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Title: HEAT PIPE COOLED REACTORS FOR MULTI-KILOWATT SPACE POWER SUPPLIES

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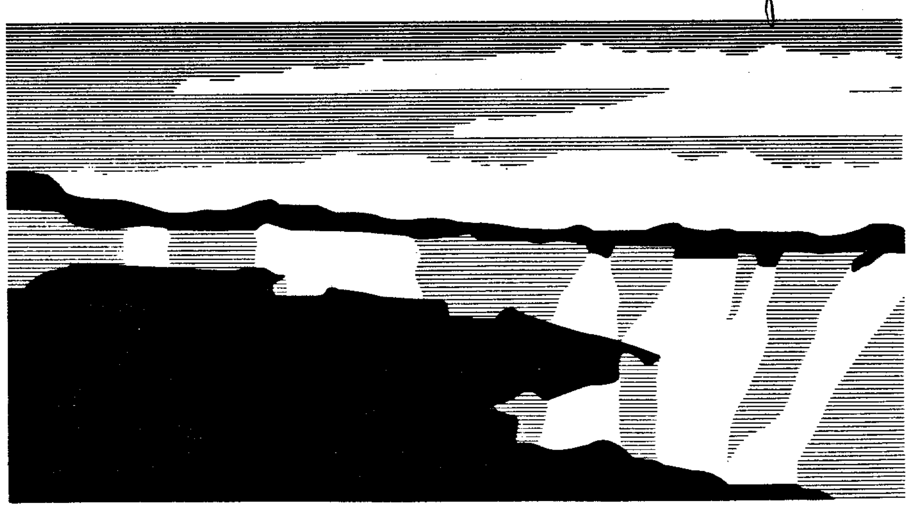

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Heat Pipe Cooled Reactors
for
Multi-Kilowatt Space Power Supplies

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Abstract

Three nuclear reactor space power system designs are described that demonstrate how the use of high temperature heat pipes for reactor heat transport, combined with direct conversion of heat to electricity, can result in eliminating pumped heat transport loops for both primary reactor cooling and heat rejection. The result is a significant reduction in system complexity that leads to very low mass systems with high reliability, especially in the power range of 1 to 20 kWe. In addition to removing heat exchangers, electromagnetic pumps, and coolant expansion chambers, the heat pipe/direct conversion combination provides such capabilities as startup from the frozen state, automatic rejection of reactor decay heat in the event of emergency or accidental reactor shutdown, and the elimination of single point failures in the reactor cooling system. The power system designs described include a thermoelectric system that can produce 1 to 2 kWe, a bimodal modification of this system to increase its power level to 5 kWe and incorporate high temperature hydrogen propulsion capability, and a moderated thermionic reactor concept with 5 to 20 kWe power output that is based on beryllium modules that thermally couple cylindrical thermionic fuel elements (TFEs) to radiator heat pipes.

INTRODUCTION

The high-temperature, liquid-metal-working-fluid heat pipe was invented for the purpose of cooling a novel design thermionic reactor. In the first years after its invention a number of reactor concepts were formulated based on heat pipe transmission of reactor heat to various conversion systems. It was recognized very early that heat pipe cooling of reactors offers a number of advantages over conventional cooling. Foremost among these is the potential elimination of single point failures in the reactor cooling system. But such capabilities as startup from a frozen state, automatic rejection of reactor decay heat in the advent of emergency or accidental shut down, and elimination of the need for electromagnetic pumps and expansion chambers for liquid metal coolant are also very advantageous from a space reactor design standpoint.

Despite their obvious merit, it cannot be said that heat pipe designs have attracted overwhelming support in the space reactor development community. This circumstance can be attributed to no single cause but appears to be rooted in a general reluctance by developers and potential users to embrace what is still considered to be new technology. However, another problem has been the tendency of space power support organizations to emphasize the technology for point designs with power output in the several tens to hundreds of kilowatts of electricity and rely on scale down of this technology to meet potential mission requirements in the range of 1 to 20 kWe. This approach has tended to discriminate against heat pipe reactor selection because heat pipe reactors are especially attractive for this low power range. This is unfortunate because it is in this range of power that the first future space reactor mission requirements will almost surely be.

By way of demonstrating what can be achieved by concentrating on the low power regime for heat pipe reactor design, this paper discusses three concepts in which nuclear heat is coupled by heat pipes to direct energy conversion systems. These are as follows:

HPR I - A 1 to 2 kWe system in which thermoelectric unicouples with individual heat rejection fins are directly mounted on Na/Nb heat pipes delivering heat from the periphery of a very compact reactor core.

HPR II - An adaptation of the above that adds the capability of heating hydrogen for direct propulsion and also increases the electrical power output to 5 kWe.

HPR III - A moderated thermionic reactor with a power output capability of 5 to 20 kWe in which beryllium modules are used to achieve direct conduction thermal coupling of thermionic TFEs to radiator heat pipes.

In each of these designs, primary attention has been given to achieving good thermal contact and conduction all along the heat transport path from reactor fuel, where heat is generated, to the radiating surface from which waste heat is rejected. This is important because the minimization of non-productive temperature drops in the electrical generation system maximizes the heat rejection temperature and, hence, reduces system mass. It also minimizes the reactor fuel operating temperature, which increases reactor longevity. A further consideration is that the achievement of low temperature drops be done in a manner that provides redundancy against the possible failure of individual heat pipes so that any potential for single point failure of the reactor cooling system can be avoided.

DESCRIPTION OF POWER SYSTEMS

HPR I

The reactor configuration used for HPR I is shown in Fig. 1. It is an updated version of the ALERT system first described by Ranken (1990a). The core consists of 8-mm-thick uranium carbide plates and 2-mm-thick molybdenum plates that are stacked alternately to form a cylinder that has a height of 210 mm and an outer diameter of 150 mm with a central hole 50 mm in diameter. This fuel stack is contained in an annular-shaped molybdenum core can having a 2-mm wall thickness. Twelve Nb/Na heat pipes, with diameters of 12.5 mm, are brazed to the external circumference of the core can and 6 are brazed to the internal circumference.

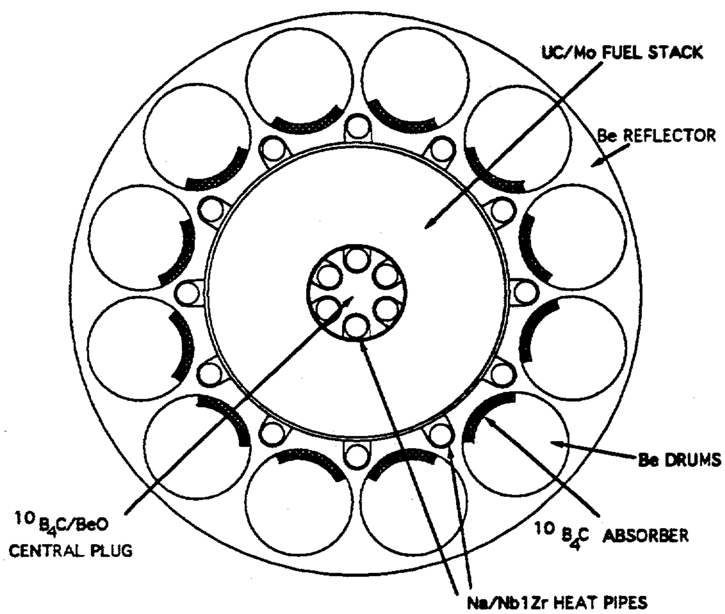

Fig. 1. Core Configuration for 1-2 kWe Heat Pipe Reactor.

The primary reason for interleaving molybdenum plates between the carbide fuel plates and for brazing the heat pipes to the internal and external circumferences of the core can is to ensure good and reliable heat transport from the fuel to the heat pipes. Maintaining fuel temperature and fuel thermal gradients as low as possible is very important in establishing fuel/cladding compatibility and avoiding fuel instability, especially swelling caused by gaseous fission products. Brazing the molybdenum plates to the sides of the core can provides the requisite thermal contact without the need for conductive cover gas, which would be a source of potential single point failure. Good thermal contact between the fuel plates and the molybdenum plates is less important because the axial heat fluxes are much less than the radial ones. Thermal stresses induced because of brazing the metal plates to both the inner and outer diameters of the core can are accommodated by radially slotting them alternately from the outside and and inside diameters in a manner that does not interfere with radial heat transport.

The function of the Nb/Na heat pipes is to transport the reactor heat around the conventional LiH/W neutron/gamma ray payload shield to the thermoelectric converters. The latter are SiGe-GaP unicouples that are mounted directly on the heat pipes as shown in Fig. 2. Details of the construction and results of the stress analysis and performance analysis of these units are given in Ranken (1990a). Potassium/stainless steel heat-pipe-assisted beryllium fins are mounted directly to the unicouples so that the conversion unit and heat rejection radiator are a single unit. The exposed parts of the Na/Nb heat pipes are insulated with multifoil to prevent excessive radiative heat loss.

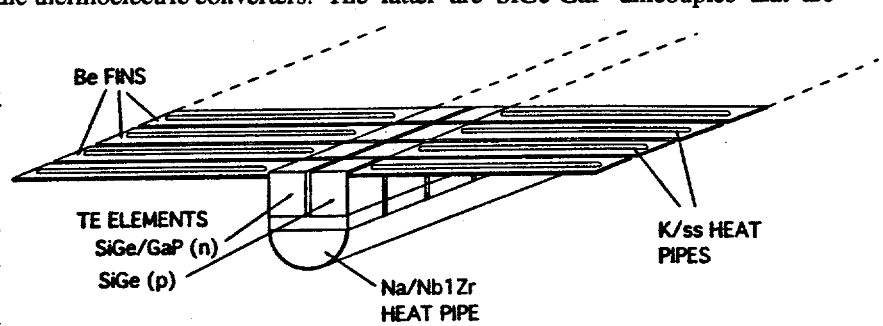

Fig. 2. ALERT Thermoelectric Unicouple Configuration.

Mass estimates of the HPR I system are given in Table 1. The mass of the power processing unit is not included because it tends to be mission dependent.

HPR II

Because low mass systems that combine low thrust direct thermal propulsion capability with electrical power production have the potential for significantly reducing the cost of launching large payloads to high level orbits, an effort was made to show how the basic concept of HPR I could be adapted and uprated to achieve desirable bimodal operating characteristics. The projected configuration for the bimodal adaptation is shown in Fig. 3 and Fig. 4. The overall configuration is similar to the ALERT power-only version shown in Fig. 1. Because of the increased power output, the number of heat pipes has been increased from 18 to 52, each carrying 2.6 kWt of thermal power to the conversion system at a temperature of 1125 K. It was also necessary to increase the core size somewhat, primarily because the core is not reflected at the end where hot hydrogen exits. The core power density has also increased. Both of the latter changes contribute to an increase in the maximum fuel temperature in the core to about 1400 K. However, the burnup for 10-yr lifetime in the power production mode is still just 0.6% so that projected fuel swelling will be less than 1%.

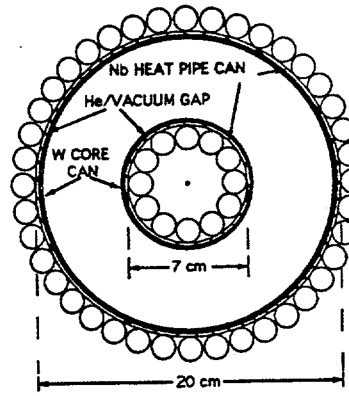

Fig. 3. Bimodal Core Layout.

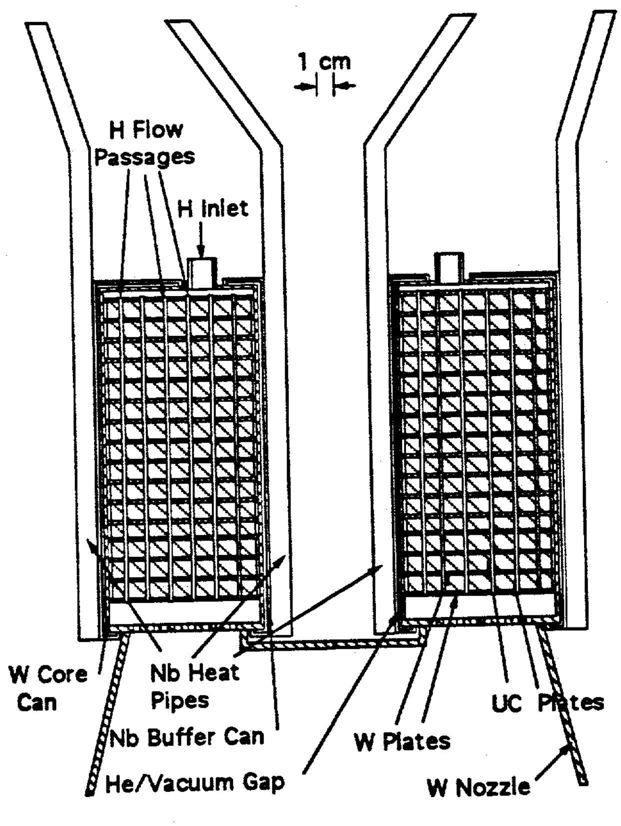

Fig. 4. 5 kWe Bimodal Reactor Configuration.

Design modifications necessitated by the addition of hydrogen heating capability include the introduction of propellent heating channels as well as the change of the refractory metal heat conduction discs and core can from molybdenum to tungsten to provide chemical compatibility with the portion of the UC fuel operating at 2000 K during the propulsion mode. The propellent channels are illustrated in Fig. 4. They total 100 in number and are partially lined with tungsten sleeves that extend up from the bottom heat conduction disc approximately 30% of the length of the core. The purpose of these sleeves is to prevent direct contact of flowing hydrogen with the UC fuel at temperatures above 1400 K. This is done to protect against removal of carbon from the UC and consequent formation of free uranium. The propellent channel design allows static hydrogen to be in contact with the UC at temperatures of 2000 to 2200 K. This is permissible because an overpressure of methane will very quickly form at the static hydrogen/UC boundary to prevent substantial carbon loss.

In Fig. 4 it can be seen that a core-can liner, brazed to the tungsten core can, has been added to the reactor design. Its purpose is to protect the heat pipes from the cold hydrogen entering the top of the reactor during propulsion operating modes (which could result in freezing the sodium working fluid in this region), and also from direct conduction contact with the hot fuel at the bottom of the reactor (which could result in heat input overload). The core-can liner is separated from the core can by a gap of 0.1 mm. This gap is filled with helium when the reactor is in the power-only operating mode. When the hydrogen propulsion mode is required, the helium is vented to space through a valve of the type used for satellite positioning control, thus isolating the core-can liner (and the heat pipes that are brazed to it) from all but radiative thermal contact with the core can. This thermal switch can be tailored to permit approximately the same heat input to the heat pipes during the propulsion mode (when the reactor is producing substantially more thermal power) as in the power-only mode, thus allowing uninterrupted electrical power production.

Criticality calculations have indicated that the reactor core shown in Figs. 3 and 4 will have several per cent excess reactivity for a fuel diameter of 200 mm and length of 280 mm if it is reflected radially, and at one end, with 70 mm of beryllium. The propellent exit end of the reactor is not reflected. Table 1 lists the masses of the 5 kWe bimodal system for the case with a 3.6-m diameter dose plane located at 10 m and a maximum allowable dose of $5x10^5$ rad and $1x10^{13}$ n/cm^2 (E=1 MeV) during a 10-year mission.

TABLE 1. System Mass Estimates (kg)

	HPR-I kWe	HPR-II 5 kWe Bimodal	HPR-III 20 kWe
Reactor	80	215	400
Heat Transfer and Power Conversion	15	130	
Shield	115	150	500
Control and Structure	45	90	50
Total	255 kg	585 kg	950 kg

HPR III

A number of studies have shown that moderated, in-core thermionic reactors are a very attractive approach in building space power supplies in the 5 to 100 kWe power range (Ranken 1960, Ponamarev-Stepnoi 1989, Space Reactor Evaluation Panel, 1988). The major advantage of in-core thermionic reactors is that no coolant is required to be in contact with the fuel or fuel cladding so that the hot side of the electrical conversion cycle can be at very high temperature. As a direct consequence, the low temperature side of the conversion cycle can be at temperatures considerably above those for other conversion systems. Furthermore, only one coolant loop is required. Both high heat rejection temperature and hot-side coolant loop elimination lead to reductions in power system mass. Further mass reduction, as well as removal of single point failure potential, can be brought about by replacing the waste heat rejection pumped loop with heat pipes.

The problem with applying heat pipe cooling to thermionic reactors with traditional cylindrical TFE design, so as to achieve good thermal contact and redundant cooling, has been a particularly vexing one. A reactor system called MOHTR has been conceived (Ranken 1990b, Ranken 1991) that solves this problem, without the need for strange heat pipe shapes, by constructing the core from beryllium modules that contain one TFE (either multicell or single cell) and three heat pipes that are directly brazed to the beryllium. In order to create a relatively compact core, these modules are alternated with cylindrical rods of ZrH, (a substantially better neutron moderator than Be), in a regular lattice configuration. One version of the overall configuration of the reactor core is shown in Fig. 5. Two alternative designs for the beryllium module are also shown in this figure. In one of these, the Zr H rods are nested between adjacent modules, to which they are thermally coupled only by thermal radiation. In the other, the rods are incorporated into the individual modules with sodium bonding. Any two of the heat pipes in a

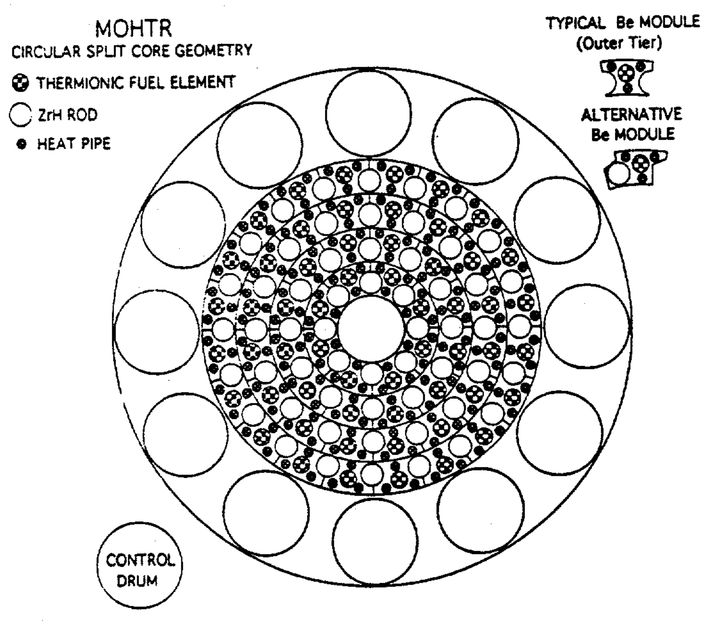

Fig. 5. 20 kWe Heat Pipe Thermionic Reactor.

given module can remove the heat generated in the TFE with no loss of the latter's electrical performance. The TFE in each module is sodium bonded to the Be to achieve good thermal contact. TFEs that contain only a single emitter can be built directly into the module, eliminating the need for sodium bonding. In this case, the capability of connecting successive modules in series is maintained by a thin sprayed coating of alumina on the external surfaces of the individual modules.

A major advantage of the MOHTR design approach is that, because of its compact size, the heat pipe radiating surface can be on the same side of the neutron/gamma ray shield as the reactor (Ranken 1990b). This eliminates the complexity and thermal management problem associated with bringing the heat pipes around the shield to a radiator located between the shield and the payload.

The mass of the HPR-III system is shown in Table 1.

CONCLUSIONS

The three reactor designs described briefly above demonstrate the feasibility of combining heat pipe heat transport with direct conversion of electricty to generate very compact and versatile reactor power systems with reduced complexity and no source of single point failure in the cooling system. These types of systems are very attractive relative to other space power systems, both solar and nuclear, in the power range of 1 to 20 kWe. They can be very competive with other types of nuclear reactor systems for power levels up to the 100 kWe level (Smith 1985). As power levels increase into the hundreds of kWe range, problems with core void, reflector control margin, complexity, and heat pipe length requirements eventually reduce the desirability of the heat pipe cooling approach.

Acknowledgments

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