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CONF - 770302 - - 2

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SUBMITTED TO: AIAA Conference on the Future of
Aerospace Power Systems, March 1-3, 1977,
St. Louis, Missouri

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UNITED STATES
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HEAT PIPE REACTORS FOR SPACE POWER APPLICATIONS*

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Abstract

A family of heat pipe reactors design concepts has been developed to provide heat to a variety of electrical conversion systems. Three power plants are described that span the power range 1-500 kWe and operate in the temperature range 1200-1700 K. The reactors are fast, compact, heat-pipe cooled, high-temperature nuclear reactors fueled with fully enriched refractory fuels, UC-ZrC or UO_2. Each fuel element is cooled by an axially located molybdenum heat pipe containing either sodium or lithium vapor.

Virtues of the reactor designs are the avoidance of single-point failure mechanisms, the relatively high operating temperature, and the expected long lifetimes of the fuel element components.

I. Introduction

The Los Alamos Scientific Laboratory (LASL) in support of the U.S. Energy Research and Development Administration and the National Aeronautics and Space Administration 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. This class of nuclear power plants is designed to meet the broad requirements that are emerging from a variety of mission studies. These requirements are high reliability for lifetimes in the range of 5 to 15 years, and compactness to meet the size and weight constraints of the space shuttle launch. The power plant must meet the required nuclear safety regulations for assembly, launch and possible abort conditions. Finally, the basic reactor design should be adaptable to a variety of electrical conversion systems such as thermoelectric, thermionic, and Brayton cycle converters. This paper discusses some of the advantages and capabilities of heat-pipe-cooled fast reactors and it describes some of the design concepts that have emerged from the current studies.

II. Design Philosophy

The mission requirements for compact size and long lifetimes imply the need for a fast, highly-enriched, densely-fueled reactor, one 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.

Compact power plants require higher temperature technology in order to obtain higher efficiencies in the power conversion systems and/or higher heat rejection temperatures and consequently a smaller radiator. Advanced developments are raising the usable source temperatures of both thermoelectric converters and Brayton turbines above 1300 K. Thermionic converters require a source temperature in excess of 1600 K. Clearly, then the reactor should employ a refractory fuel such as UN, UC, or UO_2. The relative merits of these fuels have been discussed elsewhere.[1] For low power applications the reactor size tends to be limited by the constraint of critical mass. Hence, UN or UC with their higher uranium densities are preferable to UO_2. At high power, reactor size can be determined by the requirements of heat removal and problems of fuel swelling more than by criticality limitations, permitting the use of the more dilute fuel UO_2. The advantages of UO_2 are its inertness in air, complete stability up to extreme temperatures, and its demonstrated good irradiation behavior particularly when contained in a refractory metal matrix.

A practical fuel element design consists of a molybdenum heat-pipe bonded along the axis of a hexagonal refractory fuel body. The fuel may be segmented both axially and radially to accommodate thermal expansion and fuel swelling. The use of heat pipes 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 slightly degraded but the power plant is not shutdown 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 is also 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 very small mass flows. Consequently, the inventory of coolant fluid is extremely small compared to a liquid metal system. The problems of coolant activation are correspondingly reduced 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.[2,3,4] As mentioned earlier, the core heat pipes can be connected directly to thermoelectric or thermionic converters, or, through a heat exchanger, they can be coupled to a dynamic converter such as the Brayton cycle.

The reactor designs described below all use reflector control. There are several reasons for this choice; it keeps the complexity of the core down to a minimum and results in a smaller core. Placing the control elements outside of the high temperature and high irradiation environment of the core improves the reliability of the control

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*Work performed under the auspices of the U.S. Energy Research and Development Administration and the National Aeronautics and Space Administration with the cooperation of the Jet Propulsion Laboratory.
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system. Indeed, excellent long life performance for the major components of reflector control systems has been demonstrated in a series of tests performed by Atomics International.[5,6]

These fast heat pipe reactors have attractive nuclear safety features.[7] They have a negative temperature coefficient of reactivity, and it appears that they can be designed to remain subcritical in case of water immersion, an important safety feature for space launches.

III. Computational Tools

Two very useful computer programs have been developed to assist in the design of heat-pipe cooled fast reactors. One is a heat pipe design code and the other is a heat pipe reactor design code.

The heat pipe design code treats a variety of heat pipe designs, namely the homogeneous wick, eccentric annulus, circular arteries, grooved walls, and even the helical gutters. The desired axial heat flux, the operating temperature, and the heat pipe diameter are specified and the characteristic wick dimension and minimum capillary requirement are computed so as to minimize the combined pressure drop in the vapor and liquid phases of the working fluid. Once these dimensions are obtained that define the heat pipe design, the heat transfer rate of the heat pipe is computed as a function of operating temperature. This calculation yields the performance of the heat pipe under off-design conditions. The liquid and vapor pressure profiles along the length of the pipe are also calculated. These profiles are useful in analyzing heat pipe performance and in making comparisons with experimental data.

The reactor design code was developed to facilitate parametric studies of fast, heat-pipe-cooled reactors. The material description of the reactor and the operating parameters such as power level, heat-pipe temperature, lifetime, etc., are specified. The code then computes the minimum core diameter and the corresponding void fraction that satisfy the conflicting constraints of criticality and heat removal. If desired, the core diameter and void fraction may be specified as well. All the important operating characteristics of the reactor are subsequently calculated: dimensions, weights, number of heat pipes, power densities, temperatures, burnup, fuel swelling, and reactivity requirements. The program relies on a data base of neutron reactivity calculations. The fuel swelling estimates are based on experimental data obtained by the Battelle Memorial Institute[8] and LASL,[9] and are summarized in Fig. 1.

IV. Mini-Reactor 10-100 kWt

A reactor referred to here as the "Mini-Reactor" was conceptualized to provide 1 to 5 kWe using high temperature silicon-germanium thermoelectric converters. Assuming a nominal electrical conversion efficiency of 6%, the reactor power is in the range of 10-100 kWt. The power plant was designed for a core heat-pipe temperature of 1300 K and a radiator temperature of 770 K. This rather high rejection temperature sacrifices converter efficiency in exchange for a significant reduction in radiator size. An artist's rendition of the power plant is shown in Fig. 2. The reactor core consists of 19 heat-pipe cooled, fully enriched 90UC-10ZrC (they could be UN), hexagonal fuel elements. The core is thermally shielded on all sides with multifoil insulation. Reactor control is provided by changing the configuration of the BeO (or Be) reflector, in this case by moving sliding wedges. The core heat pipes, which are molybdenum with sodium vapor, are coupled at each end of the core by a heat transfer block to a set of converter heat pipes that transfer the heat to a thermoelectric converter module located behind the radiation shield. The heat transfer blocks (molybdenum or niobium) serve as axial neutron reflectors as well. The two converter modules each consist of two planar arrays of thermoelectric converters that sandwich the set of converter heat pipes. The converter arrays are cooled directly by the radiator heat pipes. The entire power plant is supported by a telescoping boom to the payload. System parameters and operating characteristics for the power plant are listed in Table I for two power levels.

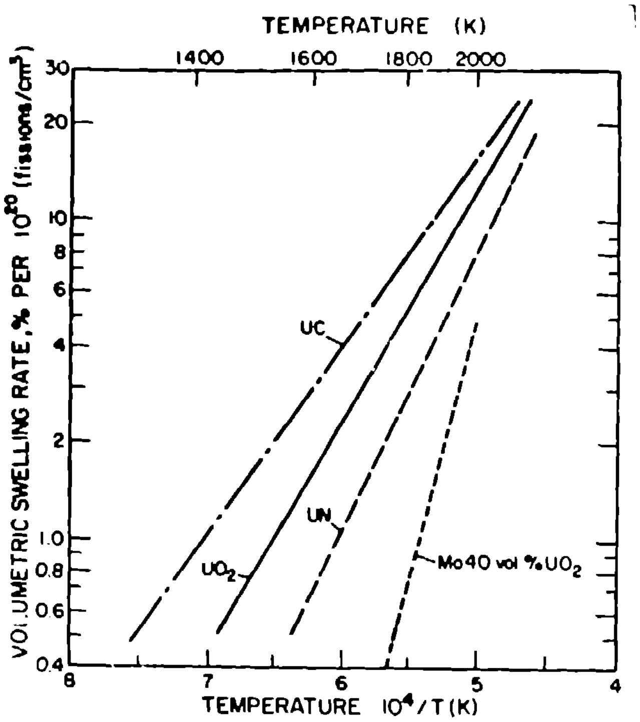


Fig. 1. Fuel swelling.[8,9]

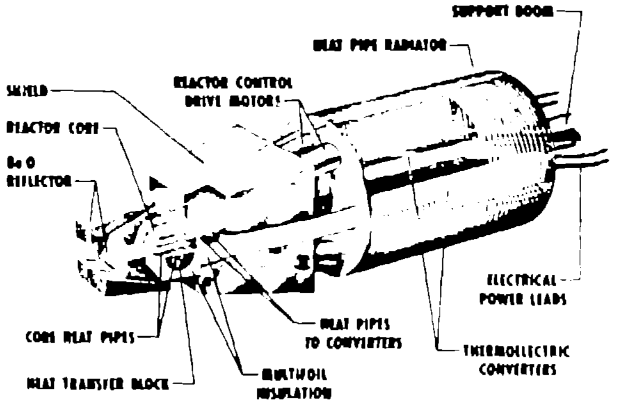


Fig. 2. Mini-Reactor.

Table IA. Mini-Reactor System Parameters

	1-5 kWe
Core equivalent diameter, mm	200
Reactor equivalent diameter, mm	400
Core height/diameter ratio	1
Number of core heat pipes	19
Width across flats of hexagonal fuel element, mm	44
Heat pipe outer diameter, mm	19

Table IB. Mini-Reactor System Weight Summary, kg

	1 kWe	5 kWe
Fuel (90UC-10ZrC)	55	55
Reflector and heat transfer blocks (Be and Nb)	110	110
Heat pipes	15	25
Control motors	15	15
Reactor support structure	15	15
LiH shield*	90	120
Thermoelectric system	6	30
Radiator	4	20
Total	310	390

*Assumes 12° cone half angle, 10^{13} nvt and 10^7 rad at 10 meters.

Table IC. Mini-Reactor Operating Characteristics

	1 kWe	5 kWe
Thermal power, kWt	16	80
Lifetime, years	7	7
Number of core heat pipes	19	19
Core heat pipe temperature, K	1300	1300
Radiator temperature, K	770	770
Average fuel temperature, K	1310	1350
Maximum fuel temperature, K*	1330	1430
Maximum fuel ΔT, K*	23	113
Core heat-pipe axial heat flux, MW/m^2	2.5	13
Average power density in fuel space, MW/m^3 or W/cm^3	3.7	19
Burnup density 10^{20} fission/cm^3	0.21	1.1
Fuel volume swelling, %	0.1	0.7
^{235}U burnup, %	0.1	0.5

*Assumes a 1.5 peak-to-average power density ratio.

Multiple redundancy against heat pipe failure is provided not only by the cross coupling of the converter heat pipes with the core heat pipes at both ends of the core, but also by thermal coupling of the radiator heat pipes at the converter modules. Assembly of the plant is relatively easy because the reactor can be separated from the system at the heat transfer blocks, and the radiator can be decoupled at the converter modules. The power plant is very compact, its weight being influenced mostly by the shielding requirements.

The practicality of the mini-reactor concept is made possible by the low power densities in the various components of the system. The core size is essentially determined by the critical mass requirements of the fuel. The simple core configuration results from the low power density in the fuel. The reactivity loss due to burnup and the fuel swelling are practically negligible even for a seven-year mission life. The use of a simple heat transfer block is permissible because the heat fluxes and corresponding temperature losses are small. The heat flux to the thermoelectric converters, however, can be made considerably higher than is employed in current radioisotope thermoelectric generator designs because heat pipes can operate at radial heat fluxes of several hundred watts/cm^2. Taking even limited advantage of the potentially large heat flux can result in very significant weight savings for the converter modules. A heat flux of 50 W/cm^2 was assumed for this study.

The growth potential of the mini-reactor above 100 kWt is limited. The number of core heat pipes must increase, the heat transfer blocks become impractical and it becomes important to try to couple the conversion system directly to the core heat pipes, if possible. Turning the reactor so that its axis of symmetry coincides with that of the rest of the power plants alleviates some of the design problems encountered with increasing the power range of the mini-reactor. Such a design is discussed below

V. Mid-Power Range (MPR) Reactor (100-1000 kWt)

The heat pipe reactor that is discussed in this section will be referred to as the MPR-reactor. A schematic drawing of a complete 1 MWt MPR-reactor power plant is shown in Fig. 3. Design studies have been carried out at a core heat pipe temperature of 1400 K over the power range 200-1000 kWt. The core heat pipes emerge from one end of the MPR-reactor in Fig. 3 and are bent to fan out and go around the radiation shield toward a circumferential bank of silicon-germanium thermoelectric converter modules. The coupling connection between the core heat pipes and the converter heat pipes, shown midway along the radiation shield, is intended primarily to facilitate assembly. This connection could also be made at the juncture between the

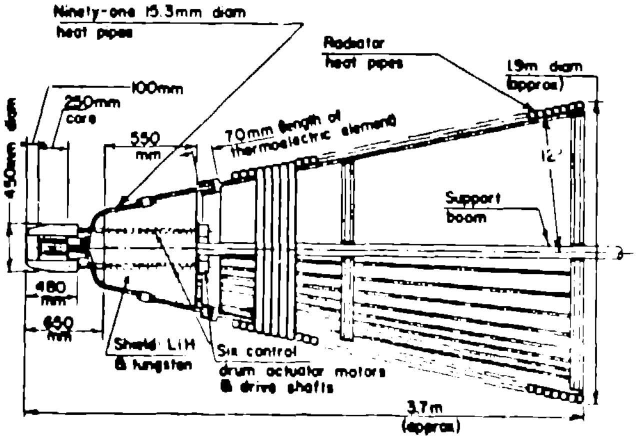


Fig. 3. Design of 1 MWt thermoelectric MPR-reactor system.

converters and the radiator. The thermoelectric modules are mounted on the high-temperature heat pipes in a concentric fashion as shown in Fig. 4.[10] The cold junctions of adjacent thermoelectric converter modules are coupled together thermally for redundancy. The rejected heat from the converters is removed by a set of stringer heat pipes. This energy is radiated to space at 770 K by a series of circumferential heat pipes. Meteroid protection is achieved by armoring and by the redundancy of the entire assembly.

A power plant using Brayton cycle converters is shown in Fig. 5. The design employs two Brayton cycle converters for redundancy. Each converter is on a separate gas flow loop and is capable of handling the full reactor power. In normal operation both converters operate at half power. The high temperature heat exchanger located above the reactor is actually two separate heat exchangers. They are designed in such a way that each one removes heat from every core heat pipe.

The MPR-reactor is shown in Fig. 6, and a fuel element for the core is described in Fig. 7. The latter consists of a molybdenum/sodium heat pipe surrounded by UC-ZrC fuel that is segmented radially and longitudinally 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). The fuel section of the heat pipe is followed by a reflector segment of BeO canned in molybdenum and by a solid molybdenum segment. The latter, by interlocking with its adjacent neighbors, serves as a rigid support slab for the core, leaving the opposite end of the core free to expand longitudinally. A thin layer of B_4C between the fuel and the BeO segments absorbs low-energy reflected neutrons. The temperature of the BeO and molybdenum segments is governed by that of the heat pipe.

The core of the MPR-reactor consists of a hexagonal array of the interlocking fuel elements described above. Radial support is provided by spring-loaded plungers that exert pressure between an external support structure and molybdenum slats that surround the core. This core assembly is surrounded by a layer of multifoil thermal insulation and a thin thermal neutron absorber. The reflector assembly and the external support structure are connected to the core through the core support ring located at the reactor end facing the radiation shield. The axial reflector at the end away from the shield and the radial reflector are beryllium. Rotating drums containing sectors of

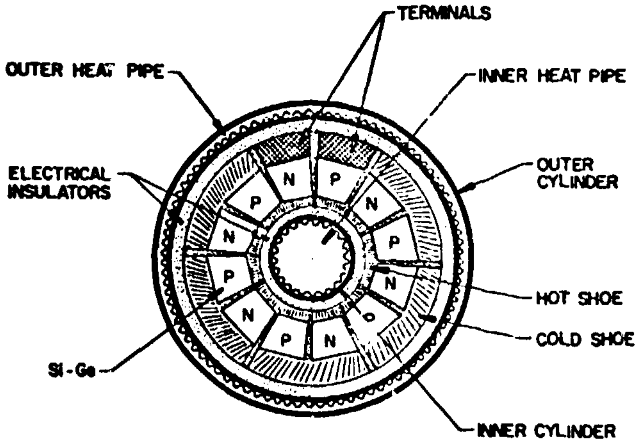


Fig. 4. Thermoelectric module concept.[10]

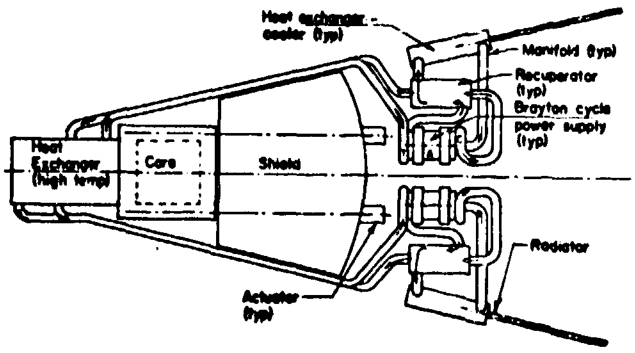


Fig. 5. Schematic of Brayton cycle MPR-reactor system.

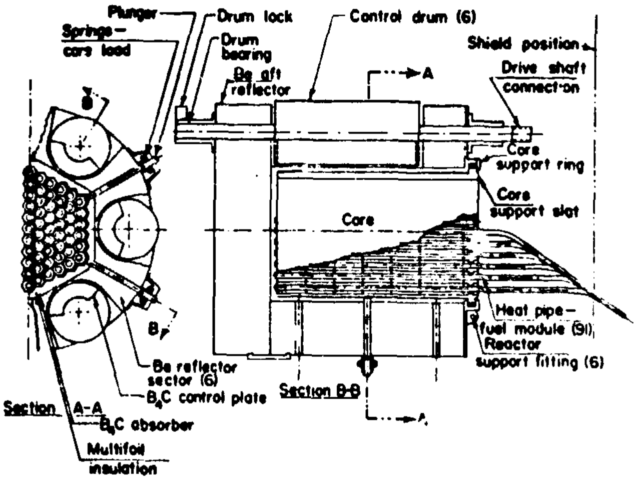
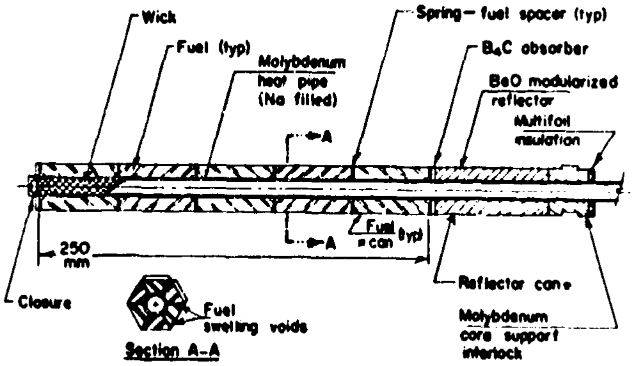


Fig. 6. Core assembly of MPR-reactor.



* Thin walled, therefore, not shown.

Fig. 7. Heat-pipe fuel element for MPR-reactor.

B_4C are located in the radial reflector assembly to provide control for the reactor.

Systems parameters and operating characteristics for the power plant are listed in Table II for three power levels. The reactors are based on a core diameter optimized for heat removal and for criticality. An axial heat-transfer limit of 100 MW/m^2 was imposed on the heat pipe performance. The design calculations were done for a core height-to-diameter aspect ratio of 1.0. At the time of this writing additional neutronic calculations are being performed to allow optimization of the aspect ratio. A fixed reflector assembly thickness of 0.1-m was selected arbitrarily for all power levels. The reflector thickness will be treated as a variable in future analysis. The reactor characteristics of Table IIC seem fairly reasonable with the exception of fuel swelling, which is becoming excessive at 600 kWt and above. The fuel swelling is directly proportional to power density. Consequently it can be reduced by increasing the core diameter and/or the core height. Increasing the latter is preferable in that the corresponding change in shield diameter would be smaller. Swelling is also a strong exponential function of fuel temperature as shown in Fig. 1. Consequently, significant gains can be made by keeping the fuel ΔT small, which can be done by adding more heat pipes. What is evident from this analysis is that as the power density exceeds 100 MW/m^3 (100 W/cm^3), fuel swelling during a mission life of seven years may exceed 10 vol% and it may be the dominant factor in determining reactor size.

Table IIA. MPR-Reactor System Parameters

	200 kWt	600 kWt	1000 kWt
Equivalent core diameter, mm	200	220	250
Reactor diameter, mm	400	420	450
Core height/diameter ratio	1.0	1.0	1.0
Number of core heat pipes	37	61	91
Width across flats of hexagonal fuel element, mm	31	27	25
Heat pipe outer diameter, mm	14	14	15

Table IIB. MPR-Reactor System Weight Summary, kg

	200 kWt	600 kWt	1000 kWt
Fuel (90UC-10ZrC)	54	64	81
Reflector (Be and BeO)	85	97	115
Heat pipes	24	54	108
Control	33	33	33
Reactor support structure	14	17	23
Total reactor	210	265	360
Thermoelectric system:			
LiH shield*	78	100	120
Converters (including coupling to radiator)	80	240	400
Radiator	52	155	260
Total (thermoelectric power plant)	420	760	1140
Specific weight (α) of total thermoelectric system, kg/kWe	42	25	23
(kWe)	(10)	(30)	(50)
Brayton cycle system:			
LiH shield*	65	90	110
Converters (including primary heat exchanger)	475	925	1280
Radiator	360	1070	1790
Total (Brayton cycle power plant)	1110	2350	3540
Specific weight (α) of total thermoelectric system, kg/kWe	22	16	14
(kWe)	(50)	(150)	(250)

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*Assumes a 6° cone half angle, 10^{13} nvt and 10^7 rad at 25 meters.

Table IIC. MPR-Reactor Operating Characteristics

	200 kWt	600 kWt	1000 kWt
Electrical power output, kWe (thermoelectric, $\eta = 5\%$)	10	30	50
Electrical power output, kWe (Brayton, $\eta = 25\%$)	50	150	250
Lifetime, years	7	7	7
Number of core heat pipes	37	61	91
Core heat pipe temperature, K	1400	1400	1400
Radiator temperature, K (thermoelectric)	775	775	775
Radiator temperature, K (Brayton)	475	475	475
Average fuel temperature, K	1460	1480	1470
Maximum fuel temperature, K*	1560	1610	1570
Maximum fuel ΔT, K*	146	179	140
Core heat-pipe axial heat flux, MW/m^2	62	100	98
Average power density in fuel space, MW/m^3 or W/cm^3	47	117	154
Burnup density, 10^{20} fission/cm^3	2.7	6.7	8.9
Fuel volume swelling, %	4	10	12
^{235}U burnup, %	1.3	3.2	4.3

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*Assumes a 1.5 peak-to-average power density ratio.

Detailed analysis of total system weight indicates that only a small penalty is paid by operating a 1 MWt MPR-reactor at 200 kWt as compared to operating a reactor optimized for 200 kWt. This important result means that a single reactor design could adequately cover the power range 0.1 to 1.0 MWt.

VI. Out-of-Core Thermionic Reactor (3 MWt)

Conceptual design studies have been performed on a 3 MWt reactor that powers a nominal 500 kWe out-of-core thermionic conversion system.[1,11] The power plant is designed for an electric propulsion system for deep space missions. Mission durations of up to 12 years are anticipated with an equivalent of 75,000 hours of full power operation. The concept is shown in Figs. 8 and 9. The power plant design assumes the development of an advanced thermionic conversion technology capable of achieving a bus bar efficiency of 15% at an emitter temperature of 1650 K.

Waste heat from the converters is carried around the radiation shield by 18 independent NaK cooling loops to the heat-pipe primary radiator which operates at 925 K. Mercury thrusters for the space craft are located just aft of the primary radiator. They are pointed at an angle away from the main axis of the spacecraft so that the exhaust

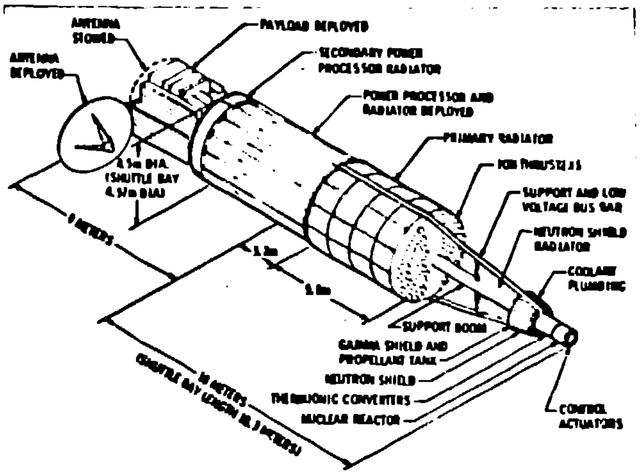

Fig. 8. Nuclear electric propulsion spacecraft.

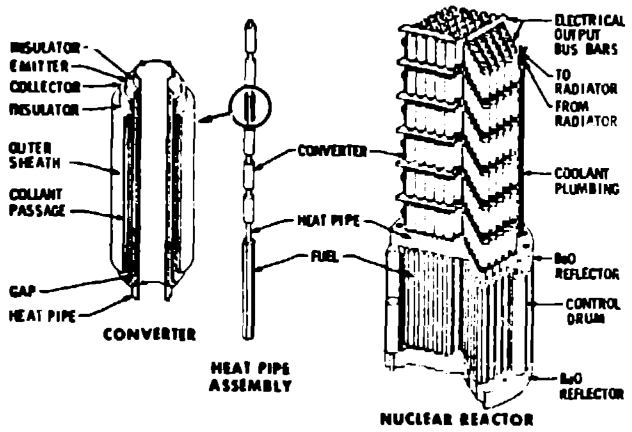

Fig. 9. Out-of-core thermionic reactor concept.

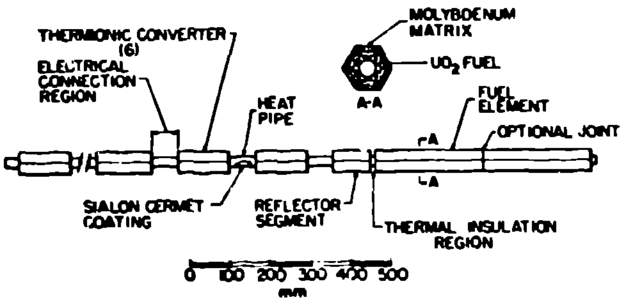

Fig. 10. Fuel element for out-of-core thermionic reactor.

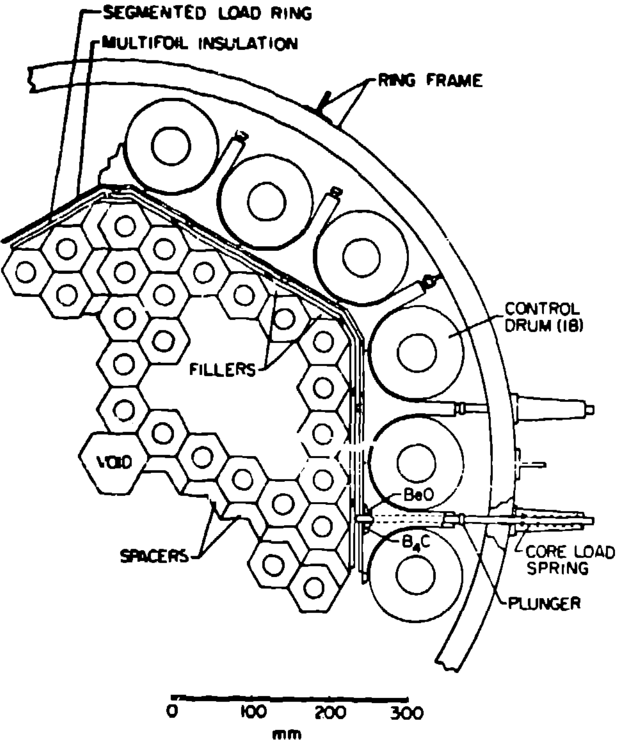

Fig. 11. Cross section of out-of-core thermionic reactor.

misses the radiation shield. The waste heat radiator for the payload and the payload itself are designed to slide inside the primary radiator for shuttle launch.

For simplicity of design, the reactor is coupled to the conversion system with straight heat pipes. The penalty for this choice is that the core diameter is governed by the spacial requirements of the converters with the result that it is larger than that of an optimum design.

The fuel elements shown schematically in Fig. 10 consist of a molybdenum, lithium vapor heat pipe, bonded along the axis of a molybdenum hexagonal matrix imbedded with small UO_2 pellets. The thermionic converters are bonded at the condenser end of the heat pipe. A molybdenum-sialon cermet sleeve is sandwiched between the pipe and the converters to provide electrical insulation.[12]

Use of the UO_2 pellet fuel concept is possible because the core is large enough that heat removal and criticality can be achieved with dilute, but fully enriched, fuel. Advantages are that the fuel body has mechanical and thermal characteristics close to those of molybdenum. It is easily bonded to a molybdenum heat pipe and it permits assembly of the reactor prior to insertion of the UO_2 pellets. The swelling characteristics are unknown but have been assumed similar to that shown in Fig. 1 for a 60 Mo-40 UO_2 cermet having nominally the same UO_2/Mo concentration ratio.

A cross-sectional view of the reactor is shown in Fig. 11. The hexagonal core consists of 90 fuel elements. It is sectioned in three identical bundles of 30 fuel elements separated by 20-mm radial gaps. These gaps and the central void are necessary to accommodate large electrical bus bars in the converter assembly. Each of the three core sections is designed to provide a symmetrical series/parallel arrangement for the converter electrical connection. The core is power flattened radially (by varying the fuel loading) to obtain a uniform power output from all the converters. Assembly of the reactor is quite similar to that of the MPR-reactor described above. Spring-loaded plungers hold the core together radially. The core is surrounded on all sides including the ends by a thermal shield, a thin thermal neutron absorber, and a BeO reflector. It may be possible to substitute beryllium in the reflectors except for one end reflector which has to be at the heat pipe temperature. Again, the radial reflector contains boron loaded rotating drums for control of neutron reactivity. Systems parameters are listed in Tables IIIA and IIIB, and operating characteristics in Table IIIC.

A comparison of this reactor with the MPR-reactor shows that the specific weight of the power plant is slightly greater for the thermionic system than for the MPR-reactor with brayton cycle conversion even though the power level of the former is greater. This comparison is deceptive and is the result of several factors. It is partly a consequence of the more advanced bent heat-pipe technology assumed for the MPR-reactor system. Bending the heat pipes in the out-of-core thermionic systems would allow a reduction in core diameter because the present power density and corresponding fuel swelling are rather modest. It would also allow placing the shield between the reactor and the thermionic converters. Both these changes would result in significantly lowering the shield weight. In addition, as evident from the footnotes in Tables IIB and IIIB, the shields for the two systems are not designed to the same criteria. Putting the two designs on the same relative basis would result in substantial weight savings in favor of the thermionic system. Finally, it must be remembered that in comparing systems specific weight, while an important parameter, is not the only factor. In particular, the redundancy to single-point failure of the thermionic system is much higher than that of the MPR-reactor with a dynamic cycle conversion system.

VII. Conclusions

A brief comparison has been presented of three nuclear space power systems covering the rather broad power range 1-500 kWe (16-3200 kWt). This comparison while seeking to demonstrate that heat pipe cooled reactors can be designed to operate effectively over this power range, also serves to illustrate the problems facing the designer at different power levels. The Mini-reactor system, which is designed to operate below 100 kWt is the simplest to assemble. The reactor design is governed basically by the constraints of critical mass for the chosen fuel. As power level is raised to the range 100-1000 kWt, attention shifts to the requirements of heat removal from the core. These requirements are no longer trivial and simple heat transfer solutions such as the heat-transfer blocks in the Mini-reactor system are no longer feasible. Enlargement of the reactor is necessary because the volume fraction occupied by the core heat pipes increases substantially. The higher power density in the core necessitates an increase in the number of heat pipes. As a result, the complexity of the system increases also. At the core temperatures of interest here, problems of fuel swelling arise in the mid-power range and they dominate the reactor design in the megawatt range. As an example, the 3 MWt out-of-core thermionic reactor could not be designed with UC fuel because fuel swelling would be intolerable. The solution to the problem of fuel swelling is either to reduce the power density by increasing the core size or to shift to a higher strength fuel such as $MoUO_2$ — also at the expense of larger core size. Fortunately, as power level increases reactor weight becomes a smaller fraction of the total system weight so that larger and less dense reactors are a practical solution.

Table IIIA. Out-of-Core Thermionic System Parameters

Core equivalent diameter, mm	560
Reactor diameter, mm	760
Reactor height, mm	760
Core height/diameter ratio	1.0
Number of core heat pipes	90
Width across flats of hexagonal fuel element, mm	54
Heat pipe outer diameter, mm	28

Table IIIB. Out-of-Core Thermionic System Weight Summary, kg

Fuel ($Mo-UO_2$	932
Reflector (BeO)	673
Heat pipes	364
Control motors	100
LiH shield*	2030
Thermionic conversion system	3038
Primary radiator	793
Support structure	400
Total system	8330

*Assumes an 11.5° cone half angle, 10^{12} nvt and 10^6 rad at 15 meters. Part of the shielding is provided by the mercury propellant tank.

Table IIIC. Out-of-Core Thermionic System Operating Characteristics

Electrical power output, kWe	500
Thermal power level, MWt	3.2
Nominal conversion efficiency, %	15
Lifetime at full power, years	8.6
Number of core heat pipes	90
Core heat-pipe temperature, K	1675
Radiator temperature, K	925
Average molybdenum matrix temperature, K	1740
Maximum molybdenum matrix temperature, K*	1875
Maximum molybdenum matrix ΔT, K*	200
Core heat-pipe axial heat flux, MW/m^2	84
Average power density in $Mo-UO_2$ space, MW/m^3 or W/cm^3	34
Burnup density in $MoUO_2$, 10^{20} fission/cm^3	8.3
Fuel volume swelling, %	1
^{235}U burnup, %	4.2

*Assumes a 1.5 peak-to-average power density ratio.

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