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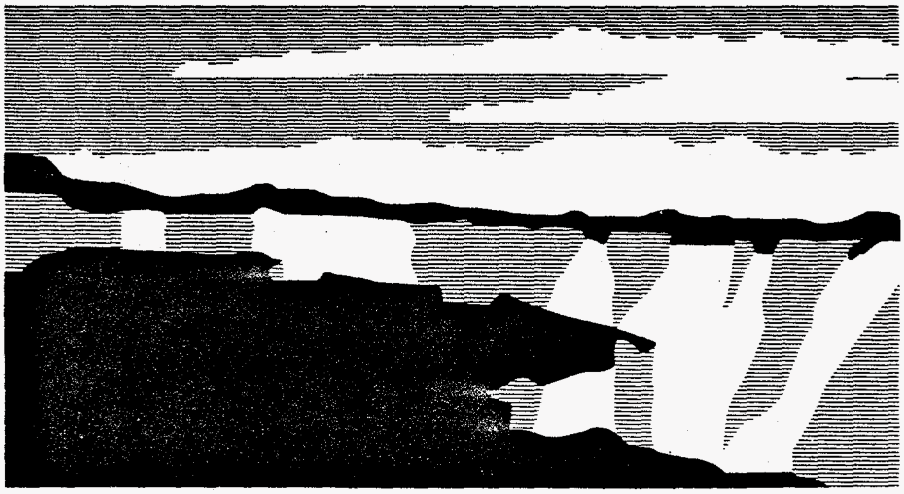

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HEATPIPE SPACE POWER AND PROPULSION SYSTEMS

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ABSTRACT

Safe, reliable, low-mass space power and propulsion systems could have numerous civilian and military applications. This paper discusses two fission-powered concepts: the Heatpipe Power System (HPS) that provides power only, and the Heatpipe Bimodal System (HBS) that provides both power and thermal propulsion.

Both concepts have 10 important features. First, only existing technology and recently tested fuel forms are used. Second, fuel can be removed whenever desired, greatly facilitating system fabrication and handling. Third, full electrically heated system testing is possible, with minimal operations required to replace the heaters with fuel and ready the system for launch. Fourth, the systems are passively subcritical during launch accidents. Fifth, a modular approach is used, and most technical issues can be resolved with inexpensive module tests. Sixth, bonds between dissimilar metals are minimized. Seventh, there are no single point failures during power mode operation. Eighth, fuel burnup rate is quite low to help ensure greater than 10-year system life. Ninth, there are no pumped coolant loops, and the systems can be shut down and restarted without coolant freeze/thaw concerns. Finally, a full ground nuclear test is not needed, and development costs will be low.

The baseline HPS uses SNAP-10A-style thermoelectric power converters to produce 5 kWe at a system mass of about 500 kg. The unicouple thermoelectric converters have a hot shoe temperature of 1275 K and reject waste heat at 775 K. This type of thermoelectric converter has been used extensively by the space program, demonstrating an operational lifetime of decades. At higher thermal power, the same core can produce over 10 kWe using thermoelectric converters, and over 50 kWe using advanced power conversion systems. The baseline HBS produces greater than 50 N of thrust at a specific impulse greater than 750 s, can operate for long periods of time (hundreds of hours, limited by propellant supply) in bimodal mode, produces 5 kWe in power or bimodal mode, has greater than 10 year power mode life, and has a mass less than 800 kg.

HPS development cost (through flight unit fabrication, thermal testing, and zero-power nuclear testing) should be less than $100M. HBS development cost will be higher than HPS development cost because of the added complexity of the bimodal system.

INTRODUCTION

Safe, reliable, low-mass space power and propulsion systems could have numerous civilian and military applications. Fission systems have the following potential advantages.

1. Cost. Once developed, the unit cost of a fission system can be less than for competing systems (solar, isotopic).
2. Scalability. Fission systems are capable of producing extremely high power.
3. Operating environment. Fission systems operate independent of solar proximity or orientation, and are well suited for missions to Mars and beyond. Fission systems can tolerate high radiation fields, and can be designed to operate in dusty environments. Fission systems are also well suited for surface operations where solar energy may not always be available.
4. Launch approval. Fission systems contain no plutonium and are nonradioactive at launch, possibly facilitating launch approval.

The most common disadvantages associated with fission systems are nontechnical in nature. One of these is the perception that fission systems will cost billions of dollars to develop. This paper proposes two concepts that through using existing facilities and technology developed over the last 40 years should have development costs on the order of $100M. Another issue that has curtailed the development of space fission systems is the large number of regulations that deal with nuclear systems. The systems proposed in this paper have two characteristics that should minimize regulatory delays: there is no requirement for a nuclear ground test, and the systems can be tested, assembled, and transported separately from the nuclear fuel. One additional issue is the negative attitude toward nuclear systems among some members of the public and user community. The driving factors behind the design of the Heatpipe Bimodal System (HBS) and the Heatpipe Power System (HPS) are simplicity and safety. This will help gain acceptance early in the program, and more importantly, keep failures from occurring.

HEATPIPE POWER SYSTEM

HPS is an extremely compact space fission power supply capable of providing over 100 kWt at 1275 K to a power conversion subsystem. The core consists of 12 modules, each containing 4 molybdenum or Nb-1Zr clad UN fuel pins bonded to a central heatpipe. If coupled to SNAP-10A-style thermoelectric converters, HPS provides 5 kWe at a mass of about 500 kg. The unicouple thermoelectric converters have a hot shoe temperature of 1275 K and reject waste heat at 775 K. This type of thermoelectric converter has been used extensively by the space program, demonstrating an operational lifetime of decades (Ranken et al. 1990). Operating at a higher thermal power and using AMTEC or other high-efficiency power conversion systems allows HPS electrical power output to exceed 50 kWe. Heat transfer issues limit maximum HPS thermal power to a few hundred kilowatts, although larger cores with higher heatpipe to fuel pin ratios could operate at greater power.

A schematic of HPS is shown in Figure 1. HPS has a low fuel burnup rate, and no fuel development program is required. In the SP-100 program, uranium nitride fuel in a very similar configuration was tested to the equivalent burnup of several decades lifetime (Makenas et al. 1994). The life-limiting feature in the baseline HPS will probably be the thermoelectric power converters, although they also have long-life potential. Fuel can be removed from HPS whenever desired, greatly facilitating fabrication and handling. HPS is inherently subcritical during launch accidents, and has no single point failures. HPS can also undergo full electrically heated system testing at existing facilities. Each of the HPS modules is independent, allowing most technical issues to be resolved with inexpensive module tests.

The key feature of the HPS is the power generation module, shown in Figure 2. Each module consists of four fuel pins bonded to a central heatpipe, with the same material (NB-1Zr or Mo) used for the fuel clad and the heatpipe wall. Mechanical bonding will be achieved by a tack weld, an electron beam weld, chemical vapor infiltration (CVI), hot isostatic pressing, or some other method. For low power cores (<100 kWt) radiation heat transfer will be adequate if finned heatpipes are used and if some reduction in power is acceptable following the loss of a heatpipe. If some thermal bonding is desired, it can be accomplished by an electron beam weld, a braze, a helium bond, the use of a refractory metal wool, CVI, or some other method. During power operation there will by some asymmetry in the fuel radial temperature profile because heat is primarily removed from one section of the fuel clad. However, the temperature asymmetry will not be severe because of the low power density.

Heat generated in the fuel is transferred to the module heatpipe. The module heatpipe transfers heat to the secondary heatpipes, with the junction located on the surface of the shield. Heat from the secondary heatpipes is transferred to thermoelectric converters that are bonded to the heatpipe surface. Excess heat is radiatively rejected to space from the cold side of the thermoelectrics.

Structural support of the core is provided by the module heatpipes, which are anchored to a molybdenum or Nb/1Zr tie plate. On the opposite end of the core the pins are confined laterally, but they are allowed to move feely in the longitudinal direction to allow for differential expansion. Neutron shielding is provided by a lithium hydride shield, and tungsten gamma shielding may or may not be required depending on the thermal power level, the payload separation, and the allowable dose. The reference shield assumes an operating power of 100 kWt, an allowable gamma dose rate of 5×10^4 rad/yr, and a neutron dose rate of 10^{12} n/cm^2/yr (1 MeV equivalent) at a 2.0 m diameter dose plane located 10 m from the core centerline. The low dose rate will enable the use of less expensive components on some missions.

HPS is designed to remain subcritical during all credible launch accidents. This has been accomplished by keeping the system radius small, the reflector worth high, and by strategically placing resonance absorbers in the core. The negative reactivity worth of the control drums in the reflector, or the negative reactivity effect of losing the reflector and surrounding the reactor with wet sand or water, offsets the positive reactivity effect of core flooding or compaction, eliminating the need for in-core safety rods. For deep space or planetary surface missions where reentry after reactor startup is impossible, passive launch safety can be obtained by fueling the reactor in space or by using retractable boron wires to provide shutdown. This allows the removal of resonance absorbers from the core and reduces system mass and volume.

HEATPIPE BIMODAL SYSTEM

HBS has the same features as HPS, and in addition can also heat flowing hydrogen to produce a thrust greater than 50 N at a specific impulse greater than 750 s. HBS uses tungsten clad UO_2 fuel in a configuration very similar to that used by the Russian TOPAZ II. A vacuum gap separates the HBS heatpipe from the hydrogen flow passages, protecting the heatpipe from dryout and hydrogen ingress. As with HPS, heatpipes transfer heat from the HBS core and provide over 100 kWt at 1275 K to a power conversion subsystem.

A schematic of the HBS module is shown in Figure 3. The uranium dioxide pins are quite similar to those tested under the TOPAZ II program (Wold et al. 1994). Extensive experience with tungsten clad UO_2 has also been gained under the TFEVP (Houts 1994) and previous programs. Cold hydrogen enters a plenum at the base of the core, then makes a single pass through the interstitial spaces between the fuel pins before exiting through a nozzle. Detailed thermal hydraulic calculations show that the hydrogen is heated to within 25 K of the adjacent clad temperature in the hot end of the core, and that flow channels can be tailored to allow hydrogen outlet temperature to be very close to peak clad temperature.

There is one heatpipe per module in the HBS. The tungsten fuel clad is bonded to a tungsten tube that surrounds a molybdenum heatpipe. The tungsten tube is radiatively coupled to the molybdenum heatpipe. During propulsion, the heat flux seen by the heatpipe is roughly equivalent to that seen during power mode, and the vacuum gap between the W and Mo walls reduces hydrogen permeation into the heatpipe. During power operation, there will by some asymmetry in the fuel radial temperature profile because heat is primarily removed from one section of the fuel clad. However, the temperature asymmetry will not be severe because of the low power density. In the combined power and propulsion mode, heat removal from the fuel will be nearly symmetric because of the hydrogen propellant.

The HBS power system is optimal for electric power generation in the 1-50 kWe range and for thermal propulsion at specific impulses up to 800 s and thrust levels up to a few hundred Newtons. Above a few hundred N of thrust, peak uranium dioxide temperature is a concern. A high-thrust HBS could be feasible if the UO_2 fuel pellets were replaced by a W/UO_2 or W/UN cermet, and hydrogen flowed directly through the cermet. The cermet would still be contained within a cylindrical clad to ease fabrication and testing of the system, and the module geometry would be quite similar to that of the baseline system. Cermet fuel fraction in the HBS cermet core is higher than in other heatpipe cooled cermet core designs, reducing core size. Tungsten clad uranium carbide fuel pins have also been tested, with favorable results. The use of tungsten clad uranium carbide would reduce HBS core size and possibly allow a hgher fuel power density.

HPS AND HBS DEVELOPMENT

HPS development will begin with a low-cost electrically heated module test. The test will demonstrate module fabricability, module heat transfer, module ability to withstand thermal stresses and thermal cycling, and the ability to couple power conversion systems (thermoelectric and AMTEC) to a 1275 K heatpipe. If the module test is successful, 12 modules will be brazed together into the reference core configuration, and the core will be used for electrical testing and zero-power critical testing. The braze between modules is not required, but it does reduce peak fuel temperature in the case of a failed heatpipe. Other methods for improving heat transfer (such as a refractory metal wool) will also be tested in this core. Information gained from the tests will then be used to design and fabricate the flight unit.

Existing facilities at the New Mexico Engineering Research Institute can be used to perform the module test (Mulder 1995), and the cost of module fabrication is estimated to be less than $100 K. Uranium nitride fuel fabricated during the SP-100 program is in storage at Los Alamos, and can be inexpensively resintered for use in the HPS zero power critical test and first flight unit (Chidester 1995). If desired, a full nuclear test of a module can be inexpensively performed in a number of countries (Batyrbekov 1995). The nuclear test of a module is not required, but would increase user confidence. Because of the low HPS module power density, low enriched uranium would provide the desired module power in most test reactors, and highly enriched uranium would not be needed for the module test.

HBS development is similar, although the modules will be joined together at a common plenum and are thus not totally independent. Plenum design and fabrication will add to the development expense. Electrically heated tests will also include a helium flow test to ensure that the desired propellant exhaust temperature is attained. A detachable nozzle is desirable to allow the fuel to remain separate from the reactor until shortly before launch.

Another technical issue to be resolved is the sealing of the HPS uranium nitride fuel pin shortly before launch. One possible solution is to bond an end cap to the fuel pin that contains a small tube at the end. Because the end cap will have a direct view of space and will be several centimeters from the fueled region of the core, a low temperature braze should be adequate for creating a seal between the end cap and the fuel pin. The fuel pin would be evacuated through the tube, back-filled with helium (if desired), and then the tube would be pinched off. This would avoid the necessity of having a specialized environmentally controlled facility at the launch site. Leak testing of all seals could be easily peformed, and the exact sealing procedure would be inexpensive to develop. HPS concepts using UC or UO_2 fuel pins could be vented to space and would not require a leak-tight seal.

SUMMARY AND FUTURE WORK

A summary of four core designs is given in Table 1. Neutronic and shielding analysis was performed using the three dimensional Monte Carlo particle transport code "MCNP" (Briesmeister, 1993). Thermal hydraulic analysis was performed using a three-dimensional code developed at Los Alamos. HPS1 is a rapid development HPS option that uses existing electrical heaters (from the TOPAZ International Program) to reduce cost and schedule. HPS2 is an HPS option suited for use outside of earth orbit. HPS3 is a higher power HPS option suitable for use in earth orbit or beyond. HBS1 is the reference HBS design. Mass estimates are given with and without the power conversion system. The estimated mass of a 5 kWe thermoelectric power conversion system is 100 kg, resulting in several options with a total mass (excluding power conditioning) of less than 500 kg. The maximum thermal power is based on a maximum HPS uranium nitride fuel temperature of 1600 K or a maximum HBS tungsten clad temperature of 1850 K, assuming 10 degrees of contact between all pins, a helium bond between the HPS fuel (UN) and clad, and full contact between the HBS fuel (UO_2) and clad. The failed heatpipe result assumes that the worst case heatpipe has failed for each respective design. The maximum thermal power shown in Table 1 also assumes that the power profile is flattened. HBS UO_2 fuel restructuring will result in an isothermal surface on the inside of the UO_2, causing partial axial power flattening. HPS power flattening can be accomplished by tailoring the rhenium concentration or fuel enrichment throughout the reactor. Flattening can also be achieved in HPS by placing material in the interstitials; this will also reduce system mass by reducing the void space and thus reducing the amount of resonance absorbing material

Table 1. Summary of parameters for 3 HPS and 1 HBS core designs.

	HPS1	HPS2	HPS3	HBS1
Description	12 Heatpipes, 48 Fuel Pins, Earth Orbit / Deep Space	12 Heatpipes, 48 Fuel Pins, Deep Space	24 Heatpipes, 96 Fuel Pins, Earth Orbit / Deep Space	30 Heatpipes, 138 Fuel Pins, Earth Orbit / Deep Space, Bimodal
Mass (Core, Reflector, Shield, Control Drums, Heat Transport)	380 kg	300 kg	400 kg	560 kg
Max Thermal Power (Nominal)	200	200	411	128
Max Thermal Power (Failed Heatpipe)	108	108	198	100
Active Core Length (cm)	32	32	38	41
Core Dimension Across Flat (cm)	20.1	20.1	19.4	26.2
Shield Mass, 100 kWt, 2m dose plane at 10 m, 5×10^4 rad/yr ; 1×10^{12} nvt/yr.	110	100	100	130
Fuel / Theoretical Density / Enrichment	UN / 96% / 97%	UN / 96% / 97%	UN / 96% / 97%	UO_2 / 85% / 97%
Clad	Nb/1Zr	Nb/1Zr	Nb/1Zr	W
Peak Fuel Burnup (10 years / 100 kWt)	0.66%	0.68%	0.63%	0.49%
Clad Thickness / Fuel Pin Diameter	0.05	0.05	0.05	0.05
Fuel Pin Clad Outer Diameter (cm)	2.54	2.54	1.70	2.00
Keff, Max Nominal at Beginning of Life	1.03	1.03	1.03	1.03
Keff, Drums in, Beginning of Life	0.92	0.89	0.91	0.92
Keff Immersed, Drums In.	0.99	<0.98	0.98	0.99
Keff Immersed, Wet Sand Replacing Radial Reflector	0.99	<0.98	0.99	0.99
Keff Immersed, Water Replacing Radial Reflector	0.94	<0.98	0.94	0.94
Launch Accident Shutdown Mechanism	Resonance Absorbers	Fuel Removed or Borated Wires	Resonance Absorbers	Resonance Absorbers

needed to ensure launch accident subcriticality. If no attempt is made to flatten the power profile, the maximum power drops by about 20% due to peaking. Preliminary calculations indicate that power flattening will result in zero or minimal mass and volume penalties.

Although additional HPS and HBS design work is needed, the most important near-term development step is the electrically heated HPS module test. The module test will demonstrate most key issues associated with HPS development.

CONCLUSION

Two inexpensive, near-term space fission power concepts (HPS and HBS) are proposed in this paper. Both concepts have 10 important features. First, only existing technology and recently tested fuel forms are used. Second, fuel can be removed whenever desired, greatly facilitating system fabrication and handling. Third, full electrically heated system testing is possible, with minimal operations required to replace the heaters with fuel and ready the system for launch. Fourth, the systems are passively subcritical during launch accidents. Fifth, a modular approach is used, and most technical issues can be resolved with inexpensive module tests. Sixth, bonds between dissimilar metals are minimized. Seventh, there are no single point failures during power mode operation. Eighth, fuel burnup rate is quite low to help ensure greater than 10-year system life. Ninth, there are no pumped coolant loops and the systems can be shut down and restarted without coolant freeze/thaw concerns. Finally, a full ground nuclear test is not needed, and development costs will be low.

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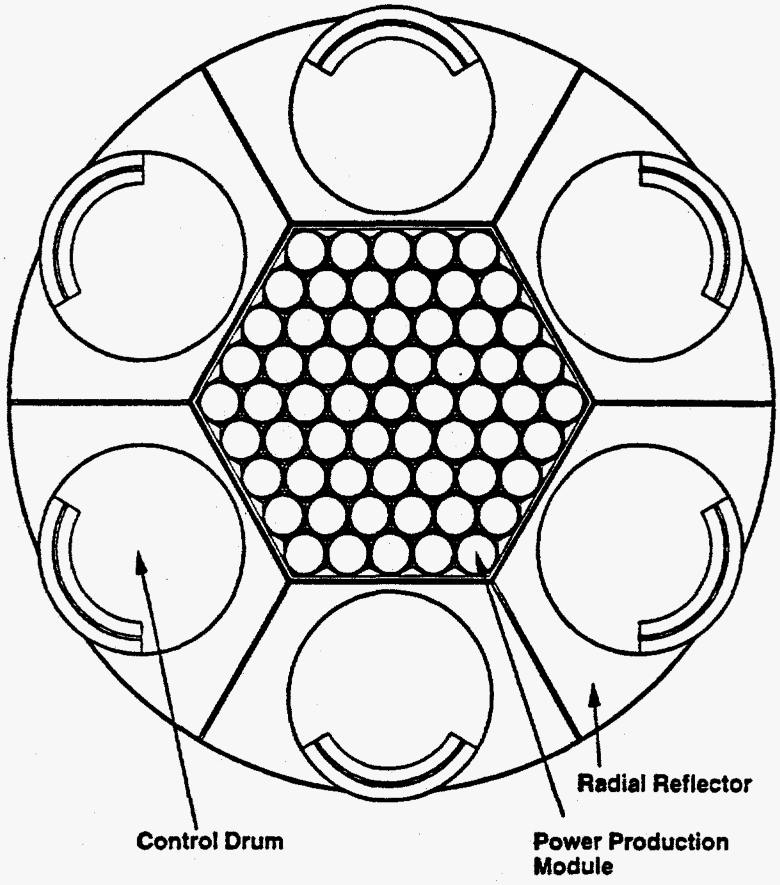

Figure 1. Schematic of HPS showing fuel pins and radial reflector.

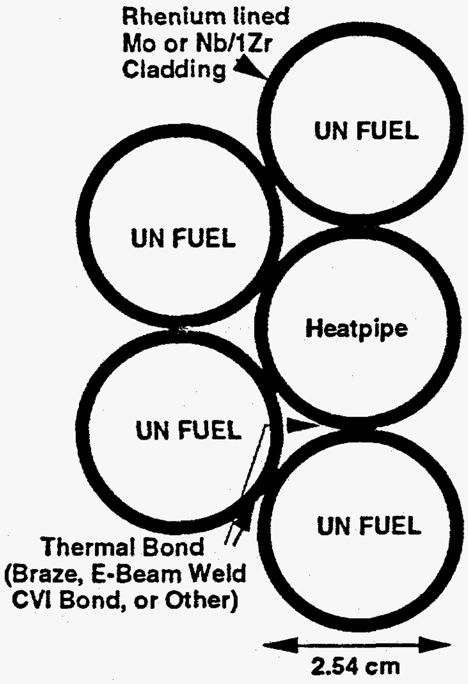

Figure 2. Schematic of HPS Power Module.

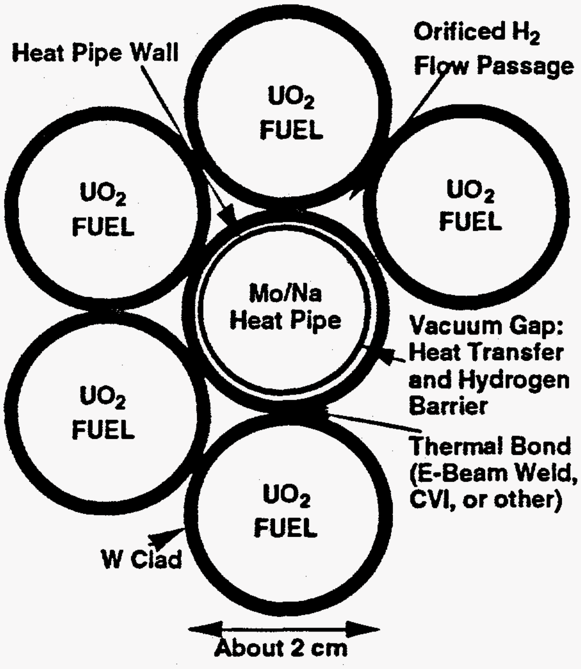

Figure 3. Schematic of HBS Power and Propulsion Module.