CONF-780531--2

LA-UR -78-643

TITLE: HEAT PIPE NUCLEAR REACTORS FOR SPACE APPLICATIONS

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SUBMITTED TO: 3rd International Heat Pipe Conference
May 22-24, 1978
Palo Alto, California
Sponsored by the AIAA

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LOS ALAMOS, NEW MEXICO 87544

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CONTRACT W-7405-ENG. 36

HEAT PIPE NUCLEAR REACTORS FOR SPACE APPLICATIONS

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Abstract

A heat pipe nuclear reactor design concept is being investigated for space power applications. The reactor can be coupled to a variety of high-temperature (1200-1700 K) electrical conversion systems such as thermoelectric, thermionic, and Brayton cycle converters. It is designed to operate in the power range 0.1-3 MW_t for lifetimes of about 10 years. The reactor is a fast spectrum, compact assembly of hexagonal fuel elements, each cooled by an axial molybdenum heat pipe and loaded with fully enriched UC-ZrC or Mo-UO_2. Reactor control is provided in the radial reflector. A comparison of several power plants employing the heat pipe reactor concept is presented for an output power level of 50 kW_e.

Introduction

The advent of the reusable space shuttle opens a new era of space exploration and exploitation. Larger satellites can be placed in orbit and at lower cost compared with present day disposable rockets. These larger satellites will perform missions that will require significantly increased power and long lifetimes. A number of potential Department of Defense (DoD) missions have been identified in communications and electro-optical and radar surveillance requiring electrical power in the range 10-100 kW_e.[1] Potential National Aeronautics and Space Administration (NASA) missions for space nuclear reactors center on planetary exploration and large satellites in geosynchronous orbits spanning a power range of 15-400 kW_t.[2,3] Lifetime goals of 7-10 years have been established for spacecraft in geosynchronous orbit and the equivalent of 10 years at full power for planetary exploration. The space shuttle can place up to 29,500 kg in low-earth orbit, but in geosynchronous orbit, the payload drops to 2270 kg.[4] The latter restriction in particular provides incentive for the development of nuclear power supplies.

Because no single, dominant DoD or NASA mission has been identified, the nuclear power plant should be designed to meet a broad range of potential mission requirements. These requirements call for power plants which are compact and hence have relatively high power density. High operating temperature is favored, not so much to benefit from better thermal efficiencies but primarily to operate at higher heat-rejection temperatures in order to achieve low radiator size and mass. A high degree of reliability is necessary to insure stable operation for long mission lifetimes and, finally, the power plant must meet the required nuclear safety regulations for assembly, launch, and possible abort conditions.

Power Plant Conceptual Designs

The Los Alamos Scientific Laboratory (LASL), in support of the U.S. Department of Energy (DOE) and NASA programs to develop nuclear reactor power plants for space, has been engaged in systems studies, conceptual design studies and technology development programs involving a new class of compact, high-temperature, heat-pipe cooled fast nuclear reactors.[5-7] What has evolved from the studies is the conceptual design of a reactor which operates in the power range 0.1-1 MW_t and which can be scaled up to several megawatts. The scope of this paper will be confined to systems in the power range up to 1 MW_t.

An example of a power plant utilizing such a reactor is shown in Fig. 1. Heat pipes emerge from one end of the reactor and go around a radiation attenuation shadow shield to transfer heat to a ring assembly of silicon-germanium thermoelectric converters. Reject heat from the cold junction of the converters is carried away by stringer heat pipes which run the full length of the conical radiator. Circumferential cross heat pipes form the outer skin of the radiator. At a power level of 50 kW_e this power plant measures less than 7 m in length and weighs about 1250 kg.

A conceptual design of a power plant employing two dynamic Brayton Cycle converters is shown in Fig. 2. Here again heat pipes emerge from one end of the reactor to a high temperature heat exchanger which consists actually of two independent heat exchangers, each capable of extracting heat from the entire reactor. Gas ducts take the heat from the heat exchanger around the shield to the two independent Brayton Cycle converters. The waste heat from the converters is dissipated in the paneled radiator by multiple, redundant liquid-metal loops. A 50 kW_e design for this power plant weighs about 1400 kg and measures under 5 m in length in the folded configuration.

Reactor Design

The mission requirements for high power, small size, and long lifetimes imply the need for developing fast, highly enriched, densely fueled reactors that will have a large inventory of fuel in a small volume. The large fuel inventory is necessary for long life to prevent large reactivity decreases due to fuel burnup. In seven years a 1 MW_t reactor will burn approximately 2½ kg of ^{235}U. This amount of burned fuel cannot represent more than a few per cent of the total fuel inventory in order to maintain reactor criticality during the mission.

The reactor concepts being developed at LASL all involve refractory nuclear fuels such as UC or UO_2. These refractory materials allow consideration of source temperatures of 1300-1400 K for thermoelectric and Brayton cycle systems and, in the case of UO_2, temperatures in excess of 1650 K for

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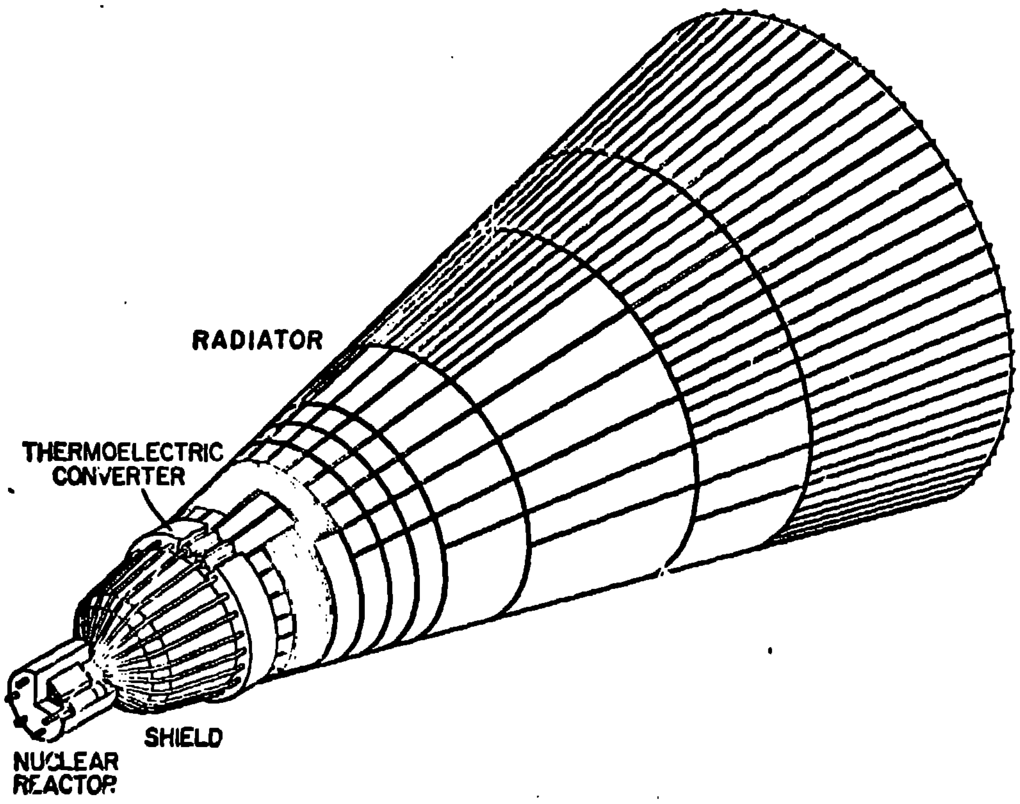

Fig. 1 Thermoelectric power plant.

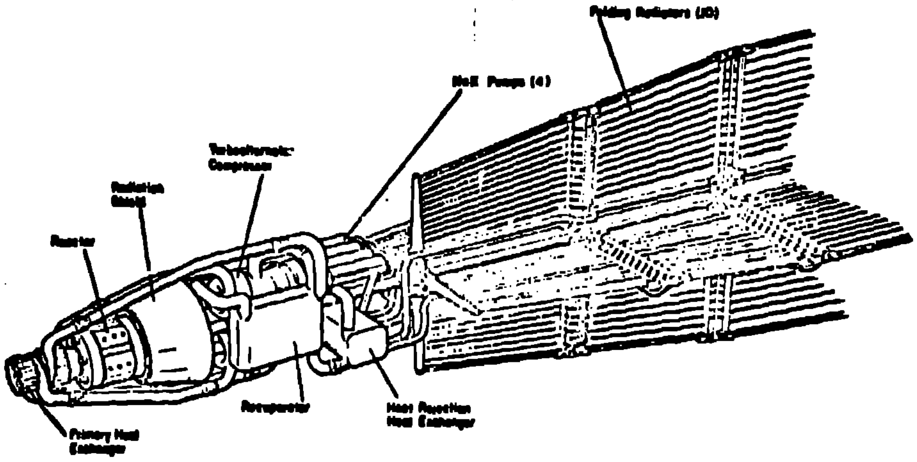

Fig. 2 Brayton cycle power plant.

thermionic converter systems. At low power (<0.5 MW_t) reactor size tends to be limited by the constraint of critical mass. In this regime the higher uranium density of UC yields a smaller core than UO_2. At high power (>1 MW_t), reactor size is influenced by the constraints of heat removal, fuel stability, and reactivity loss due to burnup. These limitations force the reactor size to grow beyond the criticality requirements, permitting if desired the use of the more dilute (in uranium content) fuel UO_2 whose advantages compared to UC are its inertness in air, its better irradiation behavior particularly when contained in a refractory metal matrix[8,9] and its excellent chemical stability at much higher temperatures. At a power level of 1 MW_t our studies indicate though, that the UC reactor is several hundred kilograms lighter than a UO_2 reactor.

The use of heat pipes to remove heat from the core offers several advantages. Foremost is the avoidance of single-point failure in the core cooling system. In the event of a core heat-pipe failure, the adjacent fuel elements carry off, by conduction and radiation, the heat generated in the failed element. The electrical output may be degraded slightly, but the power plant is not shut down, as would be the case with a gas or liquid-metal cooled reactor that developed a leak in the cooling circuit. In addition, the reliability of heat-pipe cooled reactors should be enhanced because the plumbing is simpler, and mechanical or electromagnetic pumps are eliminated. A heat exchanger between the core and the electrical conversion system also is eliminated in designs where thermoelectric or out-of core thermionic converters are bonded directly to the core heat pipes. By the nature of their operation, heat pipes involve small mass flows. Consequently, the inventory of coolant fluid is much less than that for a liquid metal system. The problems of coolant activation are reduced correspondingly and so are the corrosion problems. The high degree of reliability of properly designed heat pipes has been demonstrated in a variety of life tests.[10-12]

A typical fuel element consists simply of a molybdenum heat pipe bonded along the axis of a hexagonal UC fuel body (actually 90UC-10ZrC (atom%), to improve the chemical stability). The fuel is segmented radially and longitudinally, as shown in Fig. 3, to allow unrestrained thermal expansion and provide room for fuel swelling. The outside of the fuel element is clad with molybdenum. Advantage is taken of the thermal expansion mismatch between UC and molybdenum to obtain thermal bonding of the fuel segments to the heat pipe by pressure contact. (This mismatch is too large to make diffusion or braze bonding a practical means of establishing thermal contact.) In the case of UO$_2$, the fuel body would not be clad or segmented radially. It would consist of solid hexagonal segments of molybdenum, drilled with small holes into which UO$_2$ pellets are inserted. The maximum practical concentration of UO$_2$ within the fuel region yields an average composition of 60 vol% UO$_2$ and 40 vol% Mo. The fuel section of the heat pipe is followed by a reflector segment of BeO canned in molybdenum and by a small solid molybdenum segment. The latter, by interlocking with its neighbors, provides a rigid support slab for the core, leaving the opposite end of the core free to expand longitudinally. A thin layer of B$_4$C between the fuel and the BeO segments absorbs low-energy reflected neutrons.

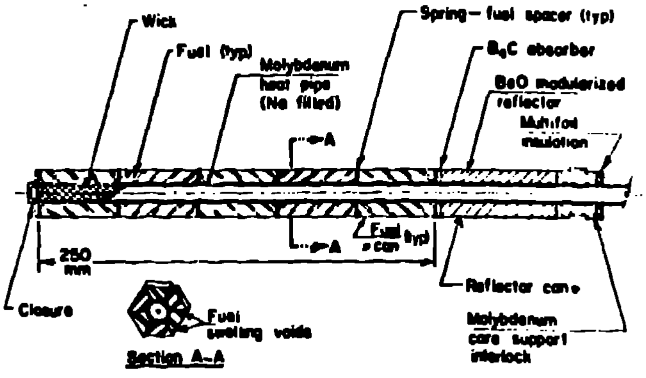

Fig. 3 Heat-pipe fuel element.

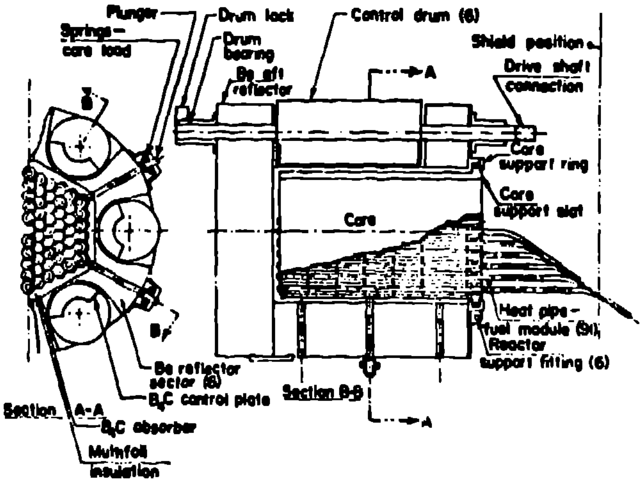

Fig. 4 Heat-pipe reactor assembly.

The core of the reactor consists of a hexagonal array of the interlocking fuel elements just described, as shown in Fig. 4. Radial support is provided by spring loaded plungers indicated in this figure that exert pressure between an external support structure and molybdenum slats that surround the core. More recent thinking is to provide radial support with metal bands around the core and eliminate the need for an external support structure. The core assembly is surrounded by a layer of multifoil thermal insulation and a thin thermal neutron absorber. The purpose of the absorber is to reduce power peaking along the periphery of the core caused by fissions produced by low-energy reflected neutrons. The reflector assembly is connected to the core through the core support ring located at the end of the reactor through which the heat pipes emerge. The axial reflector at the opposite end of the reactor and the radial reflector will be cool compared to the core and could be made from beryllium. However, recent neutronic studies have shown BeO to be the more likely choice because it is a more effective reflector material than beryllium for fast space reactors.[13] Rotating drums containing sectors of B$_4$C are located in the radial reflector assembly to provide control for the reactor. This control could be provided by rotating vanes or shutters instead of B$_4$C loaded drums. The relative effectiveness of these control schemes has not yet been investigated. The choice of reflector control is motivated by the need to minimize the complexity and the size of the core and also by the improvement of control reliability that comes from placing the control elements outside the high temperature and high irradiation environment of the core.

Core Heat-Pipe Design

The feasibility of the reactor system described in this paper depends to a large degree on the successful development of molybdenum/sodium heat pipes capable of axially transferring about 100 MW/m^2 (10 kW/cm^2) of heat at a temperature of 1300-1400 K. Design calculations described below indicate a desired heat pipe outer diameter of 15 mm and a length of 1-2 m. Recent experimental work performed at LASL, aimed in part at such a demonstration, is described in another paper at this conference.[14] One of the tests involved a 25 mm diameter, 1.2 m long stainless steel/sodium heat pipe having a multiple screen-artery (150 mesh) wick structure. This pipe was tested in the temperature range of 900–1150 K and transfered 20 kW (72 $\mathrm{MW/m^2}$ of vapor area) at 1150 K. This heat transfer rate which is much lower than the sonic limit was not an actual limit, but a stable operating point near the expected wicking limit. Extrapolation of the data from this experiment to 1300 K indicates for this rather coarse-mesh wick structure an axial heat transfer rate in excess of 110 $\mathrm{MW/m^2}$. A related experiment involving a 1.8 m long molybdenum/lithium vapor heat pipe of similar diameter but having a corrugated screen (150 mesh) wick structure showed an observed heat transfer limit of 113 $\mathrm{MW/m^2}$ (27 KW) at 1405 K, the maximum temperature reached in the test. Earlier work performed in Italy demonstrated a sodium heat pipe performance of 155 $\mathrm{MW/m^2}$ at 1218 K.[15] This performance was obtained with a 12 mm diameter, 0.5 m long pipe having a wick structure consisting of axial grooves in the pipe wall covered with a very fine screen (508 x 3600 mesh) similar in design to that shown in Fig. 5. These tests show that a heat transfer rate of 100 $\mathrm{MW/m^2}$ at 1300 K is achievable with ample safety margin. However, this rate has not been demonstrated yet for heat pipes that are bent in the configuration required to pass through or around the radiation shield.

For a variety of reasons the preferred heat pipe design is that of a covered groove wick structure such as the one shown in Fig. 5. This structure provides multiple redundant paths for returning the condensed vapor to the heat pipe evaporator. It would be easy to bend and relatively easy to build if an adequate method for grooving molybdenum pipes becomes available. A promising grooving technique is chemical milling. The porous cover would be provided either by a fine mesh screen or by a perforated molybdenum foil produced by photo-etching methods.

Electrical Conversion Systems

The two electrical converter systems already mentioned, thermoelectric and Brayton cycle, show great promise in meeting the requirements of the space power plant under consideration. A third conversion system, thermionic, is being actively developed for nuclear electric propulsion missions[3] which require more power (400-500 kW$_e$) than the present application. Our systems studies show that a 50 kW$_e$ out-of-core thermionic conversion system having an efficiency of 15% at an emitter temperature of 1650 K and a radiator temperature of 900 K would be competitive with the other two systems. However, it would require the Mo-UO_2 reactor technology with lithium vapor heat pipes because, for the long operating lifetime required, the high source temperature is beyond the capabilities of UC fuel. Such a system remains an alternative choice, particularly if the required thermionic performance can be demonstrated in the relatively near future.

The thermoelectric converter modules indicated in Fig. 1 are based on the silicon-germanium technology which appears to be limited to an upper temperature near 1300 K. A state-of-the-art conversion efficiency of 5% has been assumed in the system studies at a cold junction temperature of 800 K. A conceptual module design is shown in Fig. 6.[16] The thermoelectric converters are mounted on the high temperature heat pipes in a concentric arrangement. Several such rings of converters are placed side by side along the heat-pipe in a series-parallel assembly. The rejected heat from the converters is removed by a set of stringer heat pipes which have an annular evaporator section. Not shown is the possibility of thermally coupling the cold junctions of adjacent converter modules for redundancy. The heat flux through the converters is much higher than is employed in current radioisotope thermoelectric generator designs because the heat pipes can operate at radial heat fluxes of several megawatts per square meter. A heat flux of 0.5 $\mathrm{MW/m^2}$ was assumed for this study. As is discussed below in the section on design parameters, significant advantages would be gained if the thermoelectric converter efficiency could be increased to 10%. Consequently, the possibility of improving the silicon-germanium efficiency by reducing the thermal conductivity through the use of additives should be pursued enthusiastically.

The Brayton system displayed in Fig. 2 utilizes two independent, closed, gas-turbine engine cycles for redundancy. In normal operation each would operate at half power. Such turbines have been successfully operated by NASA at a turbine inlet temperature of 1140 K for over 30,000 hours (nearly 3.5 years) without maintenance.[17] The rotating machinery, designed from superalloy technology by AiResearch Manufacturing Company, uses gas-lubricated bearings, thus eliminating all frictional surfaces. The turbine inlet temperature for our application was raised to 1300 K to take advantage of the temperature capability of the UC-ZrC fuel. This high temperature implies the development of a refractory-metal Brayton technology. The core heat pipes operate at 1400 K

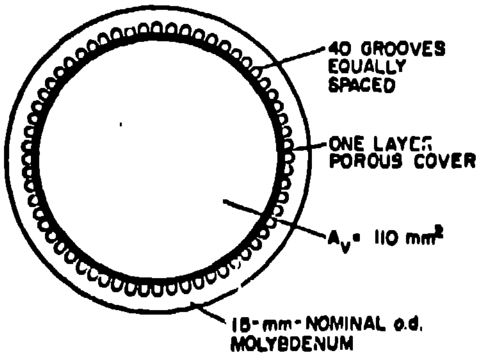

Fig. 5 Core heat-pipe design.

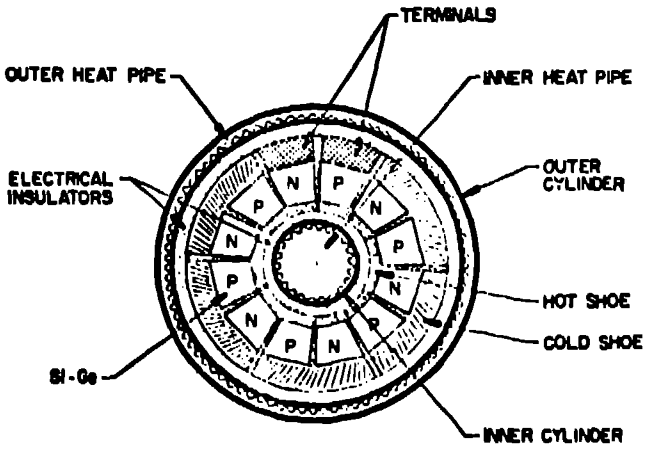

Fig. 6 Thermoelectric design concept[16]

in order to drive the primary heat exchanger. The converter efficiency was assumed to be 25% at a heat rejection temperature of 475 K. However, to account for the significant pumping requirements of the radiator the net electrical conversion efficiency was lowered to 20%. The weight of the primary heat exchanger (excluding the heat pipes which are charged to the reactor) shown in Fig. 2 is included in the Brayton converter weight.

The choice of a rather high radiator temperature for each of the electrical conversion systems discussed in this section was dictated by the process of weight optimization, where efficiency is sacrificed in exchange for a large reduction in radiator weight.

Radiator Designs

The radiator of the thermoelectric systems is reasonably small because the rejection temperature (775 K) is high and it lends itself nicely to an all-heat-pipe design. Parametric systems studies have been performed on the conceptual radiator design shown in Fig. 1.[18] Stringer heat pipes carry the reject heat from the thermoelectric modules along the skin of the conical radiator. The skin consists of several thousand small-diameter, thin-walled, cross heat pipes. The stringer heat pipes are armored to resist meteroid puncture, whereas sufficient area of cross heat pipe is provided to radiate all the waste heat in the unpunctured area remaining at the end of mission life. The most severe constraint imposed on the design was the survival probability of 99% that the radiator be functional at full power at the end of a seven-year mission.

The lightest radiator to emerge from this study consists entirely of beryllium (or beryllium-nickel laminate), potassium vapor heat-pipes. Other materials considered were, in order of increasing weight, Ti-6Al-4V, 316 ss, Inconel 718, TZM-molybdenum and tantalum. Potassium because of its higher latent heat of vaporization and higher liquid transport factor results in lighter systems than cesium or mercury. Because the heat pipe walls are thin and weight is all important, the preferred wick design is a multiple screen-artery system.

The radiator for the Brayton cycle system is very large because the mean rejection temperature is only 475 K (actually, 400-600 K). This means the radiator has to be a folding or telescoping design in order to fit into the cargo bay of the space shuttle. This design limitation poses severe doubts on the practicality of an all heat pipe radiator concept. Consequently, the reference design employed in this study and exemplified in Fig. 2 consists of several independent pumped fluid (NaK) loops to carry heat from the heat rejection heat exchanger down the full length of the radiator through flexible tubing connections. The radiating area is extended through the use of fins or cross heat pipes. The pumps require several kilowatts of electric power.

The radiator design assumed for the thermionic system is similar to that for the thermoelectric system, except for the rejection temperature which is 900 K.

Power Plant Design Parameters

System parameters and operating characteristics for the power plants are listed in Tables I - III. The last two tables show comparisons of thermoelectric, Brayton cycle, and thermionic systems at a power output level of 50 kW_e for a lifetime of 7 years. The reactor designs were sized and optimized for heat removal and criticality at 1 MW_t for all systems. This simplification was adopted because in the power range 0.1-1MW_t, reactor size is a weak function of power level[6] and in the absence of a clearly identified mission it is practical to consider a single reactor design to cover this power range. As discussed in the converter section the selection of a high rejection temperature for each systems reflects a sacrifice in conversion efficiency to reduce radiator size and minimize system weight.

TABLE I
1 MW_t REACTOR DIMENSIONS

Fuel Type	UC-ZrC	$Mo-UO_2$
Equivalent core dia., mm	270	350
Reactor diam., mm	500	580
Core height/dia. ratio	1.0	1.0
Number of core heat pipes	90	90
Width across flats of hexagonal fuel element, mm	27	35
Heat pipe outer diam., mm	15	15
Heat pipe vapor area, mm^2	110	110
Heat pipe length, m	1.5	1.5

TABLE II
WEIGHT SUMMARY FOR 50 kW_e POWER PLANTS, kg

Converters System	Thermo-electric	Brayton	Thermionic
Reactor	400[a]	400[a]	730[b]
LiH Shield[c]	190	130	180
Converters	340	460	110
Radiator	200	280	80
Structure	115	120	110
Total	1245	1390	1210
Specific weight α of total system, (kg/kW_e)	(25)	(28)	(24)

[a] Core composed of UC-ZrC fuel.
[b] Core composed $Mo-UO_2$ fuel.
[c] Assumes a 12° cone half-angle, 10^{13} nvt and 10^7 rad at 25 m.

The reactor design calculations were done for a core height-to-diameter ratio of 1.0 and for a reflector-assembly thickness of 0.1 m. Both of these parameters will be treated as variables in future analyses. As a consequence, the results presented in Table I - III, while representative, are not fully optimized. In general, the design parameters appear reasonable. Fuel swelling due to irradiation, a general concern for long life, high power missions, is not excessive even for the

TABLE III
OPERATING CHARACTERISTICS FOR 50 kW_e POWER PLANTS

Converter System	Thermoelectric	Brayton	Thermionic[c]
Thermal power, MW_t	1.0	0.25	0.33
Electrical conversion efficiency,%	5	20[b]	15
Lifetime, year	7	7	7
Number of core heat pipes	90	90	90
Core heat-pipe temperature, K	1300	1400	1675
Radiator power, MW_t	0.95	0.20	0.28
Mean radiator temperature, K	775	475	900
Average fuel temperature, K	1370	1420	1700
Maximum fuel temperature, K[a]	1480	1440	1730
Maximum fuel ΔT, K[a]	150	40	50
Core heat-pipe axial heat flux, MW/m^2	100	25	33
Core heat-pipe radial heat flux, MW/m^2	1.1	0.3	0.3
Average power density in fuel space, MW/m^3 or W/cm^3	93	23	12
Burnup density, 10^{20} fission/cm^3	6.2	1.5	0.8
Fuel volume swelling, %	4.4	1.5	1
^{235}U burnup, %	3.0	0.7	0.7

[a] Assumes a 1.5 peak-to-average power density ratio.
[b] Adjusted for radiator pumping penalty, converter efficiency is 25%.
[c] Employs $Mo-UO_2$ fuel technology.

1 MW_t thermoelectric power plant.

The weight summary in Table II shows that all systems considered are fairly close for a 50 kW_e power plant. Our studies indicate that if thermoelectric system efficiency could be increased to 10% a weight reduction of about 350 kg could be achieved making that system much lighter than the others. The Brayton system weight could be reduced by eliminating one turbine, but at a significant penalty in system reliability. Because so much of the thermionic power plant weight is in the reactor, it does not appear that much can be done to reduce that system's weight significantly.

Conclusions

A heat-pipe space reactor concept has been described. It was applied to three electrical conversion systems which were compared at a power level of 50 kW_e. The power-plant weights obtained are in a range to make nuclear space power an attractive option. The total spread in system weight for the three power plants is less than 15%. However, it is our opinion that the technology assumed for the thermoelectric system is closer at hand than that assumed for either the thermionic or the Brayton system. The assumed thermoelectric efficiency of 5% is current "state-of-the-art," although this kind of performance is yet to be demonstrated for long times at the converter power densities assumed in the study. The heat flux through the converters is 5 times that employed in current radioisotope generators. While this power density represents a significant extrapolation of current converter designs, it does not imply a new technology. The reliability of thermoelectric converter systems has been amply demonstrated for lifetimes comparable to the currently projected mission lifetimes. In comparison, the refractory-metal technology assumed for the Brayton system is being developed, but it has yet to be demonstrated for long lifetimes. The thermionic technology which is being developed has not yet achieved the 15% conversion performance assumed in the study at a temperature as low as the design emitter temperature of 1650 K nor has the emitter insulation technology required in the out-of-core concept been fully established.

Acknowledgement

This work was performed under the auspices of the U.S. Department of Energy.

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