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HEAT PIPE NUCLEAR REACTOR FOR SPACE POWER*

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Abstract

A heat-pipe cooled nuclear reactor has been designed to provide 3.2 MWth to an out-of-core thermionic conversion system. The reactor is a fast reactor designed to operate at a nominal heat pipe temperature of 1675 K. Each reactor fuel element consists of a hexagonal molybdenum block which is bonded along its axis to one end of a molybdenum, lithium vapor, heat pipe. The block is perforated with an array of longitudinal holes which are loaded with UO_2 pellets. The heat pipe transfers heat directly to a string of six thermionic converters which are bonded along the other end of the heat pipe. An assembly of 90 such fuel elements forms a hexagonal core. The core is surrounded by a thermal radiation shield, a thin thermal neutron absorber and a BeO reflector containing boron loaded control drums.

INTRODUCTION

This study describes the conceptual design of a space nuclear reactor which provides 3.2 MWth of power to a 500 kWe out-of-core thermionic conversion system described elsewhere.(1) The reactor is a fast reactor, heat-pipe cooled such that each fuel element of the core is directly coupled via a heat pipe to a string of thermionic converters as shown in Fig. 1. The reactor is unusual compared to heat-pipe cooled reactor designs previously published(2-7) in several respects. The power level which was selected to meet the needs of electric propulsion for large payloads to the distant planets is considerably higher than that previously considered. The nature of the space missions currently anticipated by the National Aeronautics and Space Administration (NASA) indicates a lifetime requirement of

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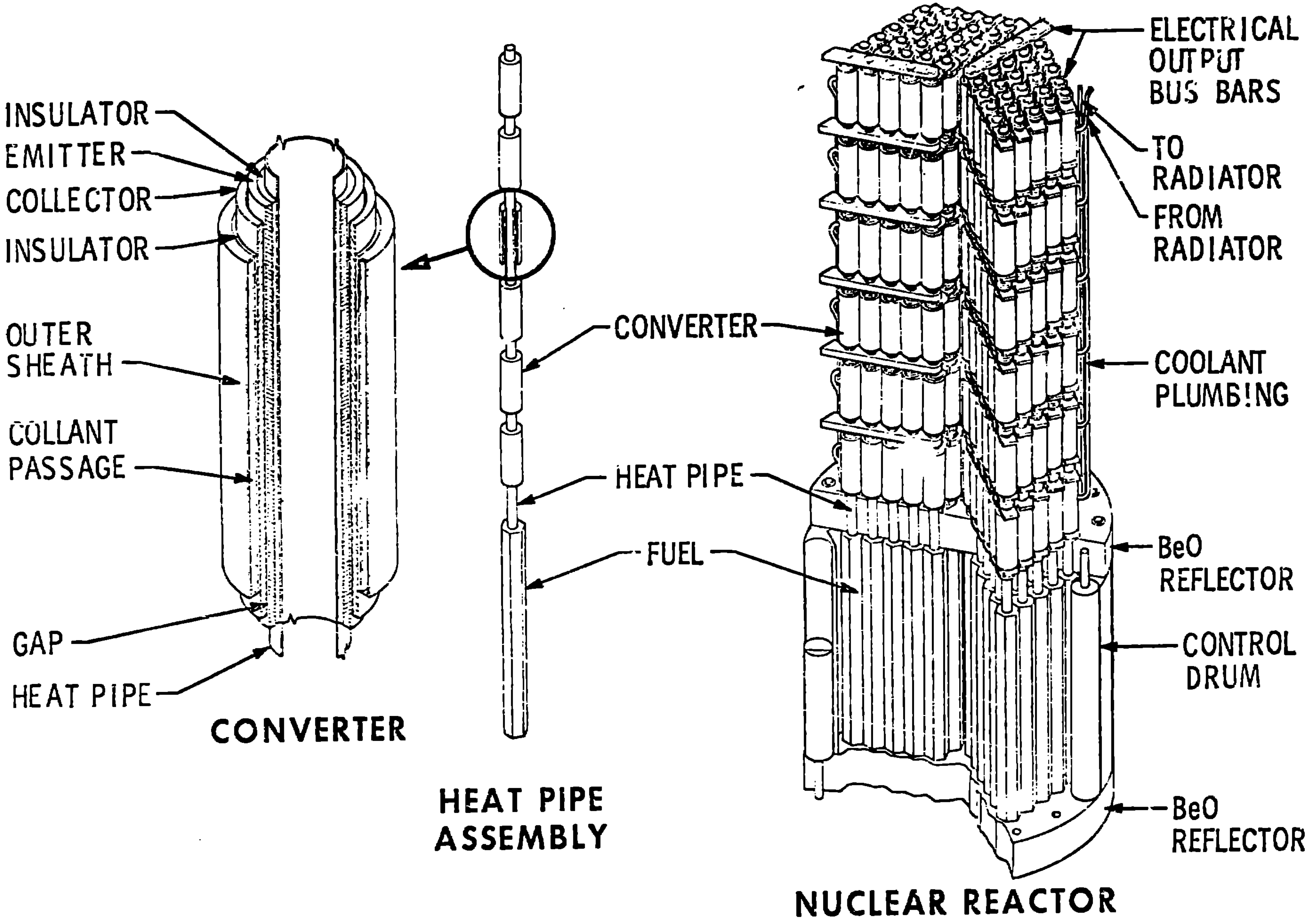

Fig. 1. Out-of-core thermionic reactor concept.

up to 75,000 full power hours, also greater than previous studies. The current design assumes the realization of an advanced thermionic conversion technology capable of achieving a bus bar efficiency of 15% at an emitter temperature of 1650 K. This rather low temperature allows the use of molybdenum heat pipes which are easier to fabricate than the tungsten pipes considered in previous out-of-core thermionic designs. The requirement for large power has caused the reactor to become sufficiently large that neutron criticality can be achieved with somewhat diluted fuels. This relaxation of criticality constraints together with the low thermionic emitter temperature has led to the selection of a rather attractive fuel consisting of a molybdenum metal matrix loaded with small UO_2 pellets.

The key to the entire concept lies in the successful development of an electrical insulator that is sandwiched between each heat pipe and the thermionic converters. This insulator should bond readily to the heat pipe and the thermionic emitters, it should have a good thermal conductivity while able to electrically isolate at 1650 K the converters from the heat pipes. Current research at the Jet Propulsion Laboratory,[8] indicates that a molybdenum sialon cermet is a promising candidate for this task.

DESCRIPTION OF THE REACTOR

The fuel elements which make up the core of the reactor consist of a molybdenum, lithium vapor, heat pipe bonded along the axis of a hexagonal fuel body as shown schematically in Fig. 2. The selection of the fuel which consist of a molybdenum matrix imbedded with small UO_2 pellets is discussed below, as is the heat pipe design. A molybdenum sialon cermet sleeve is bonded to the condenser end of the heat pipe to provide electrical insulation for the thermionic converters. The dimensions of the fuel element are listed in Table I.

An assembly of 90 fuel elements forms a hexagonal core. The core is sectioned in three identical parts comprising 30 fuel elements each as shown in more detail

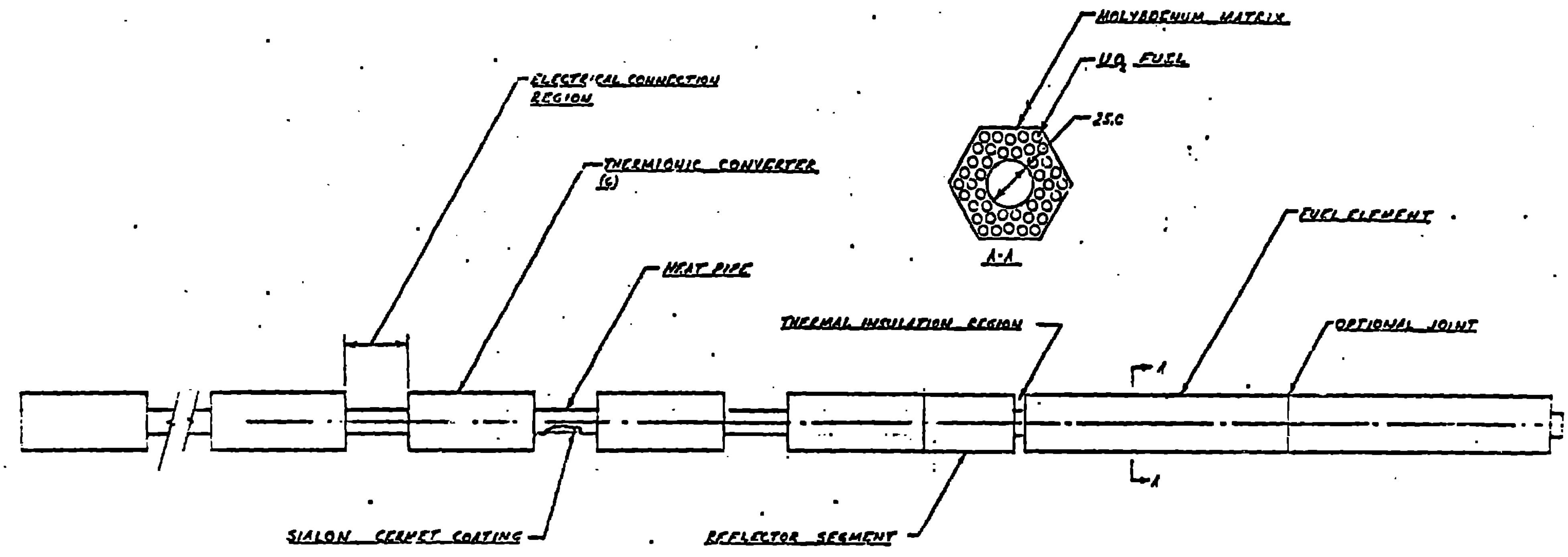

Fig. 2. Schematic design of heat pipe fuel element.

Table I. Description of Mo-UO_2 Heat-Pipe Fuel Element

Width across hexagonal flats, mm	54.0
Equivalent mean diameter, mm	56.7
Length of fuel section, mm	560
Overall heat pipe length, mm	1920
Mo heat pipe outer diameter, mm	28.0
Vapor passage diameter, mm	23.3
Vapor passage area, mm^2	426
Mo-UO_2 fuel volume fraction	0.755
UO_2 volume fraction (assuming 100% dense)	0.243
Mo matrix volume fraction	0.453
Heat pipe Mo tube volume fraction	0.064
Heat pipe liquid Li volume fraction	0.011
Heat pipe vapor volume fraction	0.169
UO_2 porosity and swelling allowance fraction	0.060

in Fig. 3. Each section is separated by a 20 mm gap. This core configuration was dictated by the requirements of the thermionic converter system as a consequence of the direct coupling between core and converters. The three sections were designed to provide a symmetrical series/parallel arrangement for the converter electrical connections. The three 20 mm gaps accommodate electrical bus bars for the converters. The center-to-center spacing, or pitch, between fuel elements was also determined by the dimensions of the converters. Several molybdenum load rings surround the core. Spring-loaded plungers between the load rings and a support structure located outside the reactor, hold the core together. The core region is surrounded on all sides, including top and bottom, by a thermal-radiation heat shield, a thin thermal-neutron absorber, and a BeO reflector. The neutron absorber reduces power peaking produced at the periphery of the core by reflected low energy heat. The radial reflector contains boron loaded rotating drums for control of neutron reactivity. The dimensions and weights of the reactor are shown in Tables II and III.

REACTOR PERFORMANCE

The operating characteristics of the reactor are listed in Table IV. The power density in the fuel is rather modest. The axial heat flux down the heat pipes of 84 MW/m^2 is fairly high but heat pipes have been operated at twice this heat flux.[9]

The temperatures listed for the fuel molybdenum matrix were calculated using the general two-dimensional heat transfer code AYER.[10] The hexagonal fuel body containing 60 $^v/o$ molybdenum was assumed arbitrarily to have 42 pellet holes symmetrically arranged in two rows around the heat pipe. Varying the number and size of the pellet holes at a constant molybdenum volume fraction should not influence greatly the maximum matrix temperature. However it would have a significant effect on the maximum pellet temperature. For this reason the latter temperature was not listed in Table IV, but it will be in the range of 1900-2000 K.

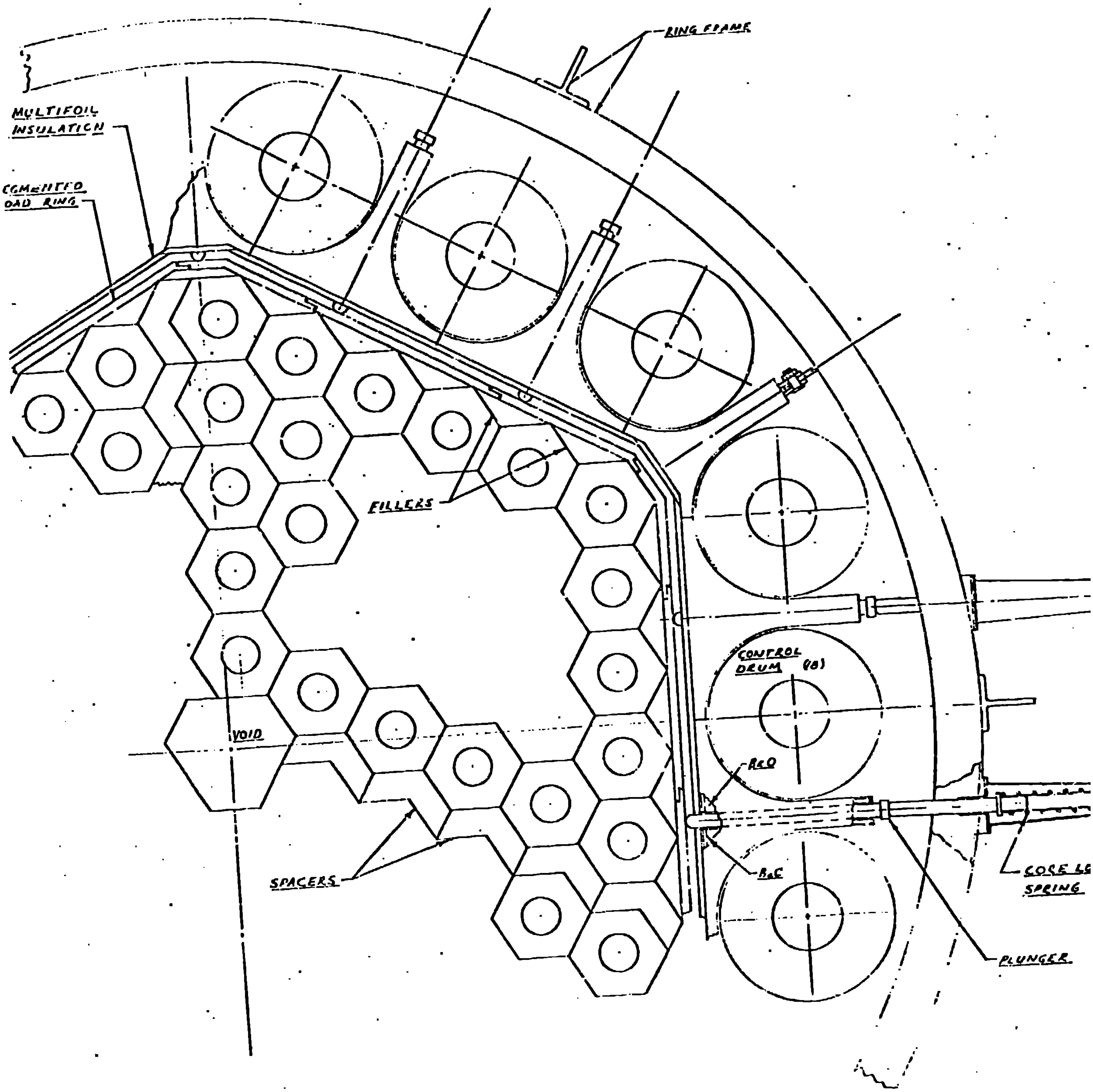

Fig. 3. Reactor cross-section.

Table II. Reactor Dimensions

Maximum core diameter, mm	621
Equivalent mean core diameter, mm	560
Maximum reactor diameter, mm	820
Core length, mm	560
Reactor length, m	760
Nominal reflector thickness, mm	100
Pitch spacing, mm	54.0
Number of heat pipe fuel elements	90
Core void volume fraction (center hole and three 20 mm radial gaps), %	7.7
Overall length of reactor and heat pipes, mm	2020

Table III. Reactor Weights

		Weight (kg)
Mo-UO_2 fuel, total weight		932
UO_2 only	338	
^{235}U only	278	
90 molybdenum heat pipes		364
BeO reflector		673
Control system		100
Reactor support structure (assume 5%)		103
Total reactor and heat pipes		2172

Table IV. Reactor Operating Characteristics

Electrical power output, kWe	500
Thermal power level, MWth	3.22
Nominal electrical conversion efficiency, %	15
Lifetime at full power, h	75,000
Number of fuel elements	90
Average power density in Mo-UO_2 fuel volume, MW/m^3 or W/cm^3	33.5
Average power density in UO_2 pellets (assuming 100% dense), MW/m^3 or W/cm^3	104
Power per heat pipe, kW	35.8
Heat pipe axial heat flux, MW/m^2	83.9
Heat pipe radial heat flux, kW/m^2	873
Heat pipe temperature, K	1675
Average fuel Mo matrix temperature, K	1740
Maximum fuel Mo matrix ΔT, K*	200
Maximum fuel Mo matrix temperature, K*	1875
^{235}U burn up, %	4.2
Burn up density in Mo-UO_2, 10^{20} fission/cm^3	2.7
Burn up density in UO_2 (100% dense) 10^{20} fission/cm^3	8.3
Mo-UO_2 fuel volume swelling, %	1
Neutron fluence in center of core (> 0.1 Mev) 10^{22} n/cm^2	2.0
Neutron fluence in center of reflector (> 0.1 Mev) 10^{21} n/cm^2	2.8
Neutron leakage, neutron/fission	0.41
Median neutron energy causing fission, Mev	0.18
Reactivity change Δk due to fuel burn up, %	2.3
Reactivity change Δk due to thermal expansion, %	1.1

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

The 1% fuel swelling was estimated on the assumption that the UO_2 pellet fuel body behaves as well as a Mo-40 $^v/o$ UO_2 cermet for which irradiation data exists as discussed below.

The calculated neutron fluence in the BeO reflector implies that microcracking accompanied by a significant swelling can be expected in the reflector unless it can be maintained above 1100-1200 K.[11-13] At this temperature annealing processes limit the swelling of BeO to 1 $^v/o$. Indeed the reflector can be designed to operate in this temperature range.

The reactivity control requirements can be met by the reflector control system of this reactor without apparent difficulty.

HEAT PIPE DESIGN

This reactor concept will employ molybdenum heat pipes using lithium as the working fluid. The preferred heat pipe design is one having a number of axial grooves, which serve as low impedance flow paths for returning liquid from the condenser to the evaporator. A fine porous structure covers the grooves and provides the capillary force required for fluid circulation. This design has a high degree of redundancy in that each covered groove acts as an independent flow path for liquid flow. Stainless stell heat pipes of this type have performed most reliably at high rates of heat transfer (> 150 MW/m^2),[9] and grooved W-Re heat pipes have been successfully tested at temperatures up to 1900 K for 10,000 hours.[14] Design calculations[15,16] indicate that a heat pipe having the dimension listed in Table I and having 40 grooves with a hydraulic radius of 0.4 mm, and a porous cover with an effective pore radius of 0.03 mm would have a heat transfer limit at 1675 K of about 75 kW, well above the operating power level per heat pipe of 36 kW.

FUEL SELECTION

The mission requirements for small size, large power and long lifetimes imply a fast, dense fuel reactor, one that will have a large inventory of fuel in a small volume. The temperature range imposed by the thermionic conversion system dictates the use of refractory fuels such as UC, UN or UO_2 and their cermets.

Of the three fuels, UN has the highest density. Unfortunately UN dissociates at an appreciable rate at the operating temperature of this reactor unless an over pressure of nitrogen is provided. Maintaining this over pressure requires either a strong impervious cladding around each fuel element or a pressure vessel around the core of the reactor. Both of these complications are undesirable, particularly because they introduce the possibility of one point failure of the reactor system.

UC has a density nearly as large as UN, it has relatively good thermal conductivity, and it is stable in the temperature range of interest here provided that the stoichiometry of the compound is tightly controlled. This last restriction can be relaxed by the addition of ZrC. A fuel consisting of 90% UC-10% ZrC is indeed an attractive candidate but it also is not without problems. It is unstable in air, it is difficult to bond or braze to a molybdenum heat pipe as is required in this design, it has a rather large thermal expansion mismatch with molybdenum, and of the three fuels mentioned, it seems to have the largest instability to radiation exposure as shown in Fig. 4.(15,17,18) The consequences of these objectives can be minimized by proper design and technology development.

By comparison though, the use of UO_2 emerges as a superior alternative. UO_2 does not react with air and it is completely stable up to much higher temperatures. Neutron criticality calculations described below indicate that a reactor of the desired size will achieve criticality with a fuel mixture of nominally 60 $^v/o$ Mo and 30-40 $^v/o$ UO_2 (fully enriched). A cermet of this composition has a low swelling rate with radiation exposure as indicated by the Mo-40 $^v/o$ UO_2 data shown in Fig. 4. This data was obtained at fission densities in the Mo-UO_2 of up to 3.5×10^{20} fission/cm^3.(18) And because of its high molybdenum content the cermet should have high thermal conductivity. However, a more practical fuel than the cermet is one

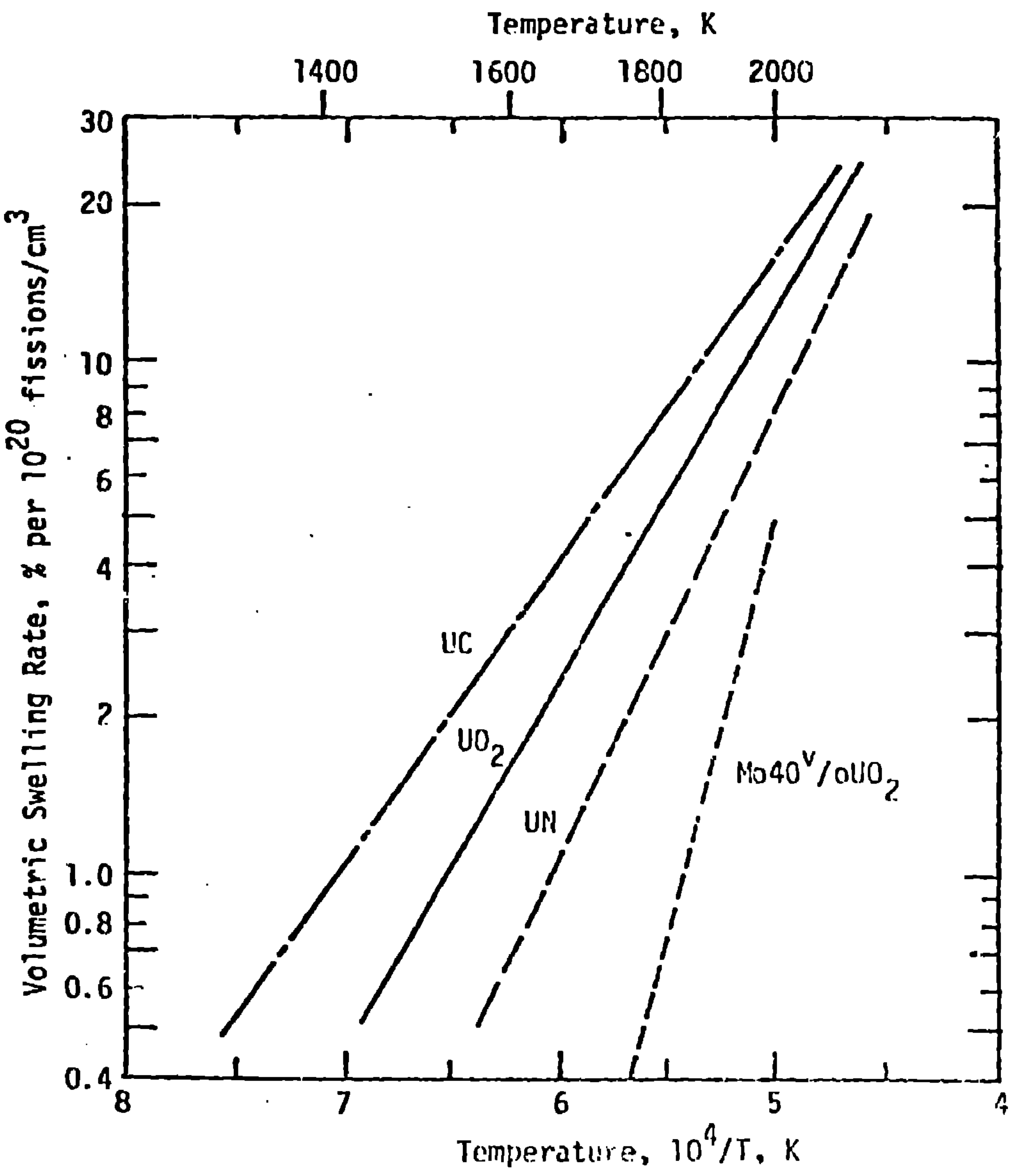

Fig. 4. Dependence of fuel swelling on fission density and temperature for UC, UN, UO_2 and Mo40^{V}/oUO_2. (Ref. 17,18)

consisting of a molybdenum metal body drilled with holes into which small UO_2 pellets are inserted in t proper volumetric ratio. Such a fuel, similar in concept to that employed in the Fast Flux Test Facility (FFTF), offers many advantages. Its physical and thermal characteristics are close to those of molybdenum. It is easily bonded to a molybdenum heat pipe. And, very significantly, it permits complete assembly of the reactor core prior to insertion of the nuclear fuel. The economic and practical benefits of this last feature are obvious because the manufacture of the fuel heat-pipe thermionic converter element is greatly simplified. The biggest unknowns for this fuel concept relative to the Mo-UO_2 cermet are its fission gas retention and swelling rate under irradiation. Extensive data has been obtained with the FFTF UO_2 fuel pellets which are clad in stainless steel. However, the cladding temperature of the FFTF irradiation tests (< 1300 K) is so much lower than that of the molybdenum matrix discussed here that the swelling characteristics of the two fuels are probably not comparable.

NEUTRONIC CALCULATIONS

One-dimensional neutron criticality calculations have been performed using the ONETRAN[19] code which is an outgrowth of the well known DTF-IV[20] transport code. A 30 group neutron cross section set was used which is based on the ENDF/B-III library maintained by the Oak Ridge National Laboratory. Homogenized cross sections for the core region were obtained by first performing a reactivity calculation on a single fuel element to obtain weighting fluxes. The cross sections for each region of the fuel element were then flux weighted, volume averaged and summed to yield the desired core cross section.

The one-dimensional reactor configuration employed in the calculations is listed in Table V. The core region was divided into six zones having approximately the thickness of a fuel element. The three radial gaps in the core were simulated by lowering the core density in each zone appropriately. The core and reactor were

Table V. One-dimensional Model of Reactor

Used in the Neutron Criticality Calculations

Material	Outer Radius (mm)
Core region	
Zone 1, central void	37
Zone 2, homogenized heat pipe fuel element	80
Zone 3, homogenized heat pipe fuel element	130
Zone 4, homogenized heat pipe fuel element	180
Zone 5, homogenized heat pipe fuel element	230
Zone 6, homogenized heat pipe fuel element	280
Void	288
Molybdenum load rings	293
Void	298
Thermal neutron absorber B_4C	300
B_4C control layer	310
BeO reflector	400

Geometric buckling height, 675 mm

approximated by right cylinders. A buckling-height to core-diameter ratio, H/D, of 1.2 was used to account for end reflection. Reflector worth calculations indicate that this value of H/D yields a conservative estimate of the reactivity worth of end reflection. The action of the boron loaded control drums was simulated by moving a layer of B_4C (natural boron) from the outer region of the reflector to the inner region. A 10 mm thick layer of B_4C yields a reactivity swing in excess of 5% which is more than the anticipated reactivity loss of 3.4% due to fuel thermal expansion and burn up. Calculations[11] show that a maximum reactivity swing of about 8.5% can be obtained with a 30 mm thick B_4C layer.

The reactor as described in Table V achieves criticality, k = 1.0, with a uniform Mo-UO_2 fuel loading consisting of 60 ^{v}/o Mo, 30.3 ^{v}/o UO_2 (100% dense) and the remainder void (available for fuel porosity and swelling allowance). Varying the UO_2 concentration in each core region to obtain radial power flattening requires an average UO_2 concentration of 32.2 ^{v}/o and yields the radial power profiles shown in Fig. 5 for the B_4C layer in the in and out positions. The average power density in each core region deviates from the core average by less than ± 6%. The UO_2 concentration in each core region is indicated at the bottom of the figure.

The results of reactivity sensitivity calculations performed for the power flattened reactor are listed in Table VI.

CONCLUSIONS

The conceptual reactor design described in this work is intended to address the power requirements of a broad spectrum of deep space missions currently envisioned by NASA. The reactor can be scaled in the range of 1-5 MWth without drastic modifications. The design is the result of compromises between the requirements for heat transfer out of the core, neutron criticality, radiation damage to materials, thermionic converter constraints on fuel element number and spacing, and considerations of system redundancy, reliability and overall size.

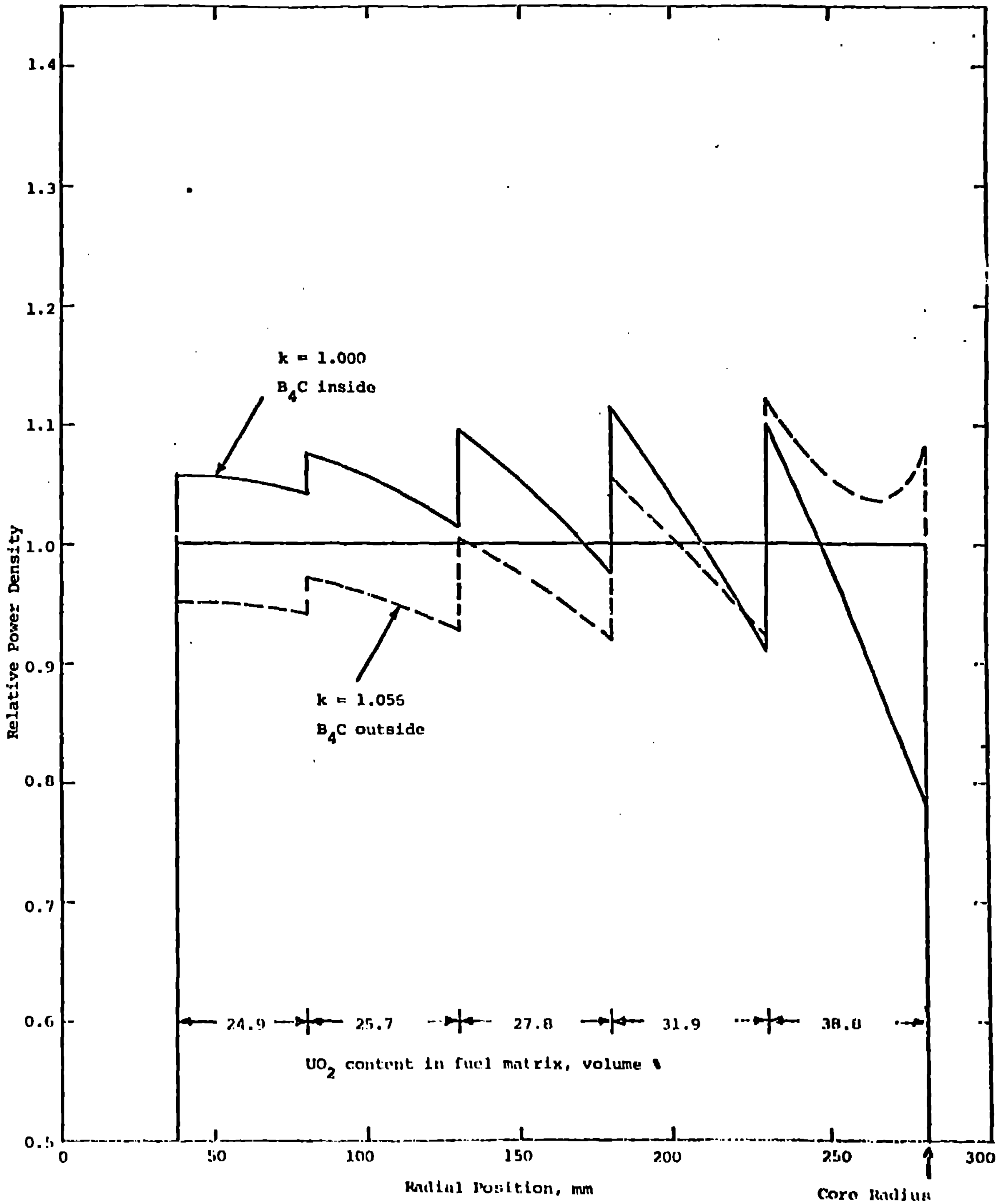

Fig. 5. Radial power profile in core with non-uniform fuel loading.

Table VI. Neutron Reactivity Sensitivity Calculations

k	$\Delta k \times 100$	Comments
1.0000	0.	Reference calculation. Power flattened core, 10 mm B_4C control layer inside.
0.9945	-0.55	Reduce UO_2 density uniformity 1%
0.9914	-0.86	1% radial thermal expansion.
0.9957	-0.43	1% axial thermal expansion.
1.0080	+0.80	Increase radius of core - zone 6 1%.
0.9965	-0.35	Reduce BeO density 10%.
0.8635	-13.65	Remove BeO and B_4C control layer.
1.0563	+5.63	Move B_4C control layer outside.
1.0483	+4.83	With B_4C control layer out, reduce BeO density 10%.

The reactor itself appears technologically feasible pending the demonstration of heat pipe performance and fuel irradiation stability. The feasibility of coupling the reactor to the out-of-core thermionic converter system hinges on the following accomplishments: the achievement of reasonable converter efficiency at an emitter temperature of 1650 K, the development of an electrical insulator that can be bonded between the molybdenum heat pipe and the converter emitters, and, finally, the demonstration that a bundle of heat pipe fuel elements and thermionic converters can be assembled into a working unit.

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