by use of a positive displacement pump. It is also proposed that the lithium 6 fill a central hole down through the center of the reactor. The expansion of lithium 6 from this central hole into the control chamber may be sufficient to provide a negative temperature coefficient of reactivity into the reactor for reactors with sufficiently long core sections. The lithium located adjacent to the fuel region in the reactor is exposed to a fast neutron spectrum in which it has a low value of absorption cross section. If the core temperature rises causing the lithium to expand, some atoms of lithium 6 will be removed from the fast spectrum region into the more-nearly thermal region.

Later calculations of a slightly modified reactor core indicate that greater values of control worth and slightly flatter power profiles may be obtained with beryllium oxide. This material would, moreover, be necessary in this concept because temperatures in the neighborhood of 1500° C are too great for beryllium. Some additional calculations have indicated that the moderating material, zirconium hydride, would be even more effective than BeO for obtaining reactivity control. However, yttrium hydride would be better from a temperature point of view because it would not have to be cooled as much. With zirconium hydride it is theoretically possible to obtain a change in reactivity as high as 25% using the geometry of figure 3. Excessively high values of power peaking are associated with this 25% change in reactivity so that this particular configuration is not proposed as a design concept. However, the magnitude of the effects obtained do indicate the versatility of this type of control scheme.

The use of beryllium oxide as the internal-reflector in the core introduces material which is susceptible to fast neutron damage. However, this application of beryllium oxide is not as demanding as its use as an electrical insulator. The dose of fast neutrons above 1 Mev in the present core is about 1.6×10^{21} in 10,000 hours at its maximum in the moderating material. Even if this dose produces powdering of the beryllium oxide it may be a tolerable condition for a canned material but would be intolerable as a seal for an in-pile diode.

Preliminary calculations indicate that a sheath of beryllium oxide with a thickness of 0.058 cm (0.023 inch) could hold electrical leakage to 5% with a total series voltage across the diodes of 50 volts. An alternative method of electrically isolating the thermionic emitters from the reactor heat pipe might be another heat pipe as shown in figure 12.

Summary of Conditions and Configuration

Figures 13 and 14 represent an overall picture of what the heat pipe-thermionic diode power reactor might look like. The core and reflector in figure 13 have an outside diameter of 30.48 cm (12 inches). The heat pipe emerging from the radial reflector has a diameter of 1.2 centimeter and is shown with an electrical insulating sheath around it. The encircling collector heat pipe is also represented in figure 13 and is shown connected to a radiator section through a transition piece.

The radiator construction would be of multiple heat pipes in a cellular arrangement similar to that proposed by Salmi (ref. 17). One possible radiator arrangement is presented in figure 14. The radiators are arranged as five circular discs having outside radii of 0.75 meters, 1.23 meters and 1.41 meters. These dimensions result from a preliminary calculation using an effective surface emissivity of 0.90, a surface view factor of 0.85 for those surfaces not covered by an adjacent disc and a sink temperature for deep space of 0° K. It is assumed that 412 killowatt was radiated from these discs. It should be re-emphasized, that this particular configuration in no way represents the optimum design for a radiator. The intended purpose of the caluclation is to provide an estimate of system size.

A summary of reactor, heat pipe and thermionic diode operating conditions is presented in table I. These conditions represented the smallest reactor to meet criticality requirements with the power output set by the 280 watts per square centimeter that may be transferred across the evaporator surfaces in the heat pipes. The electrical output available from the system is set by the obtainable efficiency of the thermionic diodes, which was assumed to be 10%, and the current and voltage losses through the network of diodes. For an assumed 8% voltage drop in the leads and a 5% current loss the unconditioned output power is 36 kwe.

Table I. Summary of Conditions

Reactor

Fuel	$U^{233}N$
Cooling	TZM (molybdenum) or tungsten heat pipes
Reactor diameter, cm	1.62 (6.0 inches)
Reactor length, cm	43.4 (17.0 inches)
Maximum fuel temperature, °C	2555
Fuel clad temperature, °C	1577
Heat flux at clad, w/cm^2	280
Reactor power to diodes, kw	412

Heat Pipes

Total number of full power heat pipes	72
Total number of half power heat pipes	48

Thermionic Diodes

Temperature at emitter heat pipe condensing surface, ^oC	1563
Total number of diodes	384
Emitter area per diode, cm^2	23.6
Emitter diameter, cm	1.32
Emitter length, cm	5.7
Heat flux at diode, w/cm^2	45.5
Emitter electrical power density, w/cm^2	4.55
Collector surface temperature, ^oC	700
Electrical power per diode, w	107.4
Diode output voltage, v	0.5

System Output

Number of parallel circuits	4
Gross output, v	48
Lead drop, v	3.8
Net output potential, v	44.2
Power lost through leakage, kw - (570) -	2.1
Total output current, a	815
Net output power, kw - (unconditioned) -	36

A summary of reactor weights and materials is shown in table II. The total weight for reactor, diodes and radiator is around 264 kg (581 pounds) providing a specific weight of 7.3 kg/kwe (16.1 lbs/kwe) excluding the required shielding.

Table II. Weights and Materials

Reactor

Material	Volume (cm^3)	Weight (kg)
UN	2,131	30.5
Lithium	927	0.4
W	111	2.1
Be*	18,997	35.0
M_o reflector	13,369	136.4
Total reactor + reflector weight		204.4 (450 lbs)

Radiator

0.076 cm (30 mil) thick Be for surface of 5 disks	49.7 (109 lbs)

Diodes

Approximately	10.0 (22 lbs)
Total weight excluding shielding	264.1 (581 lbs)

*Beryllium was used in the initial reactor calculations. Less BeO is required for the same reactivity control. Time did not permit the optimization with BeO so the beryllium was used in this initial weight estimate.

In regard to the shielding of an unmanned probe, the payload would be placed on the vertical axis of the cylindrical reactor core. The control reservoir containing lithium 6 would be placed on that axial face of the core nearest the payload. For present day electronic components and devices, an integrated fast neutron dose (>1 Mev) of 10^{13} nvt is considered acceptable and a gamma dose of 10^6 rads is considered tolerable (ref. 18). In view of these limitations, if it can be arranged so that the payload is removed from the reactor core by a distance of 45.7 m (150 ft) - there will be no additional shielding required for tolerable gamma doses but, 235 kg/m^2 (48 pounds per sq. ft) of surface area of lithium hydride will be required as a fast neutron shield to attenuate the fast flux by a factor of forty. If it becomes necessary to operate with a 15.3 m (50 ft) separation, approximately 50.8 cm (20") of LiH (366 kg/m^2 or 75 lb/ft^2) would be needed.

A summary of fast neutron shield weights is indicated in figure 15. A first-flight shadow shield for a 6.1 m wide (20 ft) wide payload would weigh 28.2 kg (62 lb). A calculation of secondary neutron and gamma scatter off the radiator is beyond the scope of this conceptual study. However, a maximum weight limit would be that connected with a radial shield providing the same attenuation as the straight shadow shield. This maximum limit would then be 335 kg (738 lb). A full four-pi shield configuration would come to 450 kg (991 lb).

With the wrap around shield included the specific weight of the system would increase to 16.6 kg/kwe (37 lb/kwe), but this does not include the weight of the 150 foot deployment structure, nor that of the lithium control system or other hardware.

SUMMARY OF RESULTS

A conceptual design of an out-of-pile thermionic space power system using concentric heat pipes for both heating and cooling the thermionic diodes has been examined. This design presents several advantages. The thermionic diode is removed from high doses of fast neutron flux and from other problems of the reactor environment. The tolerance of electrical insulation materials to fast neutrons appear to lie around an integrated flux of 10^{21} nvt, a level usually encountered within 10,000 hours in in-pile thermionic designs. Furthermore, since the diode emitter is no longer the clad material for the fuel element, small amounts of fuel swelling will no longer affect diode performance. The interdiode spacing can thus be made smaller to obtain higher power levels and efficiencies as shown in figure 4.

The thermionic diode performance has now been decoupled from radial power profiles and flux shifts. By correct design and manufacture, all the heat pipes feeding the diode emitters should run at the same temperature and minimum temperature gradients will exist along emitter lengths.

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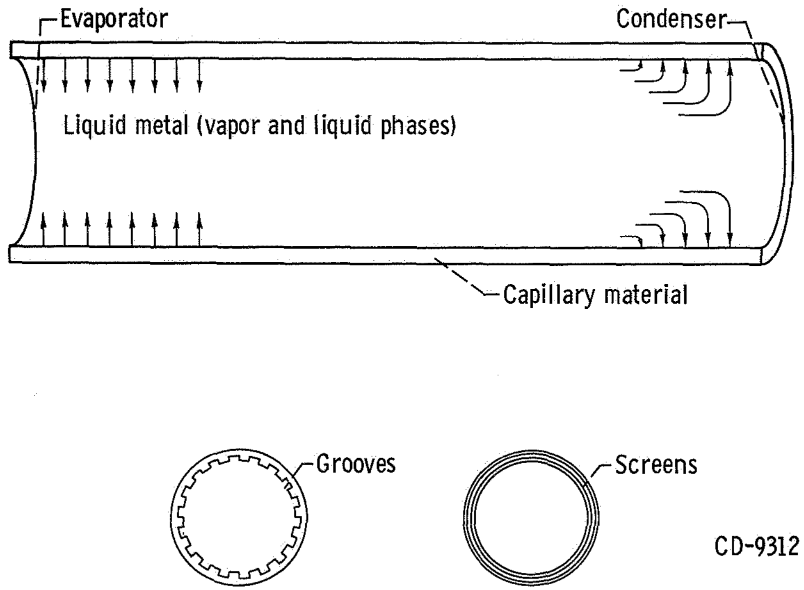

Figure 1. - Schematic of heat pipe operation.

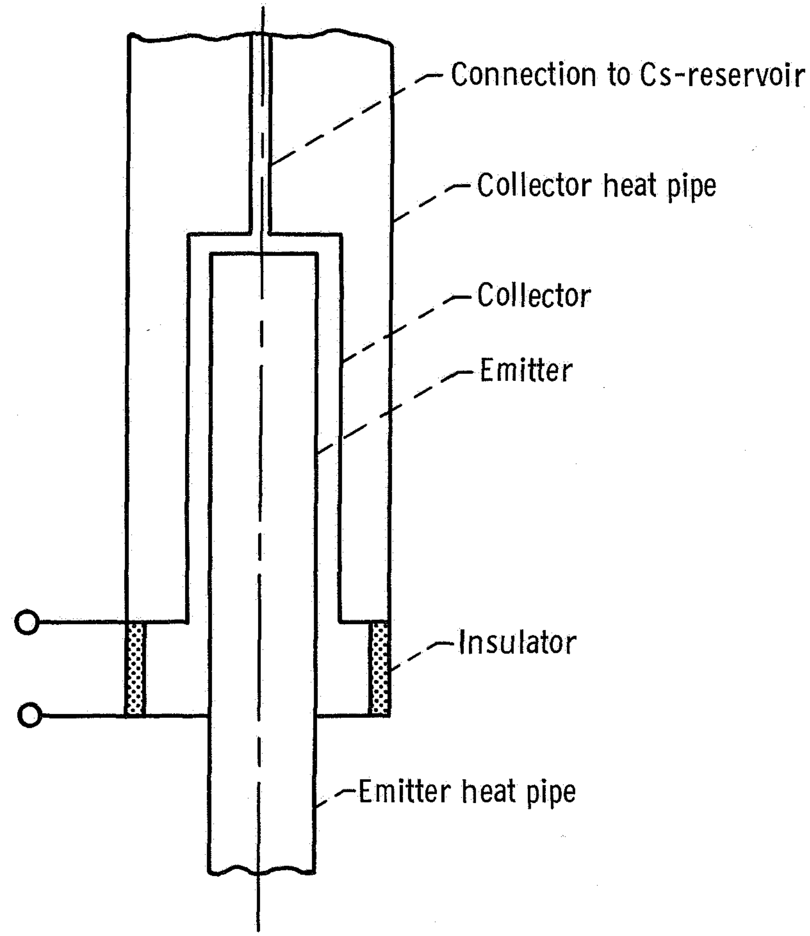

Figure 2. - Schematic of heat pipe thermionic converter of Busse, Caron, and Cappelletti (Euratom, Ispra, Italy).

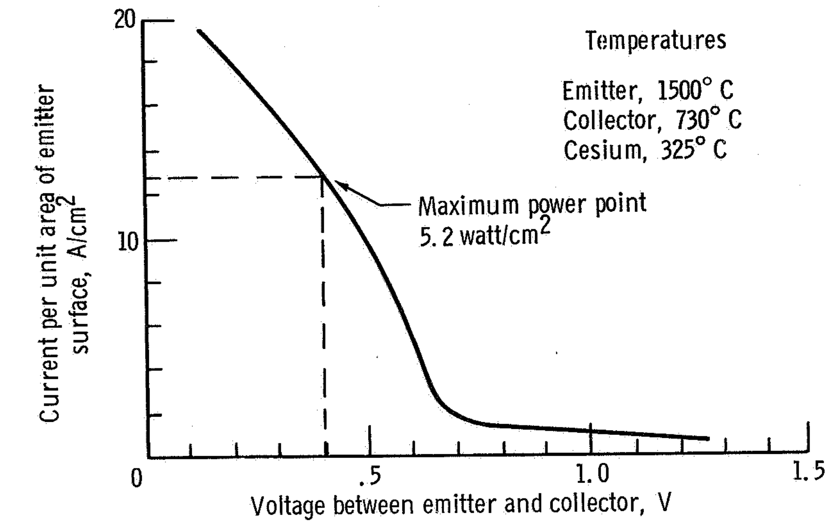

Figure 3. - Current-voltage characteristics of heat pipe thermionic converter of Busse, Caron, and Cappelletti.

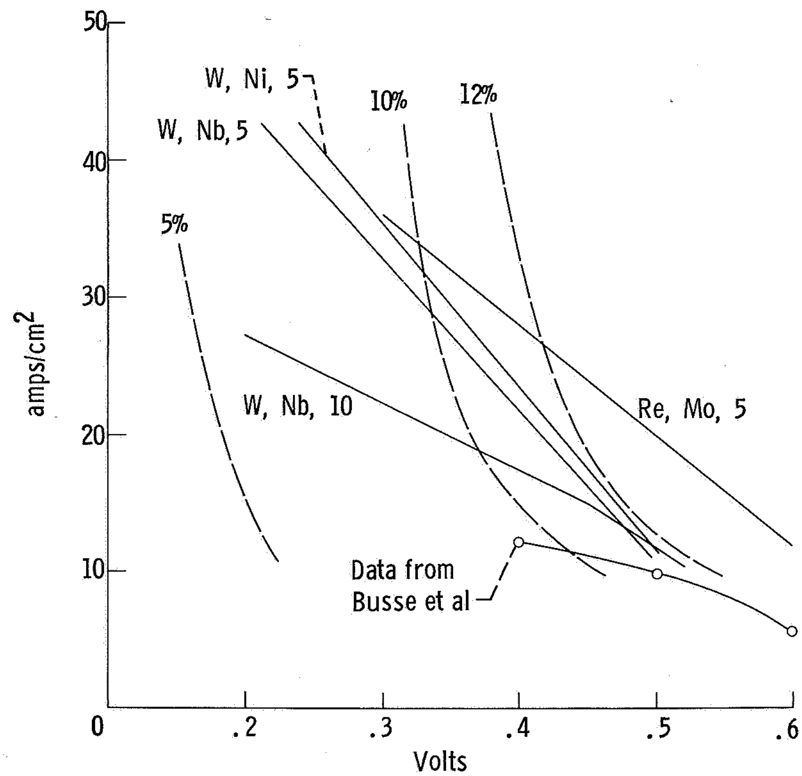

Figure 4. - Summary of experimental diode performances. Emitter temperature, 1770° K; Collector temperature, 973° K. Code: Emitter, collector, spacing in mils.

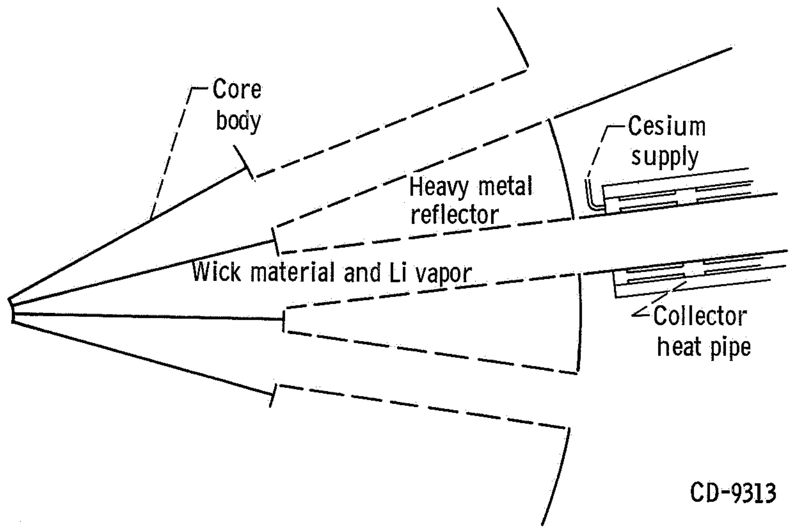

Figure 5. - Plan view through heat pipes in fast spectrum reactor.

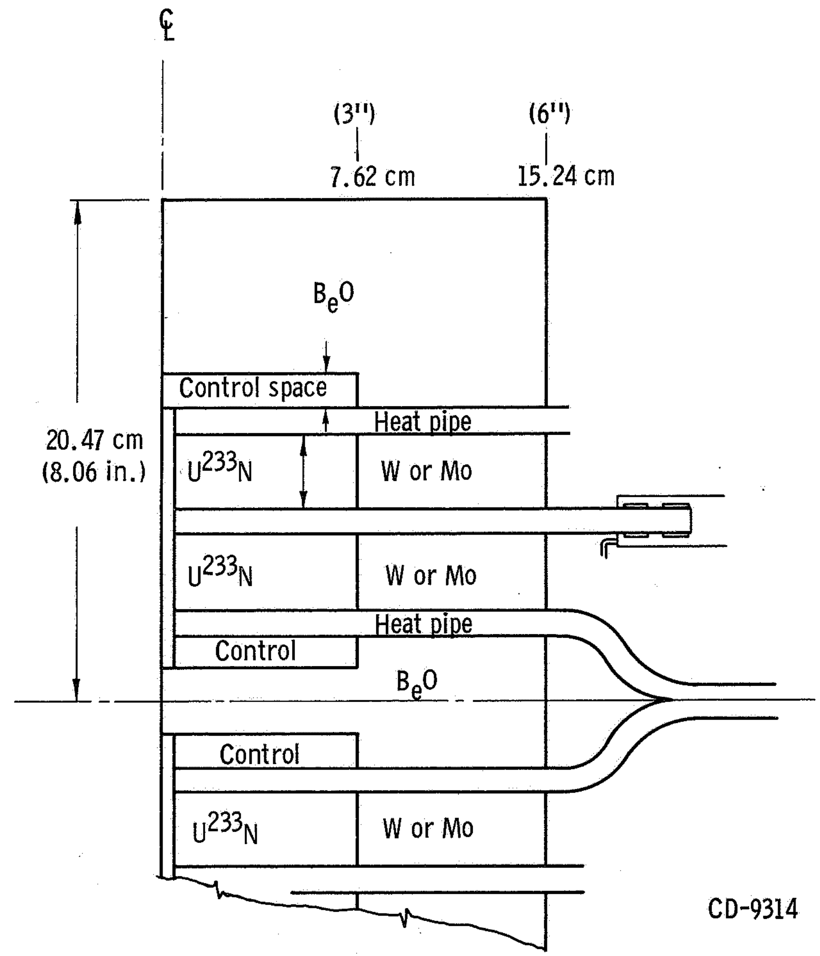

Figure 6. - Schematic of internal composition of fast reactor with spectrum softened control.

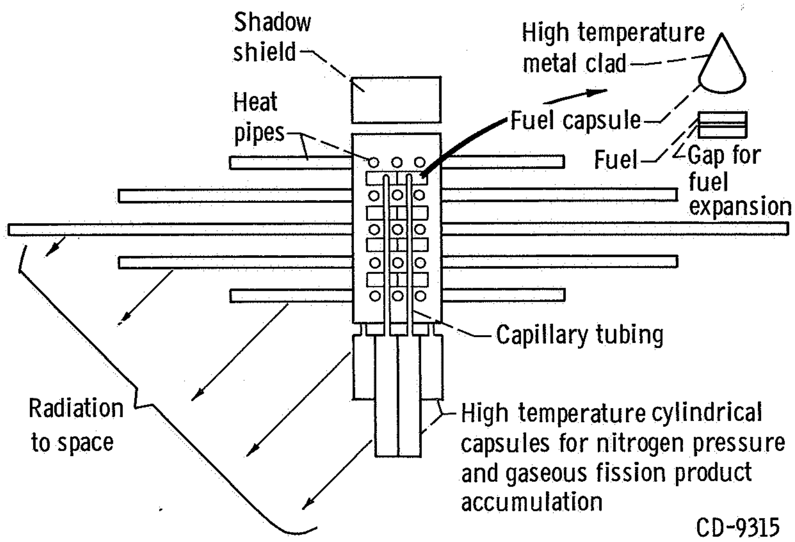

Figure 7. - Possible method for maintaining nitrogen overpressure on uranium nitride and for gaseous fission product pressure reduction within the fuel capsule.

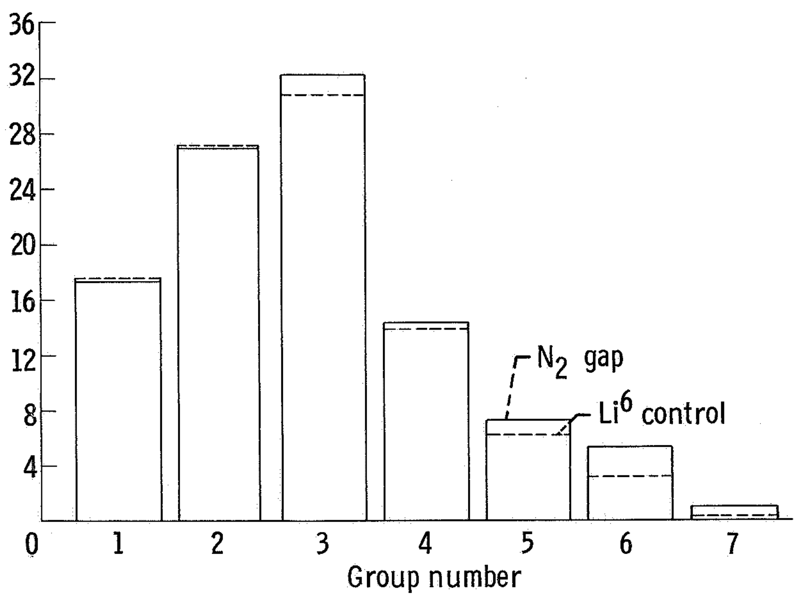

Figure 8. - Comparitive spectra of neutrons causing fissions for extremes of control swing in Be slice reactor.

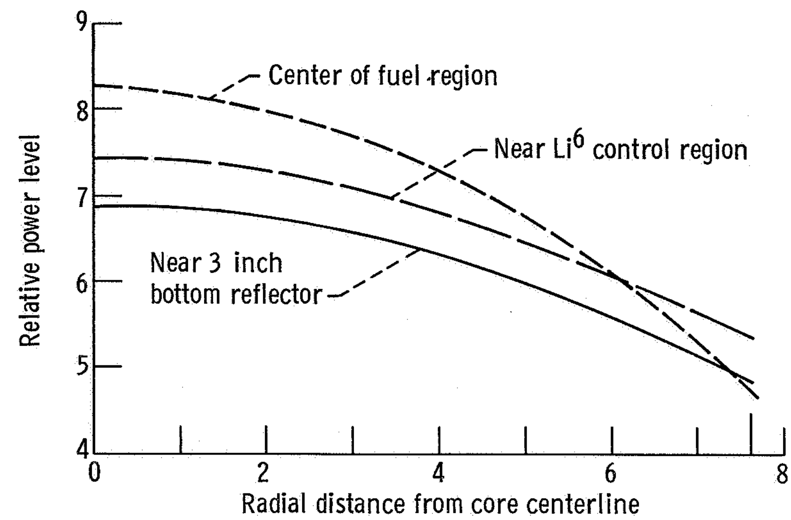

Figure 9. - Radial power profiles in UN reactor "internally reflected" and controlled.

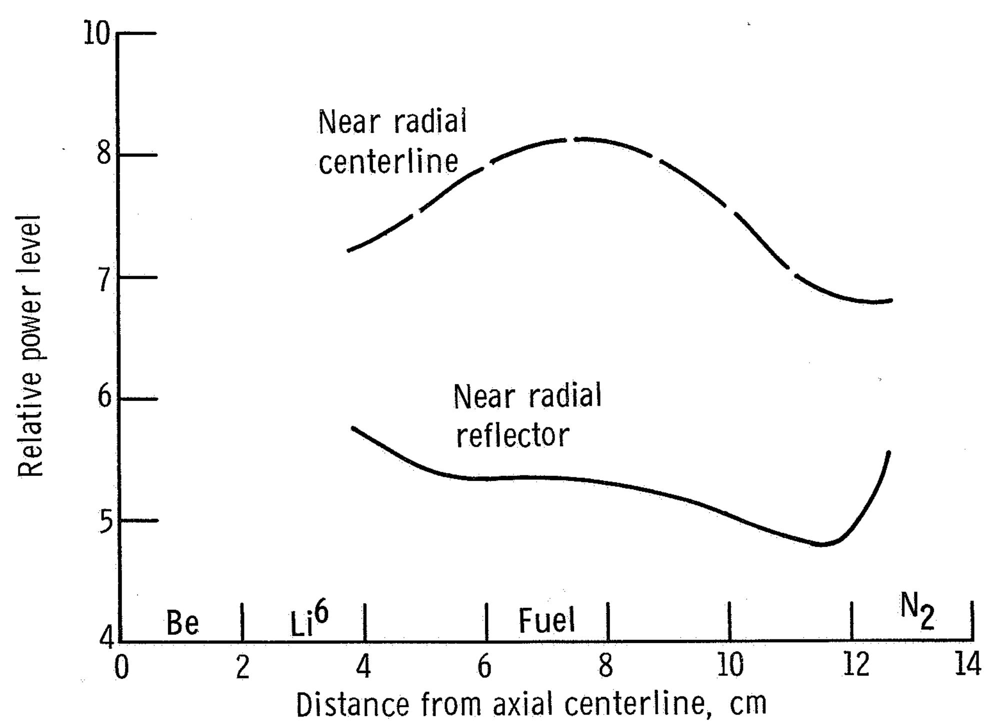

Figure 10. - Axial power profiles with control material in central region only.

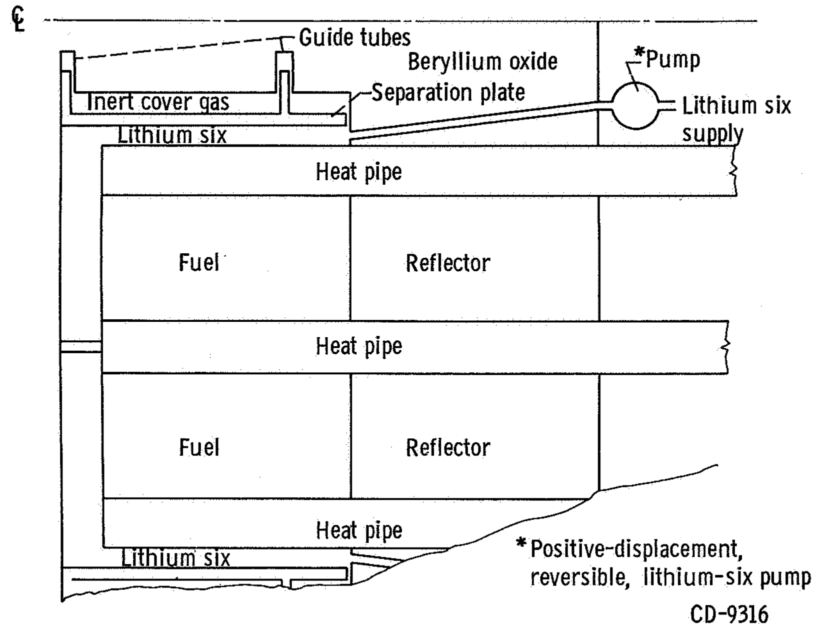

Figure 11. - Reactivity control system.

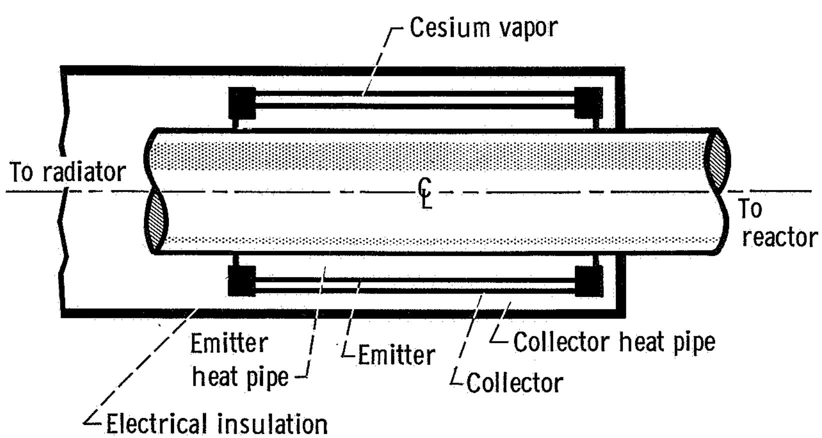

Figure 12. - An alternative method for electrically isolating multiple thermionic emitters from a source heat pipe.

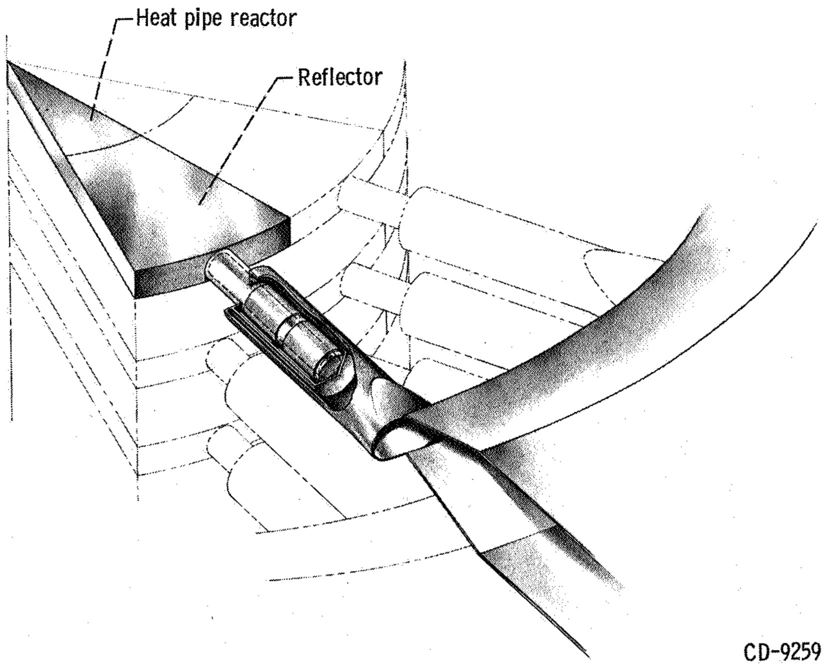

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Figure 13. - Radial heat pipe reactor.

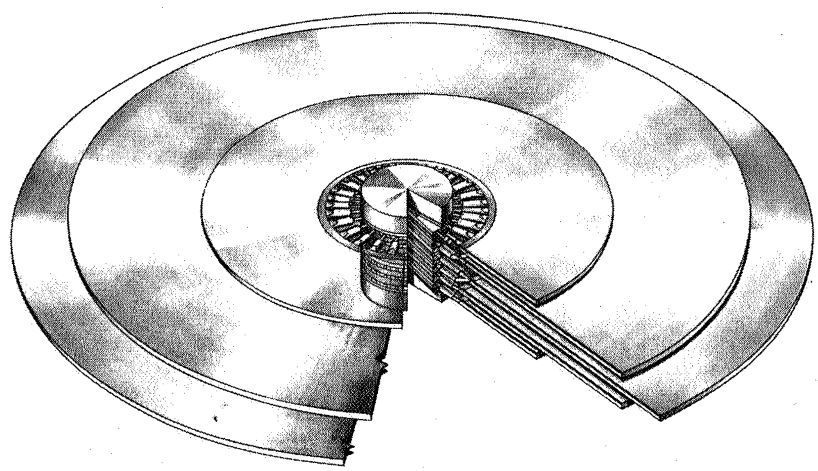

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Figure 14. - Radial heat pipe thermionic reactor system.

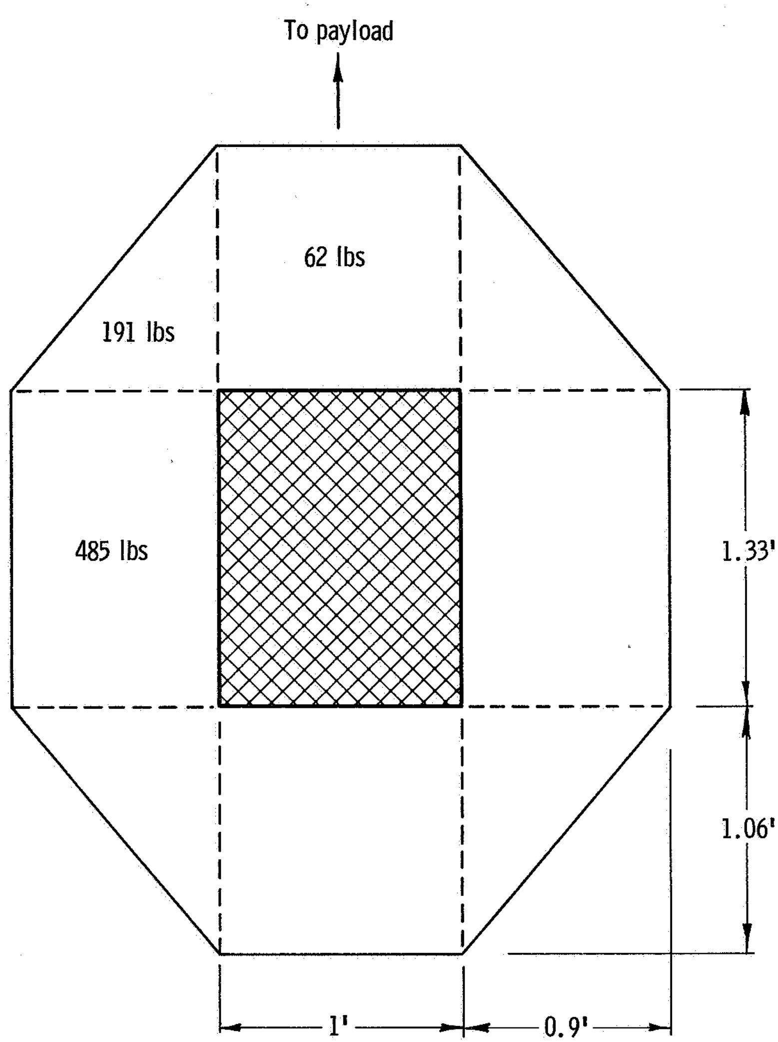

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Figure 15. - Possible shield configuration for unmanned vehicle with UN-heat pipe power supply.