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AUTHOR(S): Daniel R. Koenig and William A. Ranken

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REACTOR DESIGN FOR NUCLEAR ELECTRIC PROPULSION

Daniel R. Koenig and William A. Ranken
Los Alamos Scientific Laboratory
Los Alamos, New Mexico

ABSTRACT

Conceptual design studies of a nuclear power plant for electric propulsion of spacecrafts have been on going for several years. An attractive concept which has evolved from these studies and which has been described in previous publications, is a heat-pipe cooled, fast spectrum nuclear reactor that provides 3 MW of thermal energy to out-of-core thermionic converters. The primary motivation for using heat pipes is to provide redundancy in the core cooling system that is not available in gas or liquid-metal cooled reactors. Detailed investigation of the consequences of heat pipe failures has resulted in modifications to the basic reactor design and has led to consideration of an entirely different core design. The new design features an integral laminated core configuration consisting of alternating layers of UO_2 and molybdenum sheets that span the entire diameter of the core. Design characteristics are presented and compared for the two reactors.

The desirability of separating the reactor assembly from the thermionic converter assembly has been recognized, and an intermediate heat exchanger to couple the two subassemblies together has been conceptualized. The heat exchanger design allows independent optimization of the core and converter heat pipes. It provides some cross coupling between the two sets of heat pipes. And, if desired, it permits mating the reactor to the thermionic converter system after their respective assembly. Weight and temperature penalties associated with the heat exchanger have been estimated and appear to be tolerable.

BACKGROUND

Design studies of a nuclear reactor to provide thermal power to an electric propulsion system for deep space exploration have been ongoing for several years[1,2]. The present design goals are to produce 3 MW_T of power for 75,000 full-power hours during a mission lifetime of 12 years to drive a thermionic electrical conversion system operating at a source temperature of 1650 K. The current core design, which will be called here the reference design, consists of an assembly of 90 hexagonal fuel elements, each containing an axial molybdenum/lithium heat pipe. The core heat pipes penetrate through a radiation shadow shield before transferring their heat to thermionic converters that are bonded onto the condenser end of the heat pipes.

Detailed consideration of the consequences of core heat pipe failures has indicated that several modifications to the reference design are needed. Problem areas remaining with the modified design are significant enough that adaptation of an entirely different core design, described in detail in a related paper,[3] is being considered for the nuclear electric propulsion application. One desired modification is to increase the number of heat pipes in the core. Such an increase may make it desirable to decouple the core from the thermionic converters by having separate sets of heat pipes, optimized independently, for each of these two subassemblies. The two sets of heat pipes would be coupled, then, by a heat exchanger.

This paper describes some of the modifications to the reference core design, it discusses the applicability of a new core design and it describes a conceptual design of a heat exchanger between the core and the thermionic converters.

EFFECT OF HEAT PIPE FAILURE ON FUEL TEMPERATURE

The primary motivation for removing the heat generated in the reactor core with heat pipes is to avoid the possibility of single-point failure of the core cooling system inherent in liquid metal or gas-cooled designs. An understanding of the effects of heat pipe failures is therefore vital to the estimation of overall power plant reliability.

The fuel temperature rise in the vicinity of a failed core heat pipe was determined from two-dimensional, finite element, heat transfer calculations. Two kinds of failure were analyzed, failure of an internal heat pipe which is surrounded by six functioning neighbors, and failure of a heat pipe on the periphery at a corner of the hexagonal core assembly where there are only three neighbors.

Unless special provisions are taken on the core periphery, the latter kind of failure produces unacceptably high temperatures near the failed heat pipe. That is primarily because heat generated on the outer edge of the failed periphery element has to travel a long and narrow path around the failed pipe before reaching a functioning neighboring pipe.

The maximum fuel temperature resulting from failure of an internal heat pipe is plotted in Fig. 1 vs the number of core heat pipes. Also shown in Fig. 1 are the average and maximum fuel temperatures in a normally functioning fuel element. The fuel temperature near the failed heat pipe shown in this figure assumes perfect thermal contact between adjacent fuel elements and it must be increased by the temperature drop expected across the interface of adjacent fuel elements. This temperature drop is difficult to calculate but reasonable estimates are in the range of 50-300 K for a 90 element core, placing the maximum temperature uncomfortably close to the melting point of molybdenum (2900 K). Raising the number of core heat pipes to 162 decreases the fuel temperature very significantly without unduly increasing the complexity of the core. The number 162 corresponds to a perfect hexagonal assembly with the central and the six corner elements removed. Removing the corner elements

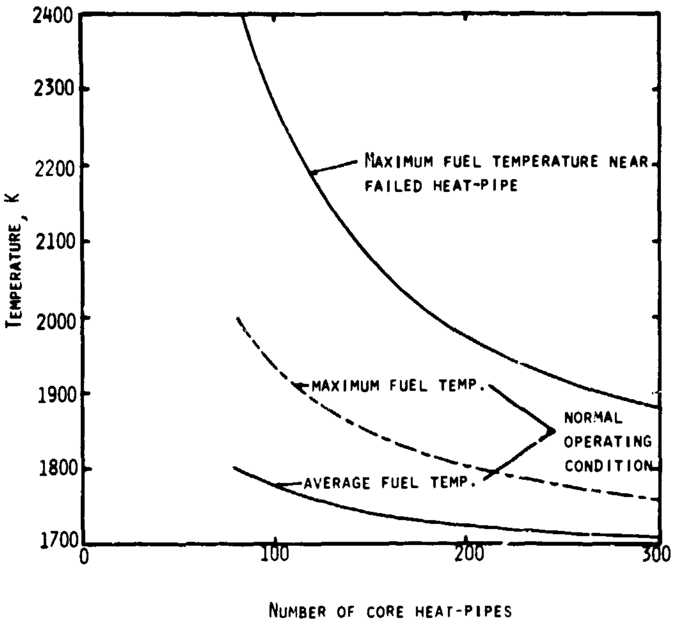

Fig. 1. Fuel temperatures vs the number of heat pipes in the core.

reduces the maximum core diameter considerably and greatly eases the circularization of the core assembly. The center element is removed for symmetry reasons.

MODIFICATIONS OF REFERENCE CORE DESIGN

The modified reference core design is shown in a partial cross-sectional view in Fig. 2. The core contains 162 heat pipe cooled, hexagonal fuel elements which are bundled together by circumferential pressure bands. The six corner and the central fuel elements have been removed and replaced with filler elements which contain no fuel but consist simply of core-length heat pipes whose function is to transfer heat to neighboring elements in case of a heat pipe failure in their immediate vicinity. The fuel elements on the periphery of the core have been sliced off flush with their heat pipes so that they contain no fuel on their outer edge.

The core assembly is surrounded on all sides by multifoil thermal insulation, a thin layer of thermal neutron absorber, and a BeO reflector assembly. The purpose of the absorber is to adjust power peaking on the periphery of the core caused by low energy neutrons reflected from the BeO. The radial reflector contains rotating drums loaded with B_4C for control of reactivity.

The configuration of the periphery fuel elements ensures that failure of a periphery heat pipe will not produce higher fuel temperatures than would result from failure of an internal heat pipe. If the radial-power-density profile is adjusted to be flat, the periphery heat pipes would carry about 30% less power than the internal ones, corresponding to the amount of fuel which has been removed from the outer edge of the periphery elements. This reduced power may complicate the design of the thermionic converter assembly. However, it is estimated that about half of the power reduction can be recovered, with only a modest increase in fuel ΔT, by adjusting the power density profile to actually peak on the core periphery. This adjustment can be accomplished by increasing the fuel concentration on the periphery and by reducing the thickness of the stationary B_4C layer whose purpose is to affect the power profile on the periphery. The use of a heat exchanger, such as the one described below, between the core and the converter heat pipes would enable further smoothing of the power delivered to each converter heat pipe to within about ± 5% of the average power.

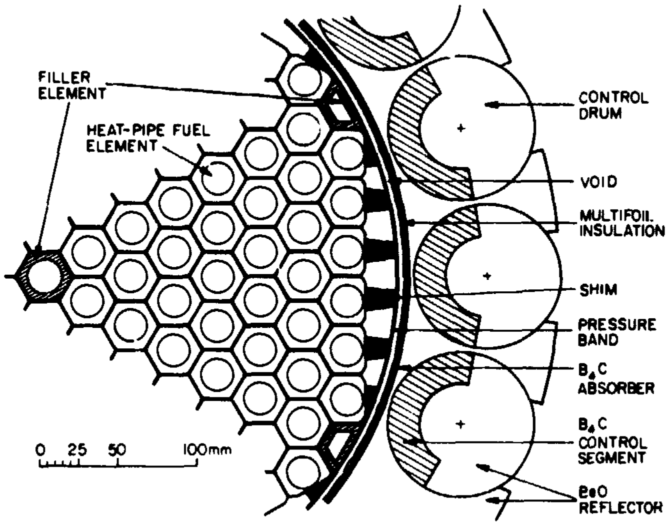

Fig. 2. Cross section of reactor. Periphery fuel elements have no fuel in their outer edge.

The fuel element for the reference core design is shown in Fig. 3. It consists of UO_2 pellets imbedded in a molybdenum matrix which is brazed onto a molybdenum/lithium heat pipe. The nominal composition of the fuel region is 60 vol% UO_2 - 40 vol% Mo. This fuel has adequate thermal conductivity, and if its radiation behavior is similar to that of a UO_2/Mo cermet of the same composition it should have a low rate of radiation swelling.[4] To achieve a flat radial power density profile in the core the UO_2 volume fraction in the fuel region must vary from 47 vol% in the center of the core to 70 vol% on the periphery. However, to compensate for the removal of fuel in the periphery elements, the UO_2 concentration there should be raised to about 80%. Such a high UO_2 concentration cannot be obtained in the pellet design without lowering excessively the effective thermal conductivity of the fuel element. Therefore, another fuel element design is being investigated which inherently has a better thermal conductivity than the pellet design and which may also be easier to fabricate. The design concept, referred to as the "UO_2 wafer" fuel element, is illustrated in Fig. 4. The wafer fuel element consists of hexagonal UO_2 wafers which are slipped over the heat pipe and sandwiched between molybdenum fins. The entire fuel region is clad in molybdenum. The fin arrangement places all the molybdenum (except for the cladding) in a direction which serves to conduct the heat generated in the UO_2 toward the heat pipe and thereby achieves a better effective radial thermal conductivity. A good bond between the UO_2 and the heat pipe is not essential because nearly all the heat is transferred to the pipe by the fins. In any case, the UO_2 will redistribute itself eventually, by evaporation and condensation, against the heat pipe which is the

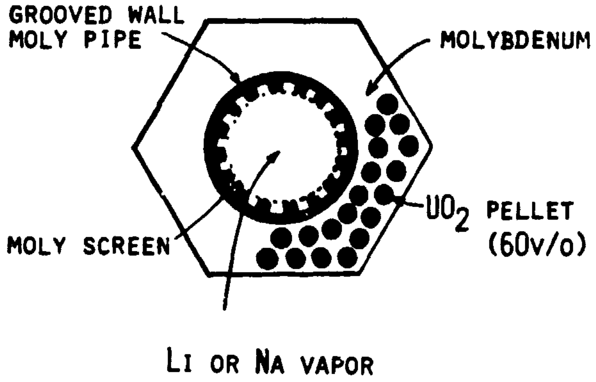

Fig. 3. Schematic drawing of "UO_2 pellet" fuel element design.

coldest part of the fuel element. A good thermal bond between the fins and the heat pipe is essential, but it does not appear to be difficult to obtain. A potential drawback to the wafer fuel element concept is that its radiation swelling behavior is likely to be similar to that of pure UO_2 which is considerably worse than that of a cermet.[5] However, by providing adequate void space in the fuel element design, it may be possible to accommodate the large (20-25 vol%) swelling estimated for pure UO_2.

LAYERED INTEGRAL CORE DESIGN

Several features of the modified reference core design shown in Fig. 2 are problematic. The main one is the lack of positive thermal contact between adjacent fuel elements. Good thermal contact is important in order to avoid the generation of excessive temperatures in the core in the event of one or more heat pipe failures. Another drawback is the need to vary the fuel composition in order to achieve a flat radial power profile. This increases the critical mass of the reactor and also renders the heat removal near the periphery more difficult because the molybdenum content of the fuel region is low there. The core is approximately hexagonal in shape. This shape is not the most efficient from the point of view of neutron economy and it places design restrictions on the reflector assembly.

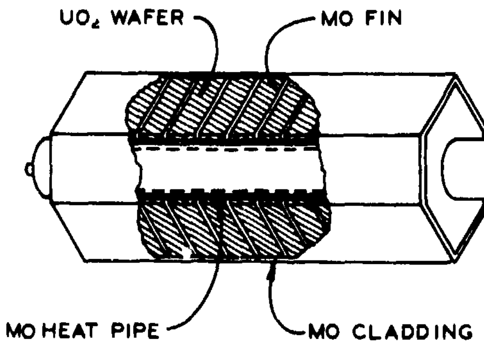

Fig. 4. Schematic drawing of "UO_2 wafer" fuel element design.

A reactor design which avoids all of these objections is shown in Fig. 5. The concept, which was developed for lower power, shorter mission lifetime and lower temperature applications as described in a related paper[3], is being investigated for use in the present application. A $3MW_t$ version of this reactor containing 162 heat pipes was designed for this purpose as shown in Fig. 6. The core consists of alternating layers of UO_2 and molybdenum. The molybdenum sheets stretch continuously across the whole core. The UO_2 is in the form of small tiles which are placed between the heat pipes. Holes, slightly undersized, are punched in the molybdenum sheets to obtain good thermal contact with the heat pipes as the sheets are slipped one at a time over the entire array of prepositioned core heat pipes. In this way effective and well characterized heat transfer paths can be provided between heat pipes throughout the core. Adequate thermal conductivity can be obtained with a fuel composition, which is everywhere uniform, of 80 vol% UO_2-20 vol% Mo. The core heat pipes are arranged in circular rows. Radial power output flattening is achieved simply by adjusting the spacing between rows so that every heat pipe removes the same amount of heat. The perfectly cylindrical core is contained in a molybdenum can of substantial thickness. This can is in good thermal contact with the molybdenum sheets and serves, in part, to redistribute heat in case of the failure of a periphery heat pipe. The cylindrical core geometry has low neutron leakage and provides more freedom and effectiveness in the radial reflector design.

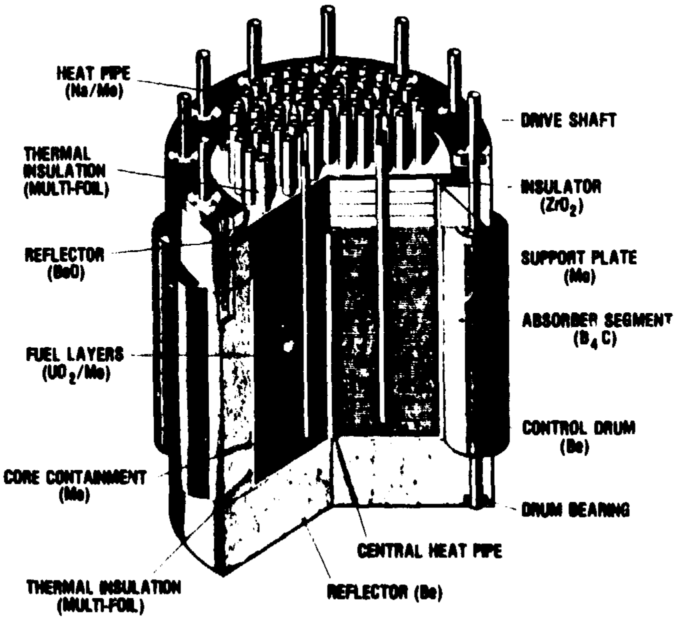

Fig. 5. Cutaway view of the integral core layered fuel reactor concept.[3]

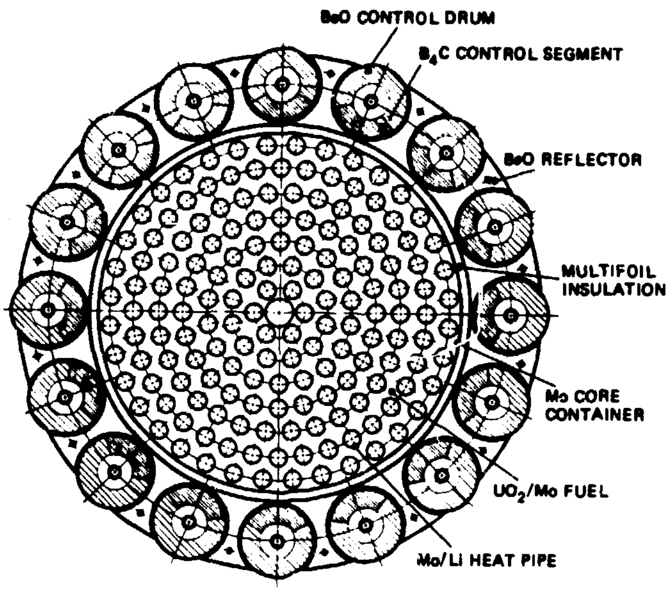

Fig. 6. Cross section of 3 MW_T layered integral core reactor

COMPARISON OF REACTOR DESIGNS

Dimensions, weights and operating characteristics for the layered integral reactor reactor concept and for the modified reference design are compared in Tables I-III. The comparison shows that the layered core reactor is a little smaller and lighter. This is favorable, but less important than the fact that this design avoids some problem areas associated with the reference design. The main area of concern in considering the layered core reactor concept for the NEPS program is the estimated fuel swelling, which at a value of 20 vol% is rather high.

The reactor designs described in Tables I-III include a void allowance in the fuel to accommodate the respective estimated swelling. Fuel swelling for the layered integral core design was estimated from BMI data[5] for pure UO_2 that appears to have a considerably higher swelling rate than UO_2 in a molybdenum matrix. It is not clear that the BMI data is directly applicable to the layered core concept because the temperature gradient in the UO_2 will be much smaller in the reactor than it was in the BMI experiments. As a consequence, it is possible that swelling extrapolated from this data is overestimated. In any case, the required void allowance for fuel swelling can easily be incorporated in the layered core design simply by including gaps between layers in the core, and between the UO_2 tiles.

HEAT EXCHANGER DESIGN

An alternative to mounting the thermionic converters directly onto the condenser end of the core heat pipes is to assemble the converters on a separate set of heat pipes which are coupled to the core heat pipes with an intermediate heat exchanger. A heat exchanger design that appears practical and feasible is illustrated conceptually in Fig. 7. The figure shows a module of six core heat pipes that penetrate through two rectangular jackets, which are in reality two molybdenum coupling heat pipes. This assembly is mated with vertical bolts to a similar assembly containing a module of four converter heat pipes and two rectangular coupling heat pipes. The function of the coupling heat pipes is to transfer the heat from the core heat pipe module to the converter heat pipe module across the flat mating interface. Thin wall sleeves internal to the coupling heat pipes allow the core or converter heat pipes to pass through. A braze is made after assembly of each module to obtain a good thermal bond to the coupling heat pipes. The wick structure in the coupling heat pipes is so arranged as to provide liquid flow paths between the sleeves themselves and between the sleeves and the flat

TABLE I
REACTOR DIMENSIONS

	Reference Core	Modified Core	Laminated Core
Core diameter, mm	427	427	390
Reactor diameter, mm	657	657	620
Core length, mm	427	427	390
Reactor length, mm	637	637	600
Reflector thickness, mm	100	100	100
Number of heat pipes	90	162	162
Average heat pipe spacing, mm	42.8	31.8	29.1
Heat pipe outer diameter, mm	26.8	20.0	20.0
Heat pipe vapor area, mm^2	339	188	188
Fuel vol. fraction (assuming 100% dense)	0.580*	0.518*	0.461**
Fuel porosity and swelling allowance fraction	0.064	0.064	0.115
Total heat pipe volume fraction	0.355	0.358	0.424
Heat pipe vapor volume fraction	0.213	0.215	0.254

* 60 vol% UO_2-40 vol% Mo fuel.
** 80 vol% UO_2-20 vol% Mo fuel.

TABLE II

REACTOR WEIGHT SUMMARY (kg)

	Reference Core	Modified Core	Laminated Core
Mo-UO_2 fuel, total weight	372	372	231
UO_2 only	229	229	187
^{235}U only	189	189	154
Mo heat pipes, 110 kg/m (to outer edge of reactor only)	60	60	54
BeO reflector	375	397	342
Control system	75	75	75
Reactor support structure	46	46	35
TOTAL	950	950	737

TABLE III

REACTOR OPERATING CHARACTERISTICS

	Reference Core	Modified Core	Laminated Core
Nominal electrical power output, kWe	400	400	400
Thermal power level, MWth	3	3	3
Thermionic converter efficiency, %	15	15	15
Lifetime at full power, h	75000	75000	75000
Number of heat pipes	90	162	162
Nominal UO_2 content of fuel, vol %	60	60	80
Average power density in Mo-UO_2, MW/m^3 or W/cm^3	78	78	114
Average power density in UO_2, MW/m^3 or W/cm^3	130	130	143
Power per heat pipe, kW	33.9	18.8	18.8
Heat pipe axial heat flux, MW/m^2	100	100	100
Heat pipe radial heat flux, MW/m^2	1.22	0.91	1.00
Heat pipe temperature, K	1675	1675	1675
Average fuel temperature, K	1789	1738	1763
Maximum fuel ΔT, K*	237	131	199
Maximum fuel temperature, K*	1964	1835	1906
^{235}U burn up, %	5.8	5.8	7.1
Fission density in Mo-UO_2, 10^{20} fissions/cm^3	6.3	6.3	9.2
Fuel volume swelling, %	5	5	20
Reactivity change Δk due to fuel burn up, %	3.5	3.5	4.3
Reactivity change Δk due to thermal expansion, %	1.5	1.5	2.1

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

interface. For the core modules, the sleeves formthe evaporator of the coupling heat pipes and the flat interface is the condenser. The roles are reversed for the converter modules.

The thermal bond between the core modules and the converter modules may be accomplished either with a deformable foil or by brazing when the reactor is brought up to power.

An attractive feature of the concept is that the number and sizes of heat pipes in the core module, in the converter module and for the coupling heat pipes are all arbitrary and can be selected to satisfy the separate requirements of core and converter designs. There are other desirable features. The modular heat exchanger provides some cross coupling and some redundancy of heat flow paths. These features are important for smoothing out differences in the power carried by each heat pipe. Both core and converter heat pipes can be cylindrical. The mating surfaces are simple and do not require close alignment tolerances. The coupling can be performed either before the core and converter modules are assembled together into a complete system or after the core and the converter system have been assembled as separate units.

All the complexity of the heat exchanger design is concentrated in the coupling heat pipes. However, each coupling heat pipe can be tested separately prior to assembly into a module and each

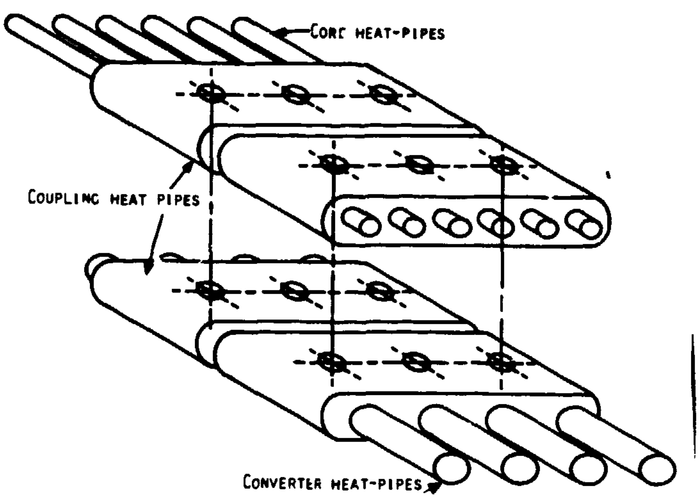

Fig. 7. Schematic design of coupling heat exchanger.

module can be tested for quality assurance prior to final assembly into the core or the converter system.

A preliminary design study of the heat exchanger was performed for a core containing 162 heat pipes arranged in 18 modules, each consisting of 9 core heat pipes and 6 coupling heat pipes. The thermionic converter unit contained 90 heat pipes arranged in 18 modules of 5 converter heat pipes and 6 coupling heat pipes. The 18 pairs of modules were arranged in 6 rows of 3 pairs each. The choice of layout is nicely compact and matches well with one of the proposed thermionic converter assemblies. In principle, the six rows can be stacked vertically closely together with bolts running through the entire height of the heat exchanger stack. This arrangement would require more careful alignment of the modules, but it would simplify assembly and it would provide additional redundancy and better heat transfer because each core module internal to the stack would be in direct contact with two converter modules and vice versa. However, in the present analysis it was assumed for conservatism that there is only one good heat-transfer interface between pairs of core and converter modules.

The width of the heat exchanger mentioned in the study refers to the overall width of one row. The length refers to the length of overlap of core and converter heat pipes. Both the length and the width of the heat exchanger were treated as variables in the parametric study. The height of heat exchanger, closely stacked, was chosen to be 0.60m. This height corresponds to making the height of the coupling heat pipes approximately twice the diameter of the heat pipes running through them.

The estimates of weight for the heat exchanger were based on the following considerations. The wall thickness of the molybdenum coupling heat pipes was taken to be 0.5 mm including the wick. The weight of the internal sleeves was neglected. The combined weight of all the overlapping core and converter heat pipes was estimated to be 220 kg/m. The weight of bolts and fittings for assembling the heat exchanger was assumed to be 26 kg/m^2 of projected area (length x width of the heat exchanger).

The temperature drop attributable to the heat exchanger is the difference between the vapor temperature at the inlet to the condenser of the core heat pipes and the vapor temperature at the outlet of the evaporator in the converter heat pipes. This temperature difference was assumed to contain only three components: the temperature drop across the wall of the core heat pipes, the temperature drop through the interface of the coupling heat pipes, and the temperature drop in the wall of the converter heat pipes. Temperature losses within the heat pipes were assumed to be negligible. Estimates for these temperature drops are listed in Table IV.

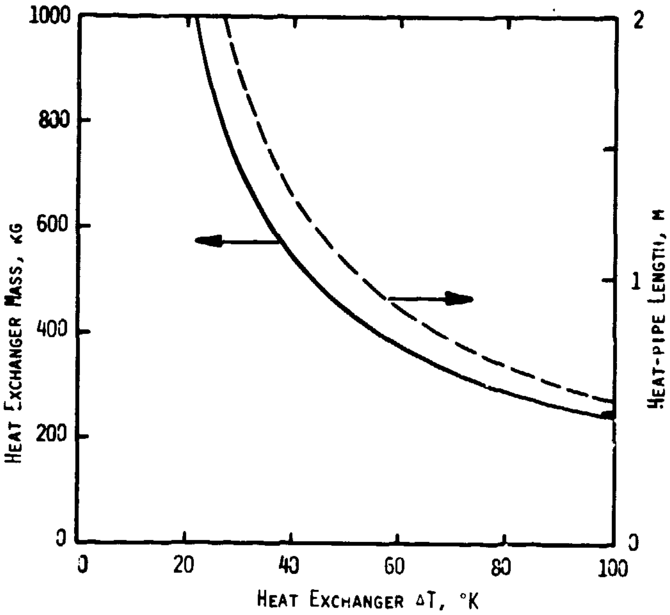

Fig. 8. Design parameters for 1-m-wide heat exchanger.

The results of the study are summarized in Fig. 8 which shows the heat exchanger mass and length as a function of the temperature drop through the heat exchanger. These curves were calculated for a heat exchanger 1 m wide. At a constant value of ΔT the mass of the heat exchanger is rather insensitive to width which can vary from 0.5 to 1.5 m and produce less than 10% variation in mass. Figure 8 indicates, for example, that a 3 MW heat exchanger designed for a temperature drop of 50 K would weigh 450 kg and would fit in a volume 0.6 m high x 1 mm wide x 1 m long.

SUMMARY

Modifications were applied to the reference reactor design to alleviate problems associated with the potential failure of one or more core heat pipes. These modifications include raising the number of core heat pipes to 162, altering the shape of fuel elements located on the periphery of the core and consideration of a "UO_2-wafer" fuel element design capable of a higher UO_2 content than the "UO_2 pellet" design.

A number of problem areas remain with the modified reference design, in particular the attainment of good thermal contact between adjacent fuel elements, and the achievement of radial power flattening. These difficulties are avoided in a radically new "layered integral core" design which also has a smaller critical mass. Design parameters for the two reactor concepts were compared. This comparison indicates that the layered integral core reactor is slightly smaller and lighter but that it may experience greater fuel swelling. The estimated fuel swelling can be accommodated in the core

TABLE IV
TEMPERATURE DROPS IN 3-MW_t HEAT EXCHANGER

Location	Temperature Drop, K	Heat Flux, MW/m^2
Core heat pipe wall, for 1 m length*	12.5	0.39
Converter heat pipe, for 1 m length*	22.4	0.43
Coupling heat pipe interface for 1 m^2 of projected area#	18.8	0.50

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* Temperature drop and heat flux are inversely proportional to length.

\# Assumes contact area is one-third of projected area. Temperature drop and heat flux are inversely proportional to product of length x width.

design, but data on fuel swelling under near isothermal irradiation conditions is needed to reduce design uncertainties.

Finally, a conceptual design for a heat exchanger between the core and the thermionic converter assembly was described. This heat exchanger would provide design and fabrication decoupling of these two subassemblies, but at an added mass penalty to the power plant on the order of 500 kg.

ACKNOWLEDGEMENT

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