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ABSTRACT

The Heat-Pipe Power System (HPS) is a near-term, low-cost space fission power system with the potential for utilizing various option for balance-of-plant options. The following options have been studied: a low-power thermoelectric design (14-kWe output), a small Brayton cycle system (60–75 kWe), and a large Brayton cycle system (250 kWe). These systems were analyzed on a preliminary basis, including mass, volume, and structure calculations. These analyses have shown that the HPS system can provide power outputs from 10–250 kWe with specific powers of ~14 W/kg for a 14-kWe model to ~100 W/kg for a 250-kWe model. The system designs considered in this study utilize a common component base to permit easy expansion and development.

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1. INTRODUCTION

The recent design of the Heat-Pipe Power System (HPS) provides a significant increase in the number of missions available for near-term space fission power because it is both safe, inexpensive, and expandable. The key to developing this near-term solution is the development of a variety of balance-of-plant options to suit a wide mission base, especially the design of various power conversion systems (PCSs) to be utilized with the reactor. For each option, the design must include the primary heat transport system (transports heat from the reactor core to the PCS), the PCS itself, the heat rejection device (radiator), and the various support systems (power regulation, reactor control, etc.).

In this preliminary study, the systems analyzed were a 14-kWe thermoelectric (TE) design, 60–75-kWe Brayton cycle system, and 250-kWe system. During this analysis, a graphite fiber composite radiator was designed and then incorporated within these systems. This radiator is designed to have a lower specific mass (mass/unit area) than most other radiator designs, while retaining ease of assembly and testing.

1.1. HPS Reactor

The HPS reactor itself is a modular system that uses heat pipes to transport thermal energy to an external power conversion subsystem at temperatures up to 1500 K. This reactor is unique among space reactor concepts because of its expandability and reliability. The HPS reactor is expandable through its use of repeated fuel/heat pipe modules (three to six fuel pins and a single heat pipe). The reactor can utilize a variety of materials to fit different missions without significantly affecting the design. Expandability is also achieved by simply adding more fuel-pin/heat-pipe modules to a reactor design, or by reducing the radial size of the fuel pins and heat pipes (thus improving their thermal transfer characteristics). For this study, two HPS options were utilized as baseline reactors—the HPS7O and the HPS12O (200 kWt and 1000 kWt, respectively, see Table 1). Both reactor options utilize UO_2 fuel (in varying enrichments and total densities) and a molybdenum (Mo-41Re for the HPS120) cladding. The heat pipes are made of the same material as the clad (minimizing brazing concerns) and utilize lithium as a working fluid (Poston 1996).

TABLE 1
HPS REACTOR SPECIFICATIONS[a]

Option Name	Power (kWt)	No. of Modules	Enriched/ Percent Theoretical Density	Pin Diam. (cm)	Core Flat/Flat (cm)	Active Core Height (cm)	Reactor Mass (kg)
HPS7O	200	30	97/92	1.80	23.6	36	325
HPS12O	1000	121	97/85	1.40	30.5	42	480

[a] (Poston 1996)

1.2. Primary Heat Transport

In each of the options, the primary heat-transport mechanism is the extension of the reactor heat pipes outside the reactor itself. These primary heat pipes are brazed to a series of secondary heat pipes (same material and working fluid) that transport the reactor heat to the PCS. The primary-to-secondary heat pipe interface (Fig. 1) is designed for redundancy and reliability in a micrometeroid environment. Each interface module consists of one primary heat pipe, two secondary heat pipes, and a "tri-cusp" to increase the heat transfer area.

Each of the secondary heat pipes is rated at the full load of the primary heat pipe. The two-to-one redundancy provides a type of "sacrificial armor" for the primary heat pipe.

It is important to minimize the temperature drop of this interface because it is necessary to keep the input temperature to the PCS as high as possible. If we assume a 40-cm interface, the maximum temperature drop from the primary-to-secondary heat pipe can be reduced to <25 K. However, if larger temperature drops are acceptable, a shorter interface section can be used.

If necessary, this interface can be eliminated to conserve mass (i.e., having the primary heat pipes extend to the PCS). However, eliminating this interface will increase manufacturing complexity because each primary heat pipe must be built with the module on one end and the power-conversion equipment on the other. With the elimination of this interface, the primary heat pipes would also need to be armored to prevent micrometeroid punctures, which would offset the mass lost by eliminating the interface.

The interface can also be eliminated, again at the expense of increasing the manufacturing complexity of the system, by constructing the heat pipes in noncircular shapes (e.g., two D-shaped secondary heat pipes brazed on two faces of a triangular-shaped secondary heat pipe).

2. POWER-CONVERSION SYSTEMS

The three options differ primarily in the PCS used. The first option utilizes a TE PCS (Fig. 2). This system utilizes an array of TE modules, each with its own small radiator panel (Fig. 3). These radiator panels are distributed around a frustum-cylinder radiator arrangement, using the secondary heat pipes as stringers (an additional structure is attached to the underside of the radiator). Each of these modules operates at a hot-shoe temperature of 1250 K and a cold-shoe temperature of 600 K. The radiating surfaces for these modules are small panels of graphite composite bonded to the cold pads of the TEs. Each module operates at a >7% efficiency ($Z>0.6E-3\ K^{-1}$) and generates ~4.2 W of electricity while radiating ~60 W of thermal power.

The TE-PCS option uses a 200-kWt HPS7O core. This core has 30 primary heat pipes and therefore, 60 strips of TE modules in the radiator.

This TE system is assumed to be a baseline for this reactor. All of the components are conservatively designed. The figure of merit of $0.6E-3\ K^{-1}$ has already been achieved, composites of this type are readily available (see Sec. 2.3.), and TE modules of this type have shown operational lives of decades (Ranken et. al. 1990). Table 2 shows the preliminary 14-kWe TE masses.

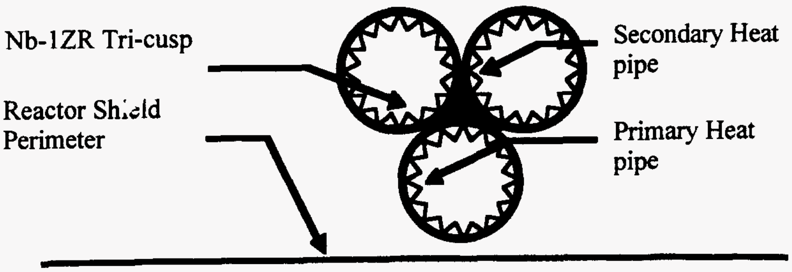

Fig. 1. Primary/secondary heat-pipe interface.

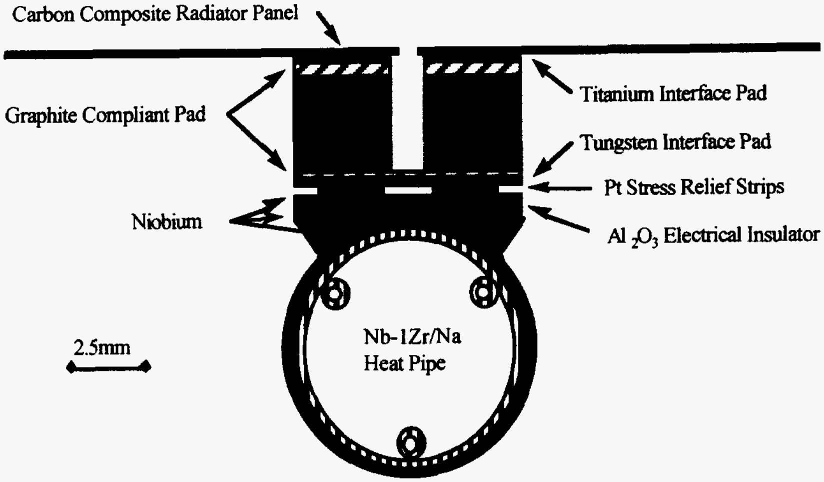

Fig. 2. TE module (Raag 1995).

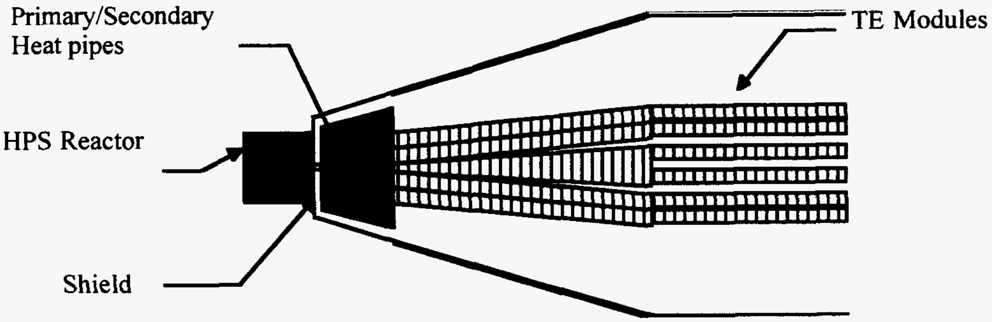

Fig. 3. HPS-TE modules and radiator.

2.1. Small Brayton Cycle PCS Option

The second PCS option for the HPS is a small (60–75 kWe), closed Brayton cycle. This system uses the same HPS core as in the TE option, but with a higher thermodynamic efficiency (~30% in this temperature range). The baseline design for this system uses two 75-kWe turbine-alternator-compressor sets. Each of these sets incorporates its own hot and cold heat exchangers, recuperators, and control hardware. The system mass breakdown is shown in Table 3.

This is a highly conservative baseline mass estimate. The masses of the PCS are derived from the total system mass of the AlliedSignal Turbogenerator™ series 75-kWe turbogenerators (AlliedSignal 1997). In the space version, many components of this system will have lower masses from lighter materials and designs.

The radiator system operates at a much lower temperature than the TE option's radiator panels (450 vs 575 K); thus, the radiator is almost twice as large. The PCS is not incorporated within the radiator; thus more options are available for the closed Brayton cycle (CBC) radiator. For this system, the radiator uses water heat pipes to disperse the heat from the cold-side heat exchanger to the radiating area. These heat pipes can easily incorporate flexible bellows to allow the radiator to deploy from a compact launch configuration.

2.2. Large Brayton Cycle PCS Option

This PCS option provides a very high, specific power system for use where a compact power source is needed (e.g., nuclear electric propulsion missions). This design utilizes the HPS12O reactor (1 MWt) with a CBC PCS to generate 250 kWe at a total system goal mass of 2500 kg. The radiator system for this power output is far larger than the simple radiator proposed for the small CBC system. In the case of the large CBC option, the area needed

TABLE 2
PRELIMINARY 14-kWe TE MASSES

Component	Mass (kg)
HPS7O	350
Shield	150
Primary heat transport	50
PCS (includes secondary heat pipes)	200
Radiator panels	50
Support components	250
10% Margin	100
Total	**1100**

TABLE 3
PRELIMINARY 75-kWe CBC MASSES

Component	Mass (kg)
HPS7O	350
Shield	150
Primary heat transport	50
PCS	700
Radiator	250
Support components	250
10% Margin	175
Total	**1925**

for the radiator is larger than the space available in a reasonable launch package without excessive heat-pipe bending; therefore, an alternate radiator was designed. The cold-side heat exchanger of the CBC system will transfer heat to a circulating liquid (rather than directly to the radiator heat pipes). This fluid will then travel through the base of each folded radiator panel, transferring heat to a series of heat pipes that will disperse the heat throughout the radiator area. This system requires some amount of armor for the liquid loops (to augment the safety provided by their redundancy) and has a greater temperature drop from the cold side heat exchanger to the radiator. The ability to package this radiator in a relatively small space (by reducing the difficulty in folding the thermal transport devices) outweighs the slight loss in efficiency. One possible use for this large CBC system is to supply power for nuclear electric propulsion spacecraft. Table 4 shows the preliminary 250-kWe CBC masses.

2.3. Advanced Composite Radiator

The advanced composite radiator (Fig. 4) is a preliminary point design of a composite radiator panel utilizing high-conductivity graphite fibers to minimize the mass of a deployed radiator panel and reduce the temperature drops across the radiator. The panel designed for these systems utilizes composite face sheets constructed of high conductivity carbon fibers in a multi-ply laminate, with the majority of the plies in the direction perpendicular to the heat-generating elements (TE modules or heat pipes). In the case of the heat-pipe radiators (associated with the CBC options), the radiator is double sided, with a honeycomb core between the face sheets to provide dimensional stability. The heat pipes are imbedded within this core region during fabrication.

This radiator provides advantages over pumped-loop aluminum heat exchangers (shuttle radiator) and carbon-carbon heat exchangers because it is safer (it contains many TE modules or heat pipes) and is extremely easy to fabricate (Byrens 1997).

2.4. Support Systems

The support systems for these options can be broken down into two primary categories: power and structural support. The power support systems include the computer and data bus for reactor and power system control, the power regulators and primary bus (derived from international space station components), and the instrumentation necessary to maintain system health. The structural components are primarily the support struts for the PCS and the reactor/shield module and the deployable boom (used to increase separation between payload and the reactor

TABLE 4
PRELIMINARY 250-kWe CBC MASSES

Component	Mass (kg)
HPS12O	480
Shield	320
Primary heat transport	100
PCS	700
Radiator	600
Support components	400
10% Margin	250
Total	**2750**

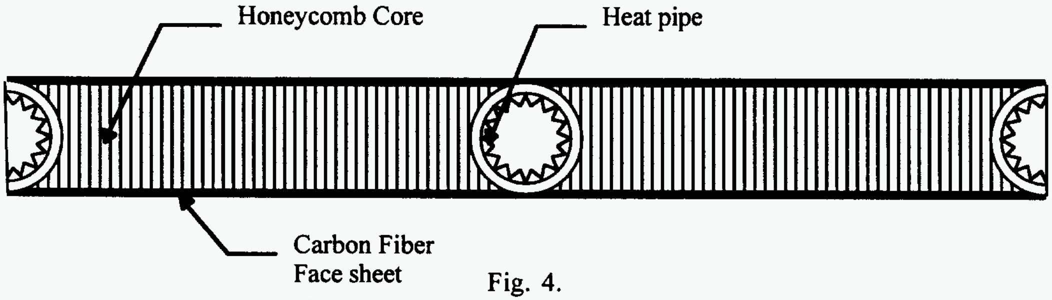

Fig. 4.
Advanced composite radiator with heat pipes.

system), such as the telescopic boom developed by Astro Aerospace Corp. This boom is stiffer than standard deployable booms (such as truss-style booms), yet still has a low mass (<80 kg for a 10-m boom) (Edwards 1997).

3. FUTURE OPTIONS

Because of the modular design of the HPS system, as well as the directability of the thermal output (the heat pipes can be incorporated into heat exchangers, boilers, TE modules, etc.), there are several additional alternatives for the HPS balance of plant option. The options currently being considered for future study or use are AMTEC conversion (the heat pipes can easily be incorporated into AMTEC cells), Rankine cycle (the HPS heat pipes provide the thermal flux necessary to construct an efficient boiler), and forced-gas radiator cooling for Martian surface applications.

4. CONCLUSION

The HPS power system can incorporate various balance-of-plant options to fit a variety of mission requirements. Point designs that have been studied are: a 14-kWe output TE design, 60–75-kWe Brayton cycle system, and 250-kWe system. These systems were analyzed on a preliminary basis, including mass, volume, and structure calculations. This analysis has shown that the HPS system can provide power outputs from 10–250 kWe, with specific powers of ~14 W/kg for a 14-kWe model to ~100 W/kg for a 250-kWe model. The HPS system also has the versatility to provide power to other possible conversion systems (such as Rankine systems or AMTEC). These options will be studied in future work.

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