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HPS: A Space Fission Power System Suitable for Near-Term, Low-Cost Lunar and Planetary Bases

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ABSTRACT

Near-term, low-cost space fission power systems can enhance the feasibility and utility of lunar and planetary bases. One such system, the Heatpipe Power System (HPS), is described in this paper. The HPS draws on 40 yr of United States and international experience to enable a system that can be developed in <5 yr at a cost of <$100M. Total HPS mass is <600 kg at 5 kWe and <2000 kg at 50 kWe, assuming that thermoelectric power conversion is used. More advanced power conversion systems could reduce system mass significantly. System mass for planetary surface systems also may be reduced (1) if indigenous material is used for radiation shielding and (2) because of the positive effect of the gravitational field on heatpipe operation. The HPS is virtually non-radioactive at launch and is passively subcritical during all credible launch accidents. Full-system electrically heated testing is possible, and a ground nuclear power test is not needed for flight qualification. Fuel burnup limits are not reached for several decades, thus giving the system long-life potential.

INTRODUCTION

Fission systems have several attributes that make them well-suited for use at lunar and planetary bases. They

- are not affected by solar proximity or orientation,
- do not require power storage to operate through lunar or planetary nights,
- are compact,
- have a high specific power,
- are virtually nonradioactive at launch,
- can be designed to remain subcritical during all credible launch accidents,
- can scale to very high power levels,
- have the potential for a very long lifetime,
- can operate in dusty environments, and
- can be used as a source of high-quality heat, in addition to electricity.

The United States (US) has launched 1 space fission power system; over 30 were launched by the former Soviet Union (FSU). However, the use of space fission power currently is limited by the perception that these systems are expensive to develop and require a long lead time. Two other major problems with previous US space fission power programs were the need for expensive ground tests and the desire to have system designs that would scale over a very wide range of power levels. The approach proposed in this paper deals with these and other problems.

HEATPIPE POWER SYSTEM (HPS)

The HPS is a near-term, low-cost space fission power concept capable of delivering up to 1000 kWt to ex-core power converters. The core consists of 12 to 121 (depending on the desired power level) independent modules, each consisting of between two and six fuel pins structurally and thermally bonded to a central heatpipe, which transfers heat to an ex-core power conversion system. The heatpipe also provides structural support for the fuel pins. Modules are independent during normal operation—if a module heatpipe fails, heat is conducted and radiated to adjacent modules. A schematic of a four-pin HPS module is shown in Fig. 1, and a schematic of an HPS that uses 12 identical four-pin modules is shown in Fig. 2. Heat generated in the fuel is conducted into the heatpipe, where it is transferred to an ex-core secondary heatpipe. Power converters are mounted on the secondary heatpipes. The hot shoe of the power converters can be operated at temperatures of up to 1500 K, although lower temperatures may be optimal for most converters. The HPS is designed such that rated power can be delivered in the event of a worst-case heatpipe failure and, in most cases, multiple heatpipe failures.

The compact core and low-core-power density of the HPS enables many desirable design attributes, such as:

1. safety. The HPS is designed to remain subcritical during all credible launch accidents without the use of in-core shutdown rods. This passive subcriticality is enabled by the high radial-reflector worth and the use of resonance absorbers in the core. The HPS also passively removes decay heat.

2. reliability. The HPS has no single-point failures and is capable of delivering rated power, even if several modules and/or heatpipes fail.

3. lifetime. The low-power density in the HPS core and the modular design give the potential for long lifetime. At 100 kWt, fuel burnup limits are not reached for several decades.

4. modularity. The HPS consists of independent modules, and most potential engineering issues can be resolved with electrically heated module tests.

5. testability. Full HPS system tests can be performed using electrical heaters, with only minimal operations required to remove the heaters and ready the system for launch. In addition, the Heatpipe Bimodal System (HBS), a system that uses the same approach as HPS, can be tested in the thermal propulsion mode using electrical heaters.

6. versatility. The HPS can use a variety of fuel forms and power converters.

7. fabricability. The HPS has no pumped coolant loops and does not require a pressure vessel with hermetic seals. There are no significant bonds between dissimilar metals, and thermal stresses are low. There are very few system integration issues, making the system easier to fabricate.

8. storability. The HPS is designed such that the fuel can be stored and transported separately from the system until shortly before launch. This capability will reduce storage and transportation costs significantly.

9. milestones. The are several milestones early in the development of the HPS that will prove the viability of the concept. The most significant early milestone is the development and testing of an HPS module.

10. near-term system. An attractive HPS can be built with existing technology.

11. bimodal system. The HPS approach readily evolves into a bimodal system.

12. dual use. Technology utilized by the HPS has military, commercial, and civilian uses in both aerospace and terrestrial applications.

13. mass. The HPS has a high fuel fraction in the core, thus reducing core, reflector, and shield mass for criticality-limited systems. The HPS has no pumped coolant loops and few system integration issues, thus further reducing mass.

14. schedule. The attributes of the HPS should allow for quick (<5-yr) development.

15. cost. The attributes of the HPS should allow for inexpensive (<$100M) development. After development, unit cost should be <$20M).

HPS CONSTRUCTION AND OPERATION

The HPS uses similar (or identical) modules to create a core with the performance and lifetime required for a given mission. Mechanical bonding within the HPS modules is achieved by methods such as a tack weld, an electron beam weld, chemical vapor infiltration (CVI), or hot isostatic pressing. For low-power cores (<100 kWt), radiation heat transfer will be adequate if finned or small diameter heatpipes are used. An electron beam weld, a braze, a helium bond, the use of a refractory metal wool, or CVI can provide thermal bonding, if desired. During power operation, there will be some asymmetry in the fuel radial temperature profile because heat primarily is removed from one section of the fuel clad. However, the temperature asymmetry is not severe because of the low-power density.

Structural support of the core is provided by the module heatpipes, which are anchored to a molybdenum or Nb/1Zr tie plate. The pins are confined laterally on the opposite end of the core but are allowed to move freely in the longitudinal direction to allow for differential expansion. Neutron shielding is provided by a lithium hydride shield; tungsten gamma shielding may be required, depending on the thermal power level, payload separation, and allowable dose. For lunar and planetary applications, the shielding probably will consist of an optimal mix of material brought from earth and indigenous material. Because of its small size and the lack of activated coolant in its radiator, the HPS can be well shielded with relatively little extra mass brought from earth. For manned missions, it may be desirable to shield the HPS such that no radiation-related exclusion zone is needed.

If a heatpipe fails, some thermal bonding between modules is desirable to reduce peak temperatures. Thermal radiation provides some thermal bonding and is adequate for relatively low power systems (<100 kWt) or for systems with small fuel-pin and heatpipe diameters. If desired, thermal bonding can be enhanced by adding helium or lithium to the interstitial spaces, brazing modules to adjacent modules, adding refractory metal wool to the interstitial spaces, or other methods. Effects of a heatpipe failure also can be mitigated by designing the core such that each fuel pin is adjacent to at least two heatpipes, with each heatpipe capable of removing full power if the other heatpipe fails. High-power (1000-kWt) HPS cores are designed in this fashion. Thermal bonding between modules can be verified during full-system, electrically heated testing. Heat generated in the fuel is transferred to the module heatpipe, which transfers heat to the secondary heatpipes, with the junction located on the surface of the shield. In the thermoelectric option, heat from the secondary heatpipes is transferred to thermoelectric converters that are bonded to the heatpipe surface. Excess heat is rejected radiatively to space from the cold side of the thermoelectrics.

HPS SAFETY

The HPS is designed to remain subcritical during all credible launch accidents by (1) keeping the system radius small, (2) keeping the reflector worth high, and (3) strategically placing neutron 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, thus 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 using retractable boron wires to provide shutdown. This allows the removal of resonance absorbers from the core and reduces system mass and volume.

HPS POINT DESIGNS

Two fuel types have been evaluated for use in the HPS: uranium nitride (UN) and uranium dioxide (UO_2). The use of uranium nitride results in the most compact core. However, uranium nitride fuel pins must be sealed hermetically, and the peak fuel temperature should be limited to ~1800 K (Matthews 1994). Uranium dioxide has a lower uranium loading than uranium nitride; however, the pins do not have to be sealed hermetically and can run at a higher temperature than uranium nitride pins.

The HPS primary heatpipes in uranium nitride-fueled systems operate at a temperature of ~1300 K and transfer heat to secondary heatpipes operating at ~1275 K. Heat is transferred from the secondary heatpipes to the thermal-to-electric power converters, and waste heat is rejected to space. The 1275 K converter hot-side temperature is adequate for many types of power conversion (thermoelectric, AMTEC, Brayton), although higher or lower temperatures could be used. One option for HPS power conversion (especially at relatively low power) is thermoelectric power conversion. Unicouple thermoelectric converters that are well-suited for use with HPS have been designed (Raag 1995). These converters have a hot-shoe temperature of 1275 K and reject waste heat at 775 K. This general type of thermoelectric converter has been used extensively by the space program and has demonstrated an operational lifetime of decades (Ranken et al. 1990). Close-spaced thermionics is another power conversion option for HPS. An HPS using close-spaced thermionics could use lithium heatpipes and uranium dioxide fuel and operate at a converter hot-side temperature of 1500 K. Efficiencies >10% should be possible in this configuration. Other types of power conversion (AMTEC, Brayton, Stirling, etc.) also could be used.

An HPS has been proposed that makes maximum use of existing hardware and facilities. This version of HPS uses 12 modules, each containing 4 rhenium-lined, Nb-1Zr-clad uranium nitride fuel pins bonded to a central heatpipe. The fuel pin's outer diameter is 2.54 cm, which allows existing electrical heaters to be used for testing (Izhvanov 1995). Fabrication cost for the first module, including the central heatpipe, is ~$100k. The use of existing electrical heaters reduces the cost of an electrically heated module test—different module sizes can be tested if an additional $40k is available for new heaters.

A summary of five HPS point designs is given in Table 1; the mass estimates given include core, reflector, and primary heat transport. Total system mass also would

TABLE 1

DESCRIPTION OF HPS POINT DESIGNS

	HPS7N	HPS6O	HPS7O	HPS10O	HPS12O
Power (kWt)	100	100	200	330	1000
Number of Modules	30	19	30	57	121
Fuel Material	UN	UO_2	UO_2	UO_2	UO_2
Fuel Enrichment	97%	97%	97%	93%	93%
Fuel Theoretical Density	96%	92%	92%	85%	85%
Clad Material	Nb1Zr	Mo3Nb	Mo3Nb	Mo3Nb	Mo3Nb
Pin Diameter (cm)	1.50	2.00	1.80	1.40	1.40
Core flat-to-flat (cm)	19.7	22.8	23.6	25.7	30.5
Core Active Height (cm)	32	36	36	36	42
Fuel Burnup per Year	0.05%	0.04%	0.04%	0.13%	0.30%
Reactor Mass (kg)	240	305	325	370	480

include shield, power conversion/conditioning, heat rejection, instrumentation and control, boom, cabling, and structure. The total system mass of the HPS7N concept is <600 kg at 5 kWe, and the total system mass of the HPS12O concept is <2000 kg at 50 kWe, assuming that thermoelectric power conversion is used.

A 5-kWe HPS with thermoelectric power conversion has a total system mass of 575 kg, giving a specific power of 8.7 We/kg. Advanced power conversion could result in a significantly higher specific power. For example, a 20-kWe HPS with AMTEC power converters (expected to be available within 5 yr) could have a specific power >25 We/kg (Schuller 1996). Specific power for planetary surface systems may be even higher because of the potential for using indigenous material for shielding and the positive effect of the gravitational field on heatpipe operation.

HPS BIMODAL OPTION (HBS)

The HPS readily evolves to the HBS, which is capable of providing both power and thermal propulsion. Although the HBS is not of interest for planetary surface missions, its utility for deep-space and other missions may be of interest to other potential users.

A key attribute of the HBS is the ability to perform full electrically heated system tests of the propulsion mode. This attribute would allow flight qualification without a ground nuclear power test, saving both development time and money. Other innovative concepts, such as the "LANTR" concept (Borowski 1996), also could be demonstrated (1) with the electrically heated ground tests and (2) in space during the first flight.

A schematic of a five-pin HBS module is shown in Fig. 3. Hydrogen propellant flows through the interstitials and out through a nozzle. Thrust levels of up to 400 N at exhaust velocities >8000 m/s can be achieved. A vacuum gap isolates the heatpipe from the hydrogen flow, allowing electric power to be generated during propulsion mode. The vacuum gap also prevents heatpipe dryout at the hot end of the core. A detailed analysis of HBS performance is presented in Poston (1996).

HPS DEVELOPMENT

The HPS has several attributes that will reduce the time and cost of development.

1. HPS fuel burnup rates and fast neutron fluxes are low, and nuclear effects are well within the database of all components. In the SP-100 program, uranium nitride fuel in a very similar configuration was tested to the equivalent burnup of several decades of lifetime (Makenas et al. 1994). Uranium dioxide fuel also has been tested to the equivalent of several decades of lifetime under the Thermionic Fuel Element Verification Program and other programs. There are also no insulators or other radiation-sensitive components within the core. Because there are no expected nuclear effects on HPS core components, a ground nuclear-power test is unnecessary and would not contribute to the development of a reliable, long-life system. However, a nuclear test of a fueled module operating at prototypic conditions could be performed relatively inexpensively in various reactors around the world if the customer wishes. Zero-power critical experiments will be performed to confirm the safety and nuclear characteristics of the core—these tests are also relatively inexpensive.

2. Fuel can be removed from the HPS whenever desired, which will facilitate fabrication and handling greatly.

3. The HPS is inherently subcritical during launch accidents and does not require in-core shutdown rods.

4. The HPS can undergo full electrically heated system testing at existing facilities.

5. Each of the HPS modules is independent, allowing most technical issues to be resolved with inexpensive module tests.

The initial step in HPS development is fabrication and electrically heated testing of a module at prototypic conditions. Module fabrication, including heatpipe, will cost <\$100k (Woloshun 1996). Performing an electrically heated module test at prototypic conditions is estimated to cost an additional \$100k.

Once module performance is verified, a core's worth of modules will be fabricated and the core assembled. The reflector, shield, and power conversion subsystem will be added, and an electrically heated system test will be performed. Zero-power criticals then will be run to confirm the nuclear characteristics and safety of the reactor before launch. HPS development costs will be <$100M, and development time will be <5 yr.

CONCLUSIONS

By drawing on 40 yr of US and international experience, it is possible to design near-term, low-cost space fission-power systems. One such system, the HPS, has several desirable features, including modular design and the use of only existing technology in the baseline systems. The total HPS mass is <600 kg at 5 kWe and <2000 kg at 50 kWe, assuming that thermoelectric power conversion is used. More advanced power conversion systems could reduce system mass significantly. System mass for planetary surface systems also may be reduced if indigenous material is used for radiation shielding. The HPS is virtually nonradioactive at launch and is passively subcritical during all credible launch accidents. Full-system, electrically heated testing is possible, and a ground nuclear-power test is not needed for flight qualification. Fuel burnup limits will not be reached for several decades, thus giving the system long-life potential.

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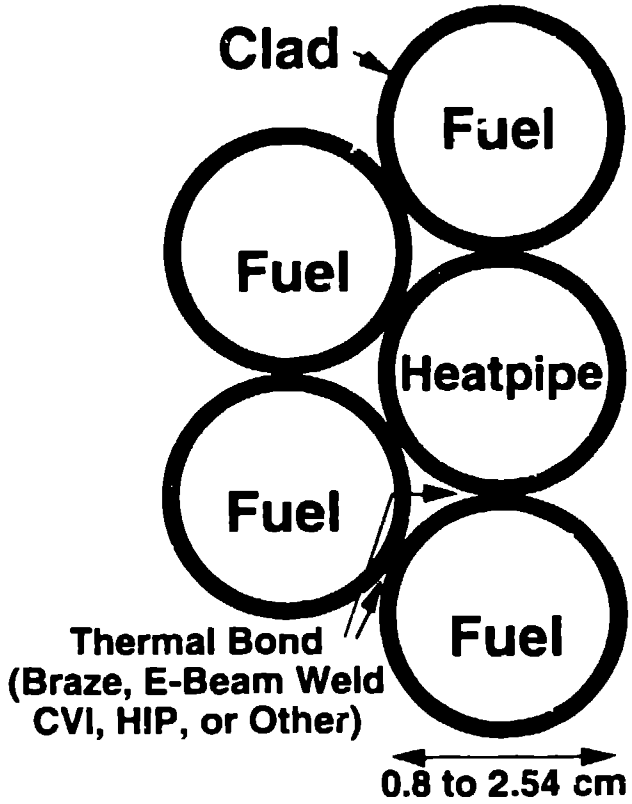

Fig. 1. Four-pin HPS module.

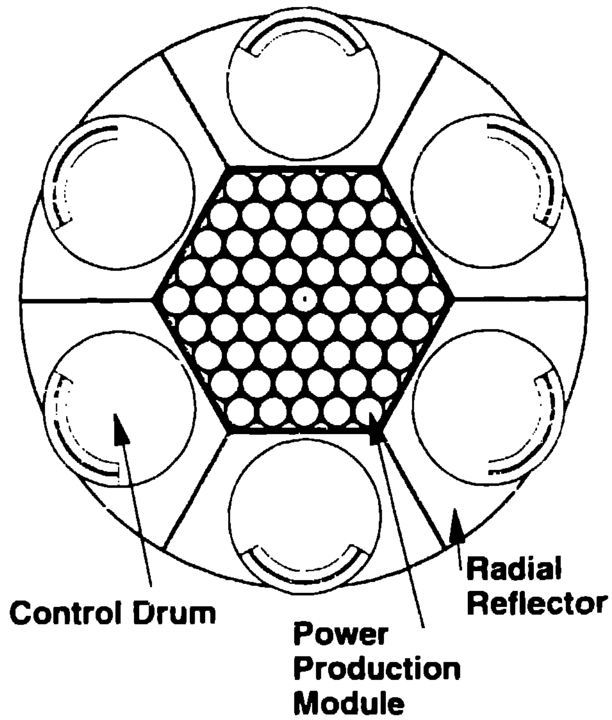

Fig. 2. HPS reactor consisting of 12 four-pin modules.

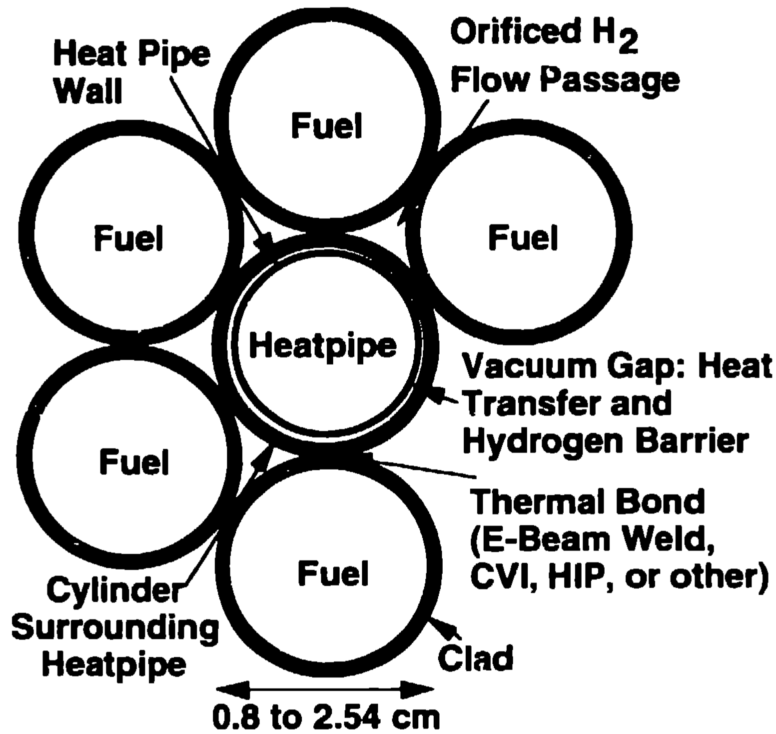

Fig. 3. Five-pin HBS module.