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HEATPIPE POWER SYSTEM AND HEATPIPE BIMODAL SYSTEM DESIGN AND DEVELOPMENT OPTIONS

Michael G. Houts and David I. Poston
Los Alamos National Laboratory, MS K551
Los Alamos, NM 87545
(505)665-4336 (W) / (505)665-3167 (F)
houts@lanl.gov

William J. Emrich, Jr.
NASA Marshall Spaceflight Center, PS05
Huntsville, AL 35758
(205)544-7504 (W) / (205)544-6669 (F)
bill.emrich@msfc.nasa.gov

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Abstract

The Heatpipe Power System (HPS) is a potential, near-term, low-cost space fission power system. The Heatpipe Bimodal System (HBS) is a potential, near-term, low-cost space fission power and/or propulsion system. Both systems will be composed of independent modules, and all components operate within the existing database. The HPS and HBS have relatively few system integration issues; thus, the successful development of a module is a significant step toward verifying system feasibility and performance estimates. A prototypic HPS module is being fabricated, and testing is scheduled to begin in November 1996. A successful test will provide high confidence that the HPS can achieve its predicted performance.

INTRODUCTION

The Heatpipe Power System (HPS) is a potential, near-term, low-cost space fission power system. The Heatpipe Bimodal System (HBS) is a potential, near-term, low-cost space fission power and/or propulsion system. The HPS and the HBS incorporate lessons learned from previous space fission power development programs to reduce both development cost and time. Both systems have the following 15 important features:

1. Safety. The HPS and HBS are designed to remain subcritical during all credible launch accidents without using in-core shutdown rods. This passive subcriticality results from the high radial reflector worth and the use of resonance absorbers in the core. The systems also passively remove decay heat and are virtually nonradioactive at launch (no plutonium in the system).

2. Reliability. The HPS has no single-point failures and is capable of delivering rated power, even if several modules and/or heatpipes fail. The HBS has very few single-point failures, which are limited to ex-core components (e.g., the propellant tank).

3. Long life. The low power density in the HPS and HBS cores and the modular design give the potential for long life. At 100 kWt, fuel burnup limits will not be reached for several decades.

4. Modularity. The HPS and HBS consist of independent modules, and most potential engineering issues can be resolved by testing modules with electric heat (used to simulate heat from fission).

5. Testability. Full HPS/HBS tests can be performed using electric heaters, with very few operations required to replace the heaters with fuel and ready the system for launch. The HBS can be tested in bimodal mode using electric heaters.

6. Versatility. The HPS and HBS 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, thus making the system easier to fabricate. The HBS may require a pressure vessel for the propulsion mode.

8. Storability. The HPS and HBS are 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.

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9. Early Milestones. Several milestones early in the development of the HPS and HBS will prove the viability of the concepts. The most significant early milestone is the development and testing of an HPS module.

10. Near term. An HPS and/or HBS capable of enhancing or enabling missions of interest can be built with existing technology.

11. Bimodal. The basic approach can be used to provide either a power-only or bimodal system.

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

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

14. Quick development. The attributes of the HPS and HBS should allow for quick (<5 years) development.

15. Low cost. The attributes of the HPS should allow for inexpensive (<$100 M) development. After development, the unit cost should be <$20 M. The attributes of the HBS (especially the ability to test bimodal operation with electric heaters used to simulate heat from fission) will significantly reduce cost as compared to other bimodal concepts.

HPS DESCRIPTION

The HPS and HBS use similar (or identical) modules to create a core with the performance and lifetime required for a given mission. A wide variety of core layouts have been evaluated, using12 to more than 100 modules. A schematic of the 12-module HPS is shown in Fig. 1, and a schematic of a 4-fuel-pin HPS module is given in Fig. 2. The fuel pins are bonded structurally and thermally 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 heatpipe fails, some thermal bonding between modules is desirable to reduce peak temperatures. Thermal radiation provides some module-to-module thermal bonding, which can be enhanced by (1) adding helium or lithium to the interstitial spaces, (2) brazing modules to adjacent modules, or (3) adding refractory metal wool to the interstitial spaces.

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). For conservatism, the peak uranium nitride fuel temperature is limited to 1600 K in all HPS designs. Uranium dioxide has a lower uranium loading than uranium nitride; however, the pins do not have to be sealed hermetically and can be taken to a higher temperature than uranium nitride pins.

The HPS primary heatpipes 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, although higher or lower temperatures could be used. One option for the HPS (especially at relatively low power) is thermoelectric power conversion. Unicouple thermoelectric converters that are well suited for use with the 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). If desired, thermoelectric converters identical those used by radioisotope thermoelectric generators (RTGs) could be coupled to the HPS. Close-space thermionic converters, alkali metal thermoelectric converters (AMTECs), and Stirling and Brayton power conversion are also options. If needed, the HPS heatpipes are capable of long-term operation at temperatures >1500 K.

An HPS has been proposed that makes maximum use of existing hardware and facilities. This version of the HPS uses 12 modules. Each module contains four fuel pins that can be either rhenium-lined, Nb-1Zr-clad uranium nitride or molybdenum-clad uranium dioxide. The fuel pin's outer diameter is 2.54 cm, which allows existing electric heaters to be used for testing (Izhvanov 1995). The fueled length is 0.31 m for the uranium nitride fuel and 0.36 m for the uranium dioxide fuel. Fabrication cost for the first module, including the central heatpipe, will be ~$75k. The use of existing electric heaters reduces the cost of testing a module—different module sizes can be tested if an additional $40k is available for new heaters. Fabrication of the first HPS module is nearly complete, and testing is scheduled to begin in November 1996.

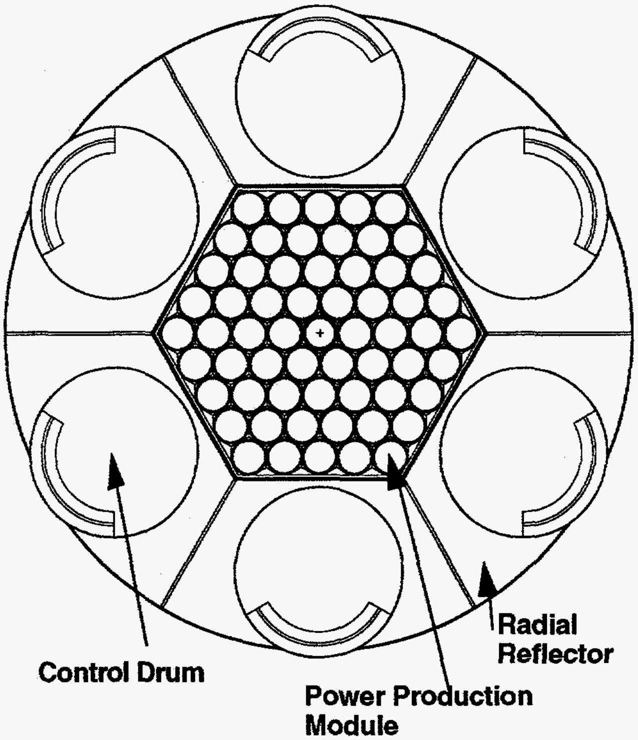

FIGURE 1. Schematic of HPS Showing Fuel Pins and Radial Reflector.

The 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 of lifetime (Makenas et al. 1994). Uranium dioxide or carbide fuel also can be used, although the system mass may increase because of the lower uranium density. The life-limiting feature in the baseline HPS may be the thermoelectric power converters, although they also have long-life potential. Fuel can be removed easily from the HPS whenever desired, which will facilitate fabrication and handling greatly. The HPS is inherently subcritical during launch accidents and has no single-point failures. The HPS can undergo full system testing (using electric heaters to simulate heat from fission) at existing facilities. Each of the HPS modules is independent, allowing most technical issues to be resolved with inexpensive module tests.

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) heatpipes are used and if some reduction in power is acceptable following the loss of a heatpipe. If needed, thermal bonding can be accomplished by methods such as an electron beam weld, braze, helium bond, use of a refractory metal wool, or CVI. 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 will not be severe because of the low power density.

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 thermoelectric converters.

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 lithium hydride; tungsten gamma shielding may or may not 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 needed from earth. For manned missions, it may be desirable to shield the HPS such that no radiation-related exclusion zone is needed.

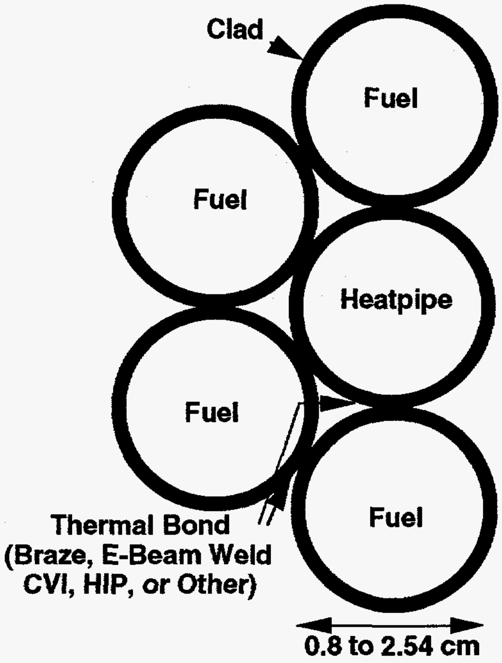

FIGURE 2. Schematic of the HPS Power Module.

The HPS is designed to remain subcritical during all credible launch accidents. This has been accomplished by keeping the system radius small, keeping the reflector worth high, and strategically placing neutron absorbers in the core. The positive reactivity effect of core flooding or compaction can be offset by (1) the negative reactivity worth of the control drums in the reflector or (2) the negative reactivity effect of losing the reflector and surrounding the reactor with wet sand or water. This effect eliminates 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 ensured 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. The HPS is virtually nonradioactive at launch (no plutonium in the system).

The HPS scales to 500 kWt with no increase in reactor mass. Above 500 kWt, the system is no longer criticality-limited, and the heatpipe-to-fuel ratio must be increased. A 1000-kWt HPS would have a reactor mass slightly higher than that of a 500-kWt system. The 1000-kWt HPS could provide 50 kWe, assuming that a 5% efficient power conversion is available (200 kWe at 20%). Higher power levels can be attained by surrounding the cylindrical fuel pin with noncylindrical heatpipes. Although there is little data on noncylindrical heatpipes, such data can be obtained inexpensively by testing electrically heated modules.

The baseline HPS has refractory metal heatpipes and fuel cladding. If the HPS is to be used on a planetary surface (e.g., Mars), it may be desirable to eliminate all refractory metals from the system. A several-hundred-kilowatt (thermal) stainless-steel or superalloy HPS can be built with cylindrical heatpipes and cylindrical fuel pins, all operating within the database. Thermal power levels of a few megawatts can be achieved using cylindrical fuel and noncylindrical heatpipes, again without the use of refractory metals.

HBS DESCRIPTION

The HPS readily evolves to the HBS, which is capable of providing both power and thermal propulsion. A key attribute of the HBS is the ability to test bimodal operation using electric heaters to simulate heat from fission. This attribute will allow flight qualification without a ground nuclear power test, saving both development time and money.

A schematic of a five-pin HBS module is shown in Fig. 3. Hydrogen propellant flows through the interstitial spaces 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 the propulsion mode. The vacuum gap also reduces heatpipe cooling of the propellant at the hot end of the core. Detailed analysis of HBS performance is presented in Poston (1996).

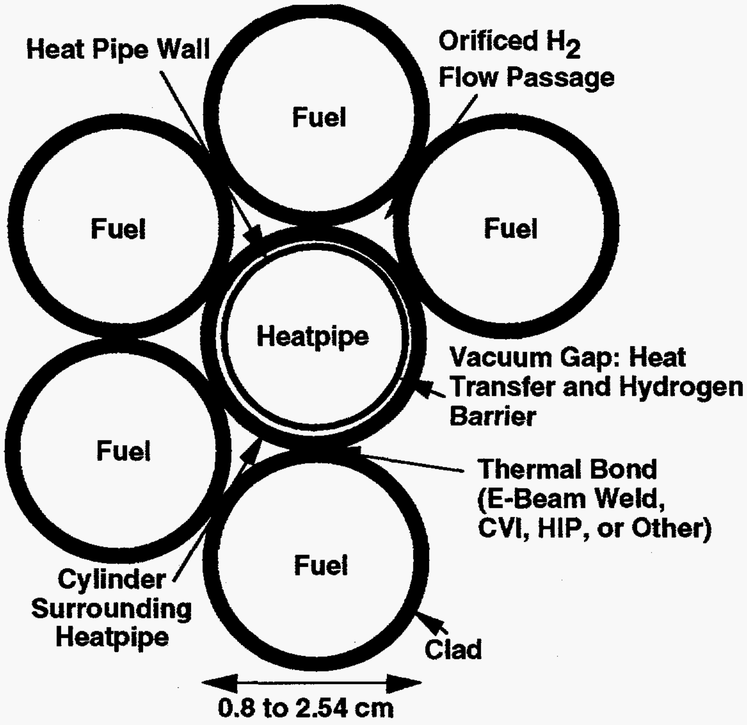

FIGURE 3. Five-Pin HBS Module.

The baseline HBS uses uranium dioxide fuel clad with polycrystalline tungsten. Programs in the US (such as the Thermionic Fuel Element Verification Program) have shown that tungsten-clad uranium dioxide has excellent dimensional stability and burnup capability at high temperatures. A second-generation HBS could take advantage of advanced US or Russian fuel. For example, using single-crystal tungsten-alloy-clad uranium-tantalum carbide fuel could increase the HBS specific impulse and decrease the HBS mass. This fuel/clad combination showed good performance during recent tests in a hydrogen environment (Bremser and Moeller 1996). If high thrust is required, cylindrical cermet fuel could be used in the HBS without changing the basic configuration and balance of plant. The primary drawback of using cermet fuel is that it eliminates the ability to test bimodal operation using electric heaters to simulate heat from fission.

FUTURE WORK

If the initial module test is successful, the next step in HPS/HBS development is to fabricate and test a quarter of an HPS core. Testing the quarter core will allow system-level issues to be investigated, including system startup, operation with a failed heatpipe, and operation under other off-normal conditions. Upon completion of the quarter-core test, a full core, including fuel, a reflector, and a control system, should be fabricated. Zero-power critical experiments then would be performed to verify nuclear-related safety and operational calculations. If all of these steps are successful, flight system fabrication then could begin.

Acknowledgments

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