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NEPS Reactor and Heat Exchanger

Summary Status (December 1978)

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Daniel R. Koenig

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NEPS REACTOR AND HEAT EXCHANGER SUMMARY STATUS (DECEMBER 1978)

by

Daniel R. Koenig

ABSTRACT

The design of a 3 MW_t heat-pipe cooled nuclear reactor for electric propulsion of spacecrafts has been evolving continually. Several modifications have been made to make the reactor design more tolerant of potential heat pipe failures. Design parameters and operating characteristics for the modified reactor are presented.

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.

I. INTRODUCTION

The reference core design for the 3-MW_t Nuclear Electric Propulsion System (NEPS) reactor contains 90 molybdenum/lithium heat pipes. These heat pipes penetrate the radiation 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 failure has indicated the desirability of increasing the number of heat pipes in the core. It has also focused attention on the need to modify the periphery of the core to avoid excessive fuel temperatures in case of heat pipe failure there. Increasing the number of core heat pipes has rekindled the desirability of decoupling the core from the thermionic converters by having separate sets of heat pipes, optimized independently, for each of these two subassemblies. Accordingly, it has motivated the design of a heat exchanger to couple these two sets of heat pipes.

This report reviews the current status of the NEPS reactor design and describes the conceptual design of a heat exchanger between the core and the thermionic converters.

II. EFFECT OF HEAT PIPE FAILURE ON FUEL TEMPERATURE

The fuel temperature rise in the vicinity of a failed core heat pipe was determined from two-dimensional finite element heat transfer calculations as exemplified in Fig. 1. Two kinds of heat pipe failures were analyzed, failure of an internal heat pipe which is surrounded by six functioning neighbors, and failure of a corner, periphery heat pipe, modeled in Fig. 1A, which has only three neighbors. Unless special provisions are taken on the core periphery, the latter failure produces unacceptably high temperatures near the failed heat pipe as shown in Fig. 1B. This is 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 heat pipe. Design modifications of the core periphery to avoid this situation are discussed below.

The maximum fuel temperature resulting from failure of an internal heat pipe is plotted in Fig. 2 vs the number of core heat pipes. Also shown in Fig. 2 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 reduces the maximum core diameter considerably and greatly eases the circularization of the core assembly. The center element is removed for symmetry reasons. Design parameters and operating characteristics for a 162 heat pipe core are described in the parameters section.

A. Computational array for periphery heat pipe failure.

B. Calculated isotherms for periphery failure.

Fig. 1. Heat transfer of a heat-pipe failure at a corner of the core periphery. The straight boundaries are assumed to be adiabatic.

Fig. 2. Fuel temperatures vs the number of heat pipes in the core.

III. FUEL ELEMENT DESIGN

The reference fuel element is still the UO_2 pellet in a molybdenum matrix design, shown schematically in Fig. 3. The heat pipe bonded at the center of the element has a wick structure consisting of axial grooves formed in the pipe wall and covered with a fine molybdenum screen. The heat pipe fluid is lithium. This kind of wick structure provides many low impedance, redundant paths for returning the liquid lithium from the condenser to the evaporator. The screen wick is easy to fabricate and if a good bond can be obtained between the screen and the land areas between the grooves,

Fig. 3. Schematic drawing of "UO₂ pellet" fuel element design.

it appears that this heat pipe can be bent relatively easily as required in the overall power plant design. There are several drawbacks to this heat pipe design, however. Because the wall is thick in order to accommodate the grooves, the pipe is relatively heavy and the radial temperature drop across the pipe wall is several times larger than it could be. Also an adequate fabrication technique for forming the grooves has not yet been developed. Consequently, a back-up heat pipe design has been selected which consists of a smooth tube lined with a distributive screen wick to that several (two to six) screen arteries are attached. This heat pipe design has a much smaller wall thickness but fewer redundant paths for liquid flow. All the components are easy to fabricate but bonding the arteries to the screened wall is difficult and a technique for bending the wick assembly has not been developed.

The molybdenum matrix, UO_2 pellet design can accommodate the range of UO_2 concentration (47-70 vol%) required to achieve a flat ($\pm 5\%$) radial power profile in the core. However, as discussed below, one way of alleviating the generation of excessive fuel temperatures on the core periphery involves achieving a radial power density profile that is peaked on the periphery. Obtaining this power density profile may require raising the UO_2 concentration on the periphery to 80 vol% or more. 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,

Fig. 4. Schematic drawing of "UO₂ wafer" fuel element design.

another fuel element design is being investigated that inherently has a better thermal conductivity than the pellet design and that 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 (except for the cladding) the molybdenum in a direction that 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 coldest part of the fuel element. A good thermal bond between the fins and the heat pipe is desirable and should not be difficult to obtain.

IV. CORE DESIGN

The core consists of a hexagonal assembly of 162 heat-pipe fuel elements as shown in a partial cross-sectional view in Fig. 5. The central and

Fig. 5. Cross section of reactor. Periphery fuel elements have no fuel on their outer edge.

corner elements are filler elements consisting only of short, core-length heat pipes. The periphery elements have been sliced off flush with the heat pipe so that they contain no fuel along their outer edge.

The entire core is held tightly with several circumferential pressure bands. This assembly is surrounded on all sides, first by multifoil thermal insulation, followed by a thin layer of thermal neutron absorber (B_4C), and a BeO reflector. 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 that 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 to 80 vol% UO_2 and by reducing the thickness of the stationary B_4C layer, whose purpose is to affect the power profile on the periphery. Increasing the UO_2 concentration to 80 vol% cannot practically be done with the pellet fuel element design but it could be done with the wafer design described above. Finally, 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 $\pm 5\%$ of the average power.

An alternative to the treatment of the core periphery just described is shown in Fig. 6. Here, the periphery fuel elements have been squared off but they have the same fuel volume as internal elements. In case of a heat pipe failure, heat generated in the outer edge of periphery elements is distributed to nearby periphery elements by circumferential heat pipes located on the flat faces of the core. Thermal contact between the core and the circumferential heat pipes, which have rectangular cross sections, is achieved

Fig. 6. Cross section of core showing circumferential periphery heat pipes. Periphery fuel elements are fully loaded with fuel.

with deformable foil. The circumferential heat pipes are held against the core by a set of pressure bands. Power flattening is easier to achieve in this alternative concept; however, the core design is greatly complicated by the additional set of heat pipes.

In concluding this section it must be pointed out that, with or without the use of an intermediate heat exchanger, the thermionic converter system design must have the flexibility to accommodate the failure of core heat pipes.

V. DESIGN PARAMETERS FOR A 162 HEAT PIPE CORE

Design parameters and operating characteristics have been computed for a core cooled by 162 heat pipes. Fuel element dimensions are listed in Table I, reactor dimensions and weights are shown in Tables II and III, respectively, and the operating characteristics are described in Table IV.

The reactor dimensions and weights are essentially unchanged from the 90 heat pipe core design except for the heat pipe weight which has been reduced almost in half. Previous estimates of this weight had been overly conservative. The increased number of core heat pipes results in a nearly 50% reduction of the temperature gradient in the fuel. The lower average fuel temperature has the effect of decreasing the estimated fuel swelling to 5 vol%.

TABLE I
DESCRIPTION OF 60 v/o UO_2 - 40 v/o Mo HEAT PIPE FUEL ELEMENT
FOR A 162 ELEMENT CORE

Width across hexagonal flats (mm)	31.8
Equivalent mean diameter (mm)	33.4
Length of fuel section (mm)	427
Mo heat pipe outer diameter (mm)	20.0
Vapor passage effective diameter (mm)	15.5
Vapor passage area (mm^2)	188
Fuel region vol. fraction (includes porosity)	0.642
Mo- UO_2 vol. fraction (assuming 100% dense)	0.578
Total heat pipe volume fraction	0.358
Heat pipe wall and wick volume fraction	0.143
Heat pipe vapor volume fraction	0.215
Fuel porosity and swelling allowance fraction	0.064

TABLE II
REACTOR DIMENSIONS

Equivalent core diameter (mm)	427
Equivalent reactor diameter (mm)	657
Core length (mm)	427
Reactor length, (mm)	637
Nominal reflector thickness (mm)	100
Pitch spacing (mm)	31.8
Number of heat pipe fuel elements	162
Core void fraction (center hole), %	0.6
Core non-fuel volume fraction	0.426
Core 60 v/o UO - 40 v/o Mo vol. fraction (assuming 100% dense UO ₂ Mo fuel)	0.574

TABLE III
REACTOR WEIGHT SUMMARY, (kg)

UO ₂ - Mo fuel, total weight	372
UO ₂ only	229
²³⁵ U only	189
90 Mo heat pipes (110 kg/m) (to outer edge of reactor only)	60
BeO reflector	397
Control system	75
Reactor support structure (assume 5%)	<u>46</u>
TOTAL	950

TABLE IV
REACTOR OPERATING CHARACTERISTICS FOR A 162 ELEMENT CORE

Nominal electrical power output (kWe)	400
Thermal power level (MWth)	3.05
Thermionic converter efficiency (%)	15
Life time at full power (h)	75,000
Number of fuel elements	162
Average power density in $\text{UO}_2 - \text{Mo}$ (MW/m^3 or W/cm^3)	78
Average power density in UO_2 (MW/m^3 or W/cm^3)	130
Power per heat pipe (kW)	18.8
Heat pipe axial heat flux (MW/m^2)	100
Heat pipe radial heat flux (MW/m^2)	0.91
Heat pipe temperature (K)	1675
Average fuel temperature (K)	1738
Maximum fuel ΔT (K*)	131
Maximum fuel temperature (K*)	1835
^{235}U burn-up (%)	5.8
Fission density in $\text{UO}_2 - \text{Mo}$ (10^{20} fissions/ cm^3)	6.3
Fuel volume swelling (%)	5
Reactivity change Δk Due to fuel burn-up (%)	3.5
Reactivity change Δk due to thermal expansion (%)	1.5

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

VI. HEAT EXCHANGER DESIGN

An alternative to mounting the thermionic converters directly onto the condenser section of the core heat pipes is to assemble the converters on a separate set of heat pipes that are coupled to the core heat pipes with an intermediate heat exchanger. Several concepts to accomplish this thermal coupling are illustrated in Fig. 7. Each of the ideas depicted was rejected as being impractical. Radiation coupling requires more surface area than is available in a reasonable length (2 m) of overlapping heat pipes. The one-on-one concept involves a complex annular heat pipe and a thermal bond that is difficult to achieve. The direct parallel coupling scheme requires that the core and converter heat pipes have either a rectangular or hexagonal cross section. The cross-coupling concept also requires rectangular

Fig. 7. Several schemes for thermally coupling the core heat pipes to the thermionic converter heat pipes.

heat pipes and requires extra lengths of heat pipes (making it heavier) to turn the core and converter heat pipes so that they cross each other. The liquid-metal-loops heat exchanger is very heavy and requires pumps to circulate the liquid. The pumps require electrical power and tend to decrease the reliability of the system.

A heat exchanger design that appears practical and feasible is illustrated in Fig. 8. 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. Several coupling heat pipes are used to provide the desired amount of redundancy in case one should fail. 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 interface. For the core modules, the sleeves form the 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.

Fig. 8. Schematic design of coupling heat exchanger.

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 as well. 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 before the core and converter modules are assembled together into a complete system. Or the coupling can be made 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 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. This choice of layout matches well with the current thermionic converter assembly. In principle, the 6 rows can be vertically stacked close 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 the

heat exchanger, closely stacked, was chosen to be 0.60 m. 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 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/m² 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 V. A plot of the temperature drop in the heat exchanger vs length is shown in Fig. 9 for several values of width. Similarly, a plot of heat exchanger mass versus length for several widths is shown in Fig. 10. Also included in

TABLE V
TEMPERATURE DROPS IN 3-MW_t HEAT EXCHANGER

<u>Location</u>	<u>Temperature Drop (K)</u>	<u>Heat Flux (MW/m²)</u>
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

*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.

Fig. 9. Temperature drop in heat exchanger vs length of heat pipe overlap for several values of heat exchanger width.

Fig. 10. Heat exchanger mass vs length for several values of heat exchange width. Also shown are curves of constant temperature drop in the heat exchanger.

Fig. 10 shows curves of constant temperature drop. These latter curves show a minimum mass at a heat exchanger width of about 0.75 m, indicated by the dashed line. Near the minimum, mass is rather insensitive to the heat exchanger width that can vary from 0.5 to 1.5 m and produce less than 10% variation in mass. The results shown in Figs. 9 and 10 are summarized in Fig. 11, which shows heat exchanger mass and length vs temperature drop for a constant width of 1 m. This figure indicates, for example, that a 3 MW_T heat exchanger designed for a temperature drop of 50 K would weigh 450 kg and would fit in a volume 0.6 m high by 1 m wide by 1 m long.

Fig. 11. Design parameters for 1-m-wide heat exchanger.

VII. CONCLUSION

The current status of the NEPS 3 MWT reactor shows the following:

- Detailed analysis of the effects of heat-pipe failures has indicated the desirability of raising the number of heat pipes in the core above 90 to, perhaps, 162.
- Design parameters for a core containing 162 heat pipes were presented.
- As the result of a more realistic weight analysis, the core heat pipe weight has been reduced by nearly a factor of two.
- Special attention was given to the design of the core periphery and to the design of a new fuel element potentially capable of containing in excess of 80 vol% UO_2 in the fuel region. This effort yielded solutions to the difficulties caused by heat pipe failures on the core periphery.
- 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 for these two sub-assemblies but at an added mass penalty to the power plant on the order of 500 kg.