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TERRESTRIAL APPLICATIONS OF THE HEATPIPE POWER SYSTEM

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Abstract

A terrestrial reactor that uses the same design approach as the Heatpipe Power System (HPS) may have applications both on earth and on other planetary surfaces. The baseline HPS is a potential, near-term, low-cost space fission power system. The system will be composed of independent modules, and all components operate within the existing database. The HPS has 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, refractory-metal 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. An HPS incorporating superalloys will be better suited for some terrestrial or planetary applications. Fabrication and testing of a superalloy HPS module should be less challenging than that of the refractory metal module. A superalloy HPS core capable of delivering >100 kWt to a power conversion subsystem could be fabricated for about $500k (unfueled). Tests of the core with electric heat (used to simulate heat from fission) could demonstrate normal and off-normal operation of the core, including the effects of heatpipe failure. A power conversion system also could be coupled to the core to demonstrate full system operation.

INTRODUCTION

A terrestrial reactor that uses the same design approach as the Heatpipe Power System (HPS) may have applications both on earth and on other planetary surfaces. The baseline HPS is a potential, near-term, low-cost space fission power system.. The HPS incorporates lessons learned from previous space fission power development programs to reduce both development cost and time. The terrestrial version of the HPS will retain the following 14 important features of the space-based version.

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 results from the high radial reflector worth and the use of resonance absorbers in the core. The system also removes decay heat passively and is virtually nonradioactive at launch (no plutonium in the system). The terrestrial HPS could be fueled after delivery to its operational site, thus eliminating concerns of accidental criticality during transportation.

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. Long life. The low power density in the HPS core 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 consists 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 tests can be performed using electric heaters, with only minimal operation required to replace the heaters with fuel and ready the system for launch.

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, thus making the system easier to fabricate.

DISCLAIMER

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. A terrestrial HPS could be fueled after delivery to the site.

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

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

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

12. Mass. The HPS has 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.

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

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

HPS DESCRIPTION

The HPS uses 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, using 12 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 (superalloy for terrestrial applications) 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. Carbide fuels also may be well suited for the HPS. For relatively low-temperature operation, uranium-zirconium hydride fuel or metal fuel may be used.

The baseline HPS (for use in a vacuum) has primary heatpipes that 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. Heatpipes also can be operated at lower temperatures, allowing the use of superalloys.

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 an electrically heated 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. A lower-temperature core suitable for use in an oxidizing environment could be fabricated from superalloys using the same module geometry. However, more optimal geometries could be used because electric heaters for testing low-temperature cores are less expensive and more readily available. The availability of heaters is not a significant driver for module design in superalloy cores.

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 of 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 heat 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. Low-temperature versions of the HPS may be able to use uranium-zirconium hydride fuel or metal fuel.

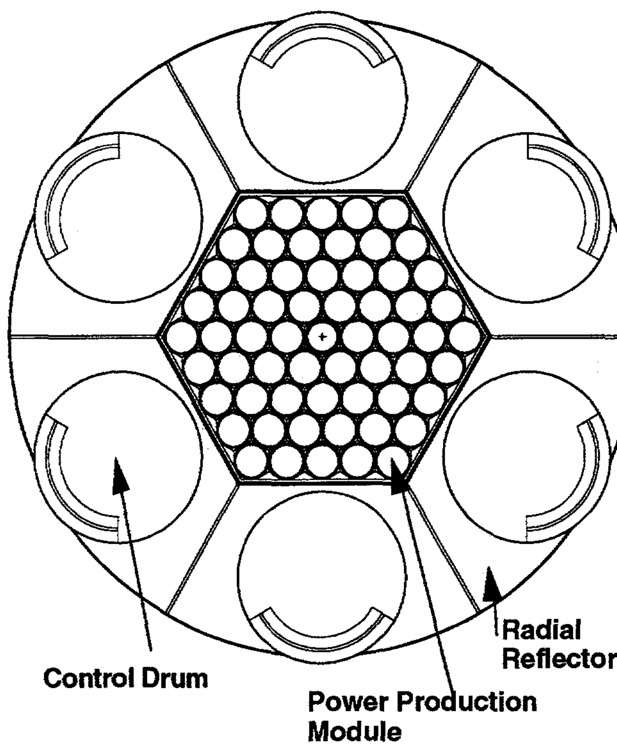

FIGURE 1. Schematic of HPS Showing Fuel Pins and the Radial Reflector.

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 refractory metal 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 some thermal bonding is desired, it can be accomplished by methods such as an electron beam weld, a braze, a helium bond, the use of a refractory metal wool (stainless steel or superalloy for low-temperature systems), 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 thermoelectrics.

Structural support of the core is provided by the module heatpipes, which are anchored to a molybdenum or Nb/1Zr tie plate (stainless steel or superalloy for low-temperature systems). 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 brought from earth. For manned missions, it may be desirable to shield the HPS such that no radiation-related exclusion zone is needed.

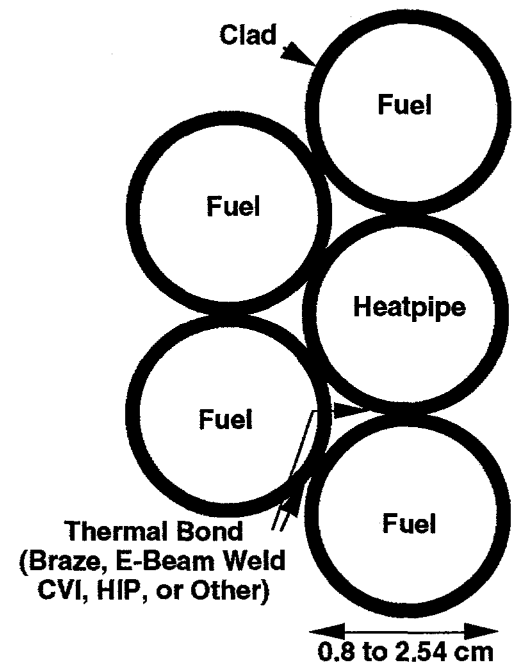

FIGURE 2. Schematic of the Baseline HPS Power Module.

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 system 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 inexpensively obtained with module tests using electric heat to simulate heat from fission.

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 existing database. Thermal power levels of a few megawatts can be achieved using cylindrical fuel and noncylindrical heatpipes, again without the use of refractory metals.

TERRESTRIAL HPS DESCRIPTION

The HPS approach readily can be applied to the development of a terrestrial system. These systems would be suitable for use on earth as well as on the surface of the moon or Mars. If the terrestrial HPS is not contained in a vacuum (or high purity inert gas atmosphere), then superalloys would be used instead of refractory metals in first-generation systems. This reduces the maximum temperature available to the power converters to ~1000 K. Superalloys also have a lower conductivity than refractory metals, thus reducing the thermal power rating of the system in a given configuration. High thermal power ratings (up to 1 MWt with the worst-case failure of a heatpipe) can be attained by using cylindrical fuel elements coupled to noncylindrical heatpipes. The modules with the noncylindrical heatpipes still could be developed using only tests of electrically heated modules, and no nuclear fuel development would be required. An example of such a module is shown in Fig. 3. The heatpipes also could be shaped to form a hexagonal module.

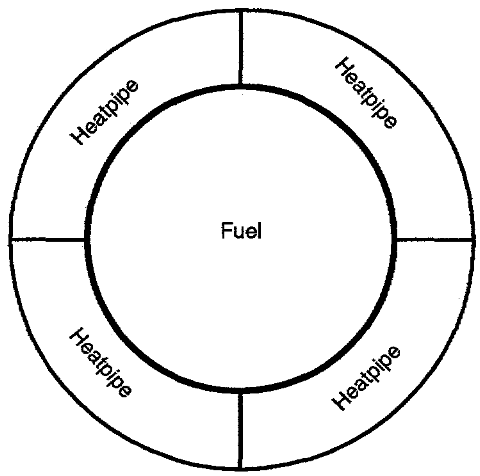

FIGURE 3. HPS Module Option for High Thermal Power.

Second-generation systems may be able to use silicide-coated refractory metal alloys to allow high-temperature operation in an oxidizing environment. One promising alloy is WC-3015, a niobium-based alloy that contains hafnium, tungsten, and zirconium (Ring 1996). The alloy is inherently resistant to oxidation, and pinpoint defects or failures in the coating do not result in catastrophic oxidation of the base material.

For earth applications, it may be desirable to use reduced-enrichment uranium, possibly with an enrichment as low as 19.9%. A moderated version of the terrestrial HPS could be developed that delivers reasonable performance while using reduced-enrichment uranium as a fuel. The moderated system could use yttrium hydride pins to provide moderation and/or uranium zirconium hydride fuel (depending on system operating temperature). For very high temperature operation, separate moderator heatpipes could be used to keep moderator temperature at an acceptable level. The use of moderator heatpipes would increase system complexity.

The baseline HPS has excellent safety characteristic, many of which result from the high radial reflector worth and the presence of resonance absorbers in the core. For terrestrial applications, passive safety also can be attained by fueling the reactor at the site or using retractable boron wires to provide shutdown. This process allows the removal of resonance absorbers from the core and reduces system mass and volume. The HPS is virtually nonradioactive before operation (no plutonium in the system).

Heatpipe-cooled reactors have been proposed previously for terrestrial applications, and several potential applications exist. HPS attributes (such as full electrically heated system testability) may make the HPS design approach the most attractive approach for some applications. In general, reactors can be designed that are less expensive and more environmentally benign than nonnuclear power options. The attractiveness of the reactor option increases with the difficulty in accessing the site where the power supply is needed. Because they do not require refueling and have no effluent, nuclear reactors also are attractive for use at sites that are environmentally sensitive to effluents from nonnuclear power supplies.

FUTURE WORK

If the initial module test is successful, the next step in HPS development will be to fabricate and test a quarter of an HPS core. Testing of the electrically heated 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 reactor, 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.

The development approach for a terrestrial HPS would be the same as that for the baseline HPS, with a few differences. First, for stationary applications, gravity-assisted heatpipes could be used. Second, if the system is not contained in a vacuum (or a high-purity inert gas atmosphere), then superalloys would be used instead of refractory metals. A superalloy HPS core capable of delivering >100 kWt to a power conversion subsystem could be fabricated for about $500k (unfueled). Testing of the core (with electric heat) would demonstrate normal and off-normal operation of the core, including the effects of heatpipe failure. A power conversion system also could be coupled to the core to demonstrate full system operation.

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