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A HEAT PIPE COOLED MODULAR REACTOR CONCEPT FOR MANNED LUNAR BASE APPLICATION

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ABSTRACT

A lithium heat pipe cooled modular fast reactor (HPCMR) power system concept has been developed for manned lunar base application. The system is designed to use the static thermoelectric conversion module to produce over 100kW electricity for up to ten years. Waste heat is rejected by potassium heat pipe radiator. This system has advantages of low mass, long lifetime, no pumped liquid coolant, and no single point of failure. Main parameters of the system are also given in this paper.

INTRODUCTION

Early prior research demonstrated the superiority of ceramics for bearings (1, 2) and the existence of elasto-hydrodynamic (ehd) lubricant films at ball and roller contacts (3), the calculation of which is now an accepted part of bearing engineering. These new concepts are now used in the design of lubrication systems with solid lubricants that operate in much more severe environments than oils and greases (4, 5). Proprietary computer codes and unique patented bearing configurations for optimizing the performance of bearing/solid-lubricant systems have been developed (6, 7 and 8). In this way, patented self-contained solid-lubricated all-steel and hybrid-ceramic ball and roller bearings are now available for environments that do not contribute to their lubrication, such as in air or vacuum.

With the development of space exploration technologies and urgent demand for resources exploitation, many countries have made their plans to explore the moon in the next few years. China is carrying out the moon exploration project - ChangE and already made great achievement. In the foreseeable future, China will actualize manned lunar exploration and build lunar outpost.

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For human missions, power requirements may vary from 10s of kWe to support initial human visits to 100s of kWe for a permanent lunar base, especially if in-situ resource utilization processes are required. In such output power range, preponderant planetary surface nuclear power is being considered because it can provide constant energy for human life-support systems, recharging rovers, mining for resources, and so on. Alternatives such as solar power systems are limited because the moon is dark for up to 14 days at a time and has deep craters that can obscure the sun.

A lunar nuclear power system is different from traditional nuclear reactors because of the special application environment. The system should be small, compact, robust and low mass to satisfy the launch requirement. The system should be simple and highly reliable because it is difficult, even impossible to maintain the reactor in the lunar surface. The system should be safe and easy to operate considering lack of professional operators. The system must be suitable for the lunar environment such as low gravity and near vacuum. Also, we hope the reactor system is a long life time and has no single point of failure. Considering the lunar reactor characteristics mentioned above, a lithium heat pipe cooled modular fast reactor (HPCMR) conceptual design has been developed to support future China manned lunar base application. The system has a solid reactor core and is designed to use static thermoelectric conversion to produce over 100kW electricity for up to ten years. Whole system efficiency is ~7% and has a mass of ~3.2 tons. Waste heat is rejected by potassium heat pipe radiator. HPCMR has advantages of low mass, long lifetime, no pumped liquid coolant, and no single point of failure.

HPCMR POWER SYSTEM GENERAL DESIGN

Figure 1 demonstrates the HPCMR power system. HPCMR is comprised by three modules (Figure 2) to easily satisfy China current launch vehicle load requirement. Each module (Figure 2B) is comprised by 1 reactor core block, 1 shield block, 2 thermoelectric conversion modules, 2 Potassium heat pipes radiator panels and other support structures. The Potassium heat pipes radiator panels are folded in the delivering period. The maximum width and length of folded HPCMR module are 2.3m and 3.7m respectively. The HPCMR modules are launched to the moon separately and assembled to a whole system on the moon surface. Then the reactor core is either set into a lunar regolith hole of 1.8m deep, 1m diameter (Figure 3) or regolith can be piled up around it. Lunar regolith is used to shield the radial radiation from the reactor to decrease the whole system mass. And the Potassium heat pipes radiator is deployed to a 45 degree angle with the lunar surface.

The Lithium heat pipes penetrate the axial reflector and surround the shield above the reactor core. The condenser section is connected to the thermoelectric conversion module by the heat exchangers, thus transfer the reactor core heat to the hot end of thermoelectric conversion module. Part of heat is converted to electricity when it passes through the thermoelectric couple conversion module. The left heat (waste heat) is conducted to the Potassium heat pipe's evaporator section connected to the cold end of thermoelectric conversion module, and is rejected to environment by radiator.

This system has following merits:

1) Modularization design satisfy China launch vehicle load requirement. Launch critical accident is avoided because only one module can not reach critical.

2) Such design with solid core reactor, heat pipes cooled and thermoelectric conversion has no moving or rotating parts for fatigue failure, no flowing cooling fluids that can leak failing the whole system. Such design also has merits of robust, simple and high reliability.

3) Reactor core is cooled by Lithium heat pipes. Single Lithium heat pipe failure almost has no influence to the operation of whole system. Waste heat is rejected by potassium heat pipe radiator. Single or several Potassium heat pipes failure also won't fail the whole system. Thermoelectric couple conversion also has the merit of no single point of failure.

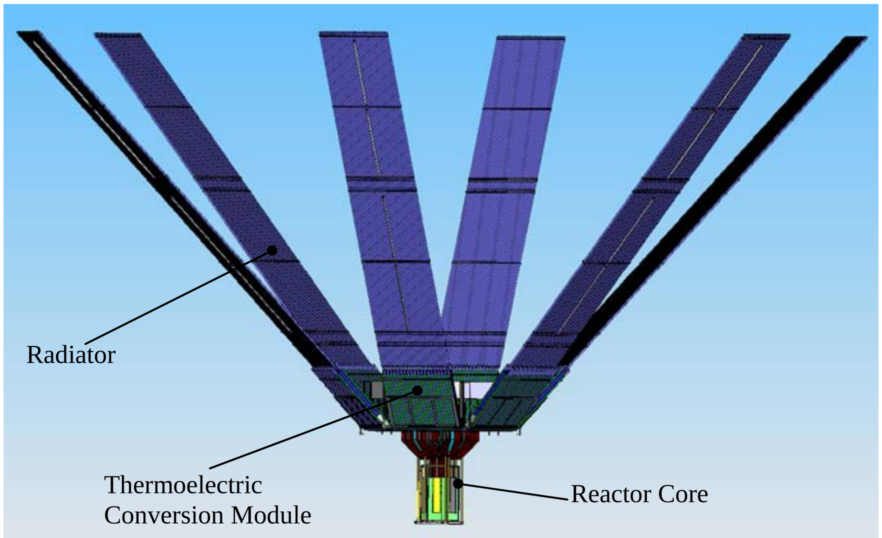
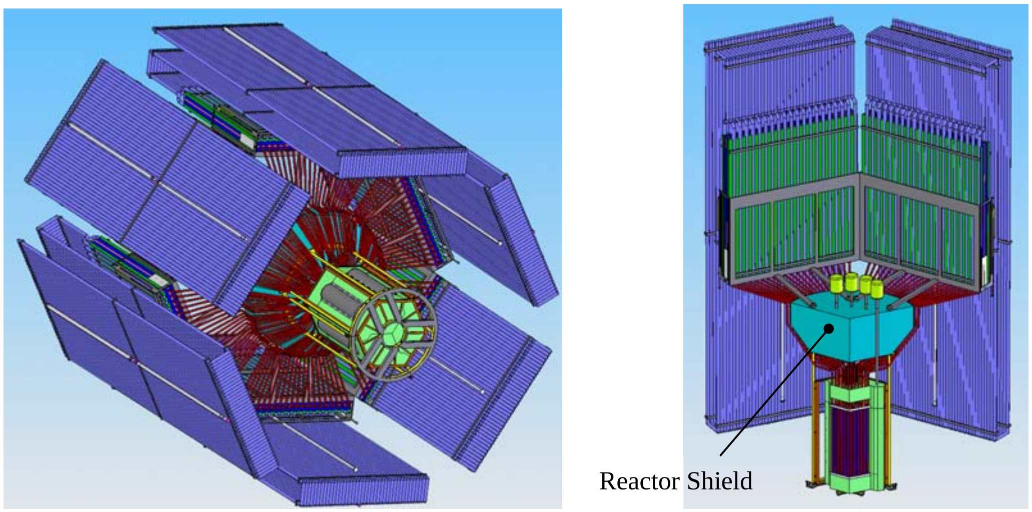


Figure 1. DEPLOYED STATE OF HPCMR



A. FOLDED HPCMR **B. 1 OF 3 HPCMR MODULES**

Figure 2. FOLDED STATE OF HPCMR

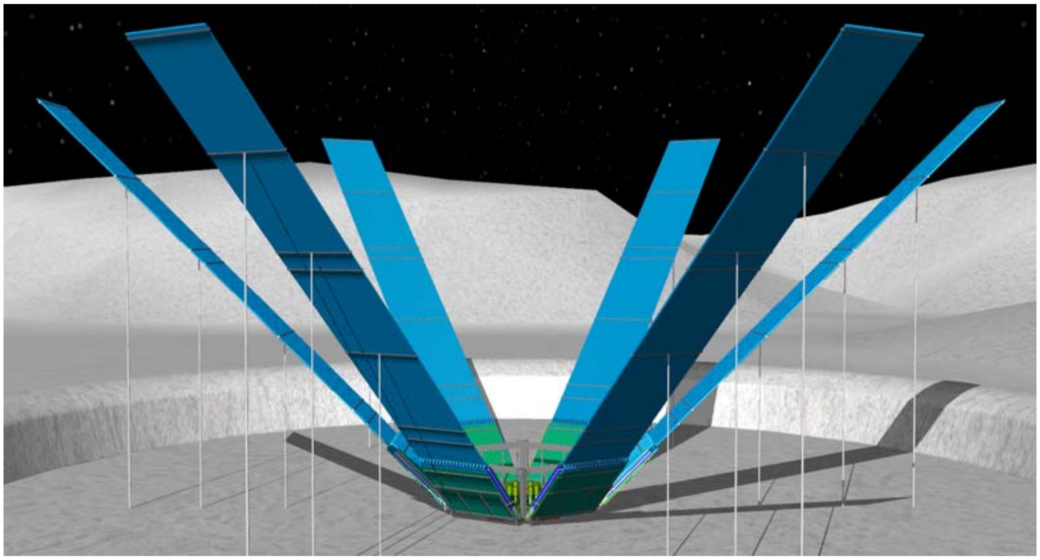


Figure 3. VISION OF HPCMR

REACTOR CORE LAYOUT

The reactor, including the radial and the axial BeO reflectors, is 90 cm long and 54.2 cm wide flat to flat, and the active core is 60 cm long and 34.2 cm wide flat to flat (Figure 4).

The hexagonal HPCMR core is separated to three blocks (Figure 4 and Figure 5). Each reactor core block contains 42 Lithium heat pipes and 102 UN fuel rods. Thus, the whole reactor contains 126 Lithium heat pipes and 306 UN fuel rods. The UN, Mo-14%Re clad fuel rods arranged in a triangular lattice to a lithium heat pipe with a Mo-14%Re wall of the same outer diameter (1.5 cm). The design parameters of the fuel rods are shown in table 1. The enrichment of ^{235}U is 42%. The fuel clad thickness is 0.52mm. The thickness of helium gas gap between clad and fuel pellets is 0.1mm. The design parameters of the Lithium heat pipes are shown in table 2. The lithium heat pipe wall inner diameter is 14.2mm and vapor cavity diameter is 13.2mm. The heat pipe wick porosity is 0.8. The evaporator length of the lithium heat pipes is the same as that of the active core (60 cm) (Figure 5). The average insulator length of the lithium heat pipes is 1.8m. The average condenser length of the lithium heat pipes is 1.3m.

Every fuel rod is adjacent to at least two Lithium heat pipes to avoid fuel destruction caused by single heat pipe failure. Central distance between fuel rod and heat pipe is 16mm. Interspace between fuel rods and heat pipes is filled with Mo-14%Re random fiber matrices with 35% porosity (Figure 6). The porose fiber matrices can contain thermal expansion of the core and have relatively high thermal conductivity.

The reactor core is surrounded by 10 cm thick radial and axial BeO reflectors. The reactor reactivity is controlled by 6 large and 6 small BeO/B_4C control drums in the radial reflector.

The B_4C segments (5 mm-thick 120^o sectors) in the control drums face the reactor core during launch. The diameter of large control drums is 13.6cm. The diameter of small control drums is 10cm. Each reactor core block contains 2 large and 2 small control drums (Figure 5). The 12 BeO/B_4C control drums have a total reactivity worth of 8.6 △k/k% that is sufficient for operating the reactor at full power for more than 10 years.

Table 1. DESIGN PARAMETERS OF FUEL RODS

Parameter	Value
Fuel material	UN
Clad material	Mo-14w%Re
Outer Diameter(mm)	15
Active Length(cm)	60
Clad Thickness(mm)	0.52
Helium Gas Gap(mm)	0.1
Radial Nuclear Factor	1.3

Table 2. DESIGN PARAMETERS OF LITHIUM HEAT PIPES

Parameter	Value
Wall and Wick Material	Mo-14w%Re
Evaporator Length(cm)	60
Average Length(m)	3.7
Outer Diameter(mm)	15
Wall Thickness(mm)	0.4
Capillary Wick Thickness(mm)	0.5
Wick Porosity	0.8
Vapor Cavity Diameter(mm)	13.2

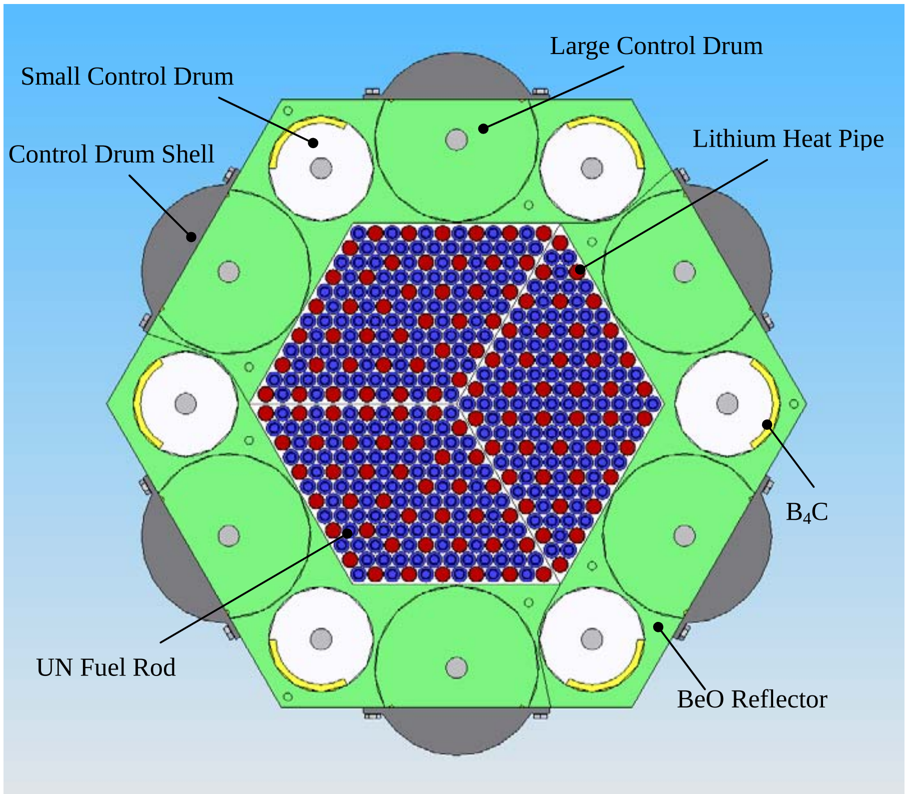


Figure 4. RADIAL CROSS-SECTIONAL VIEW OF HPCMR CORE

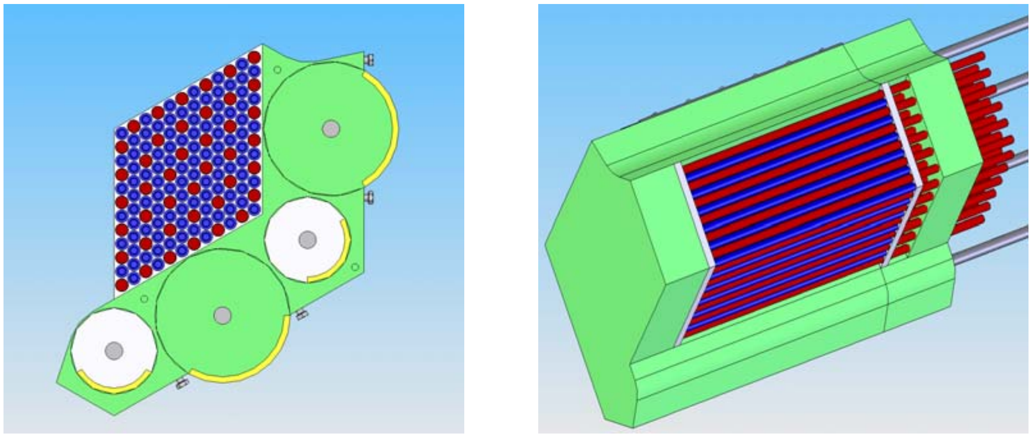


Figure 5. 1 OF 3 HPCMR CORE BLOCKS CROSS-SECTIONAL VIEWS

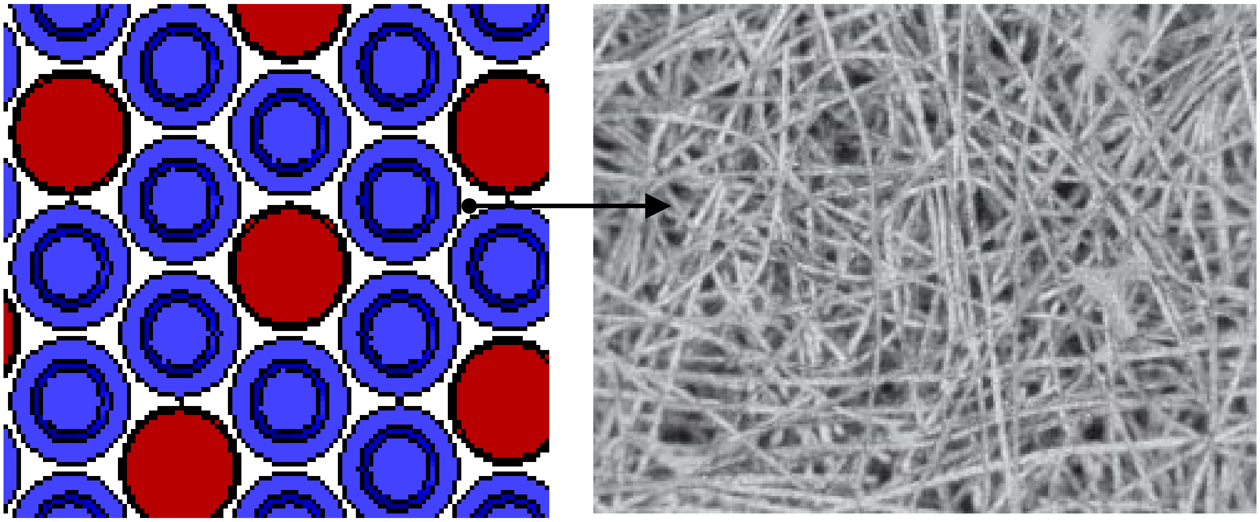


Figure 6. RANDOM FIBER MATRICES USED TO FILL INTERSPACE BETWEEN FUEL RODS AND LITHIUM HEAT PIPES

RADIATION SHIELD

Shielding is required to protect components from radiation and to provide human protection. Each HPCMR module contains 1 neutron shield block (Figure 7). The actuators (or drive shafts) of the BeO/B_4C control drums penetrate the shield to the control unit behind it. The system is assembled and set into a hole in the lunar surface so that the radial neutron and gamma radiation is shield by lunar regolith. A 2m thick lunar regolith wall surrounding the HPCMR power system is set to enhance the radiation effect (Figure 3). HPCMR power system is located 260m away from lunar base. Lunar regolith shield will minimize the whole system mass markedly. Preliminary calculation shows that this design can satisfy <50mSv/y dose requirement for lunar base.

The upper shield uses LiH to shield neutron. LiH is a good material to shield neutron with light weight. The maximum diameter and height of LiH shield are 56 cm and 45cm respectively. The part facing reactor core is shaped to 45 degree. In this concept, gamma radiation upward released will not be shield because it has no clearly influence to the operation of HPCMR power system and lunar base. No heavy shield also minimizes the system mass. More detailed radiation analyses are required for a final design.

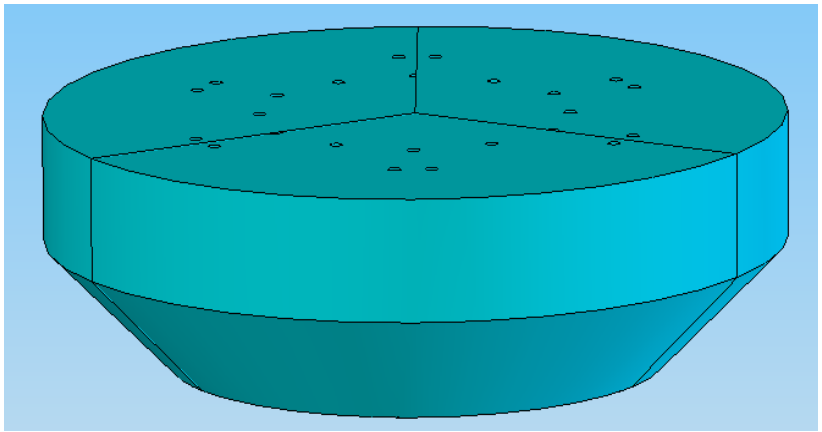


Figure 7. UPPER SHIELD

POTASSIUM HEAT PIPES RADIATOR

The system uses 6 Potassium heat pipes radiator panels (Figure 8) to reject waste heat. The length and width of each panel are 9m and 1.2m respectively. Each panel is comprised by 40 flexible Potassium heat pipes. The design parameters of the Li-heat pipes are shown in table 3. The structure material of Potassium heat pipe is Ti to minimize mass. Surface of heat pipe is coated by C-C layer with high emissivity (0.85). The diameter of Potassium heat pipe is 3cm. The Potassium heat pipe wall inner diameter is 2.9cm and vapor cavity diameter is 2.8cm. The Ti wick porosity is 0.8. The evaporator length of Potassium heat pipe is 1.3m. The condenser length of Potassium heat pipe is 7.7m. The panel is folded in the delivering period and is deployed to a 45 degree angle with the lunar surface at the operating state. The overall area of the emissive surface is ~130 m^2. The emissive area can satisfy waste heat rejection requirement at the end of the system life considering the area damage rate of 3% per year due to a meteoroid impact.

Table 3. DESIGN PARAMETERS OF POTASSIUM HEAT PIPES

Parameter	Value
Wall and Wick Material	Ti
Evaporator Length(cm)	1.3
Average Length(m)	9
Outer Diameter(mm)	30
Wall Thickness(mm)	0.5
Capillary Wick Thickness(mm)	0.5
Wick Porosity	0.8
Vapor Cavity Diameter(mm)	28

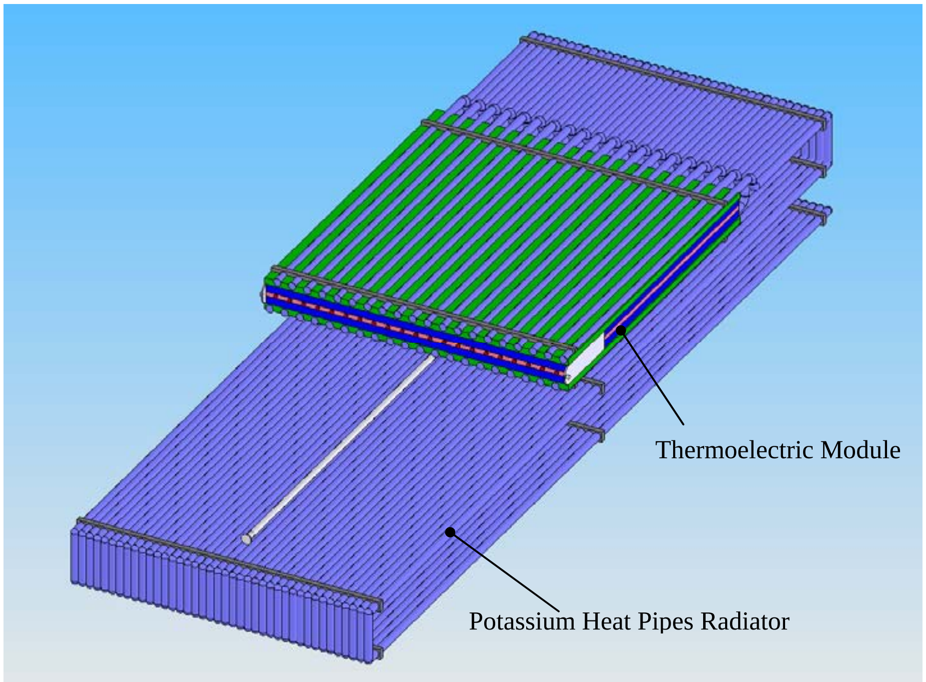


Figure 8. FOLDED POTASSIUM HEAT PIPES RADIATOR PANEL

THERMELECTRIC COUPLE CONVERSION MODULE

HPCMR power system converts thermal energy to electricity through SiGe thermoelectric couple conversion module (Figure 8, 9). The length and width of thermoelectric conversion module are 1.3m and 1.2m respectively. The thickness is ~6cm. The module is comprised by 5 layers. The middle layer is Lithium heat pipes exchanger (~18mm thick, Mo-14%Re) (Figure 10). Each side of Lithium heat pipes exchanger is connected to a thermoelectric panel (~15mm). And Potassium heat pipes heat exchanger (Ti) is connected to the cold end of thermoelectric panel. There are grooves on the surface of Potassium heat pipes heat exchanger. Potassium heat pipes are welded to the grooves.

SiGe devices can operate at temperature up to about 1300K without significant degradation [1]. Recently a significant figure-of-merit improvement in the most-studied existing thermoelectric materials has been achieved by creating nanograins and nanostructures in the grains using the combination of high-energy ball milling and a direct-current-induced hot-press process [2]. Enhanced thermoelectric figure-of-merit in nanostructured p-type and n-type SiGe bulk alloys has been achieved [3, 4]. Figure-of-merit of p-type $Si_{80}Ge_{20}B_x$ reaches 0.95 at temperature of 1073~1173K [3]. Figure-of-merit of n-type $Si_{80}Ge_{20}P_2$ reaches 1.3 at temperature of 1173K [4]. Thermoelectric couple conversion module of HPCMR power system is designed to work at temperature of 748-1215K. When average figure-of-merit (ZT_M) is initialized to be 1.1, the efficiency can be estimated to be ~8.4% by the equations [1]:

$$\eta = (\frac{T_1 - T_2}{T_1}) \cdot \frac{(1+ZT_M)^{1/2} - 1}{(1+ZT_M)^{1/2} + T_2/T_1} \quad (1)$$

$$T_M = \frac{T_1 + T_2}{2} \quad (2)$$

The whole system efficiency is designed to be 7% considering the circuit loss is reasonable. At the end of life, the system can also produce over 100kW electricity considering the degradation of thermoelectric material.

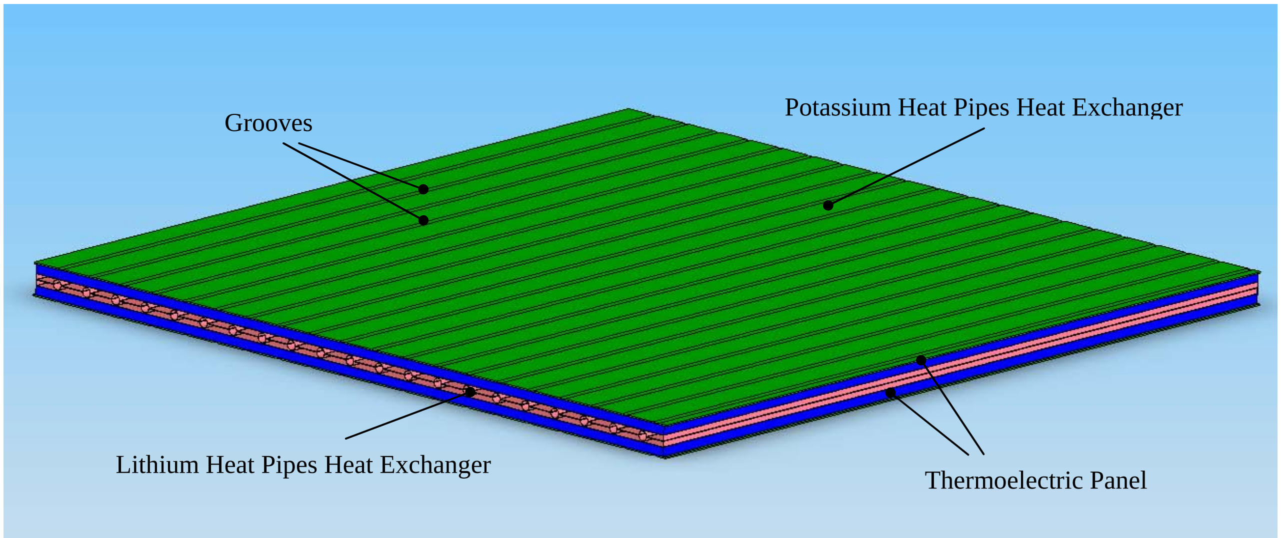


Figure 9. THERMOELECTRIC CONVERSION MODULE

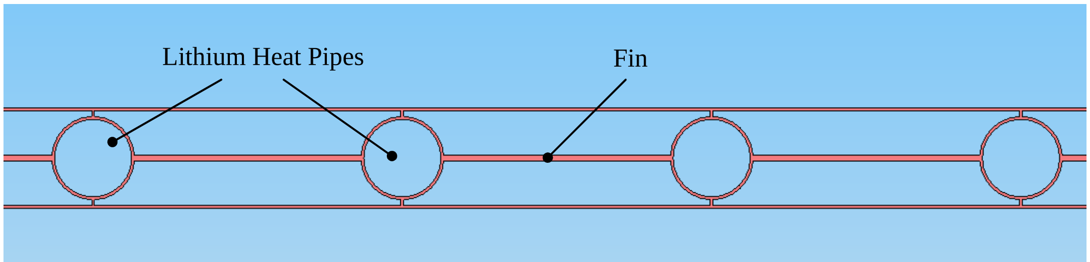


Figure 10. CROSS-SECTIONAL VIEW OF LITHIUM HEAT PIPES HEAT EXCHANGER

STSTEM MASS ESTIMATION

Table 4 shows the preliminary system mass estimation.

Table 4. HPCMR POWER SYSTEM MASS ESTIMATION

Item	Main Material	Density（g/cm^3）	Mass（kg）
Fuel Rods	UN	13.6	371
Fuel Rods Clad	Mo-14%Re	12	52
Random Fiber Matrices	Mo-14%Re	7.15	92
Lithium Heat Pipes	Mo-14%Re	12	82
Reflector	BeO	3.03	304
Control Drums	BeO /B_4C	3.03/2.52	297
Control Drum Actuators	Ti	4.54	72
Upper Shield	LiH	0.72	80
Potassium Heat Pipes	Ti	4.54	543
Thermoelectric Panels	SiGe	2.99	550
Lithium Heat Pipes Heat Exchanger	Mo-14%Re	12	279
Potassium Heat Pipes Heat Exchanger	Ti	4.54	169
Support Structures	Ti Alloy	4.54	140
Residual			150
Total Mass			3181

SYSTEM MAIN PARAMETERS

Table 5 shows the preliminary system parameters.

Table 5. HPCMR POWER SYSTEM MAIN PARAMETERS

Parameter	Value	Annotation
Rated Thermal Power, MW	1.6	
Lifespan, year	10	
System Efficiency, %	7	
Electricity Output, kW	112 100	BOL EOL
System Mass, t	3.2	
UN Mass, kg	371	
^{235}U Enrichment, %	42	
^{235}U Mass, kg	147.2	
Burnup, MWd/t	15741	EOL
Built-in Reactivity, △k/k%	2.35 -6.25	B_4C Segment Facing Outside B_4C Segment Facing Inside
Reactivity, △k/k%	0.037	B_4C Segment Facing Outside, EOL
Control Drums Total Reactivity Worth, △k/k%	-8.6	
Fuel Rod Peak-to-Average Power Ratio	1.158-1.39	
UN Average Linear Power Density, W/cm	87.1	
UN Maximum Linear Power Density, W/cm	136.9 190.3	Average Channel Hot Channel
Lithium Heat Pipe Heat Transfer Limit, kW	26.2 26.9	Average Channel, BOL, 106% Margin Hot Channel, BOL, 52% Margin
Lithium Heat Pipe Evaporator Temperature, K	1525 1529	Average Channel, BOL Hot Channel, BOL
Maximum Temperature of Fuel, K	1694 1754	Average Channel, BOL Hot Channel, BOL
Working Temperature of Thermoelectric Couple, K	748-1215 808-1274	BOL EOL
Potassium Heat Pipe Transfer Limit, kW	8.5 16.3	BOL, 36% Margin EOL, 83% Margin
Potassium Heat Pipe Condenser Temperature, K	739 799	BOL EOL

CONCLSUIONS

In order to support future China Lunar exploration, a lithium heat pipe cooled modular fast reactor power system concept has been developed. The system is designed to have a thermal power of 1.6MW and use thermoelectric conversion module to produce over 100kW electricity for up to ten years. Whole system efficiency is ~7% and has a mass ~3.2 tons. Waste heat is rejected by potassium heat pipe radiator.

HPCMR power system is comprised by three modules to easily satisfy China launch vehicle load requirement. The HPCMR modules are delivered to the moon separately and assembled to a whole system on the moon surface. Then the reactor core is either set into a lunar regolith hole or regolith can be piled up around it. Lunar regolith is used to shield the radial radiation from the reactor to decrease the whole system mass. And the Potassium heat pipes radiator is deployed to a 45 degree angle with the lunar surface.

HPCMR power system has advantages of low mass, long lifetime, no pumped liquid coolant, and no single point of failure. Main preliminary parameters of the system are also given in this paper.

NOMENCLATURE

η —conversion efficiency

T_1 —source temperature, K

T_2 —sink temperature, K

ZT —figure-of-merit

ACKNOWLEDGMENTS

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