/N-20
14441

NASA Technical Memorandum 104401

p8

Design of Multihundredwatt DIPS for Robotic Space Missions

D.J. Bents, S.M. Geng, J.G. Schreiber
and C.A. Withrow
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio

P.C. Schmitz
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio

and

T.J. McComas
University of Florida
Gainesville, Florida

Prepared for the
26th Intersociety Energy Conversion Conference
cosponsored by the ANS, SAE, ACS, AIAA, ASME, IEEE, and AIChE
Boston, Massachusetts, August 4-9, 1991

NASA

DESIGN OF MULTIHUNDRED-WATT DIPS FOR ROBOTIC SPACE MISSIONS

D.J. Bents, S.M. Geng, J.G. Schreiber, and C.A. Withrow
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

P.C. Schmitz
Sverdrup Technology, Inc.
Lewis Research Center Group
Brook Park, Ohio 44142

and

T.J. McComas
Nuclear Engineering Department
University of Florida
Gainesville, Florida 32601

E-6216

ABSTRACT

Design of a Dynamic Isotope Power System (DIPS) based on the DOE General Purpose Heat Source (GPHS) and small free piston Stirling engine (FPSE) is being pursued as a potential lower cost alternative to radioisotope thermoelectric generators (RTG's). The design is targeted at the power needs of future unmanned deep space and planetary surface exploration missions ranging from scientific probes to SEI precursor missions.

These are multihundred-watt missions. The incentive for any dynamic system is that it can save fuel, reducing cost and radiological hazard. Unlike a conventional DIPS based on turbomachinery conversion, however, the small Stirling DIPS can be advantageously scaled to multihundred-watt unit size while preserving size and weight competitiveness with RTG's. Stirling conversion extends the range where dynamic systems are competitive to hundreds of watts—a power range not previously considered for dynamic systems. The challenge of course is to demonstrate reliability similar to RTG experience.

Since the competitive potential of FPSE as an isotope converter was first identified, work has focused on feasibility of directly integrating GPHS with the Stirling heater head. Extensive thermal modeling of various radiatively coupled heat source/heater head geometries has been carried out using data furnished by the developers of FPSE and GPHS. The analysis indicates that, for the 1050 K heater head configurations considered, GPHS fuel clad temperatures remain within safe operating limits under all conditions including shutdown of one engine.

Based on these results, preliminary characterizations of multihundred-watt units have been established. They indicate that, per electrical watt, the GPHS/small Stirling DIPS will be roughly equivalent to Mod RTG in size and weight but require only a third the amount of isotope fuel.

Effort is currently underway to produce a more detailed reference conceptual design. The design addresses system level issues such as mission environment, user vehicle integration, launch and transit for a typical planetary spacecraft, in addition to basic requirements associated with launch safety, assembly and loading, ground handling and storage. The emerging design will be the basis for showing how these requirements can be met, will permit further specification of components, and enable potential users to independently evaluate the small Stirling DIPS as an alternate power source.

INTRODUCTION

The civil space missions likely to occur within the next two or three decades will require nuclear power sources in the multihundred-watt (MHW) range. These include the deep space and outer planet missions presently in the OSSA strategic plan or proposed by the solar system exploration and space physics subcommittees [1], and many robotic planetary surface missions which would be precursors to later human exploration.

These missions, most of which do not take place until 10 years or more hence, are listed in table I. From the known characterizations of these missions and the capabilities of the vehicles and spacecraft involved, none will require more than 700 W. All are remote missions, in locations ranging from the lunar surface to deep space. High performance and minimum weight are desirable, but the key requirement is for reliable operation in a harsh environment, without intervention, over extended periods of time.

RTG'S

The only power source that is available presently to meet the requirements of these missions is the radioisotope thermoelectric generator (RTG) developed for NASA by DOE. This power source, which is basically an array of radiatively coupled thermoelectric cells enclosing a stack of General Purpose Heat Source (GPHS) blocks as shown in figure 1, is the product of a long evolutionary history of development and flight experience. The GPHS RTG's powering the Galileo and Ulysses missions draw their design heritage and 1300 K Si Ge unicouple technology from their predecessors, the MHW RTG's used on Pioneer and Voyager, still operating after being launched more than a decade ago. Scheduled for service on the Cassini and CRAF missions, GPHS RTG will be superceded for the later missions (Solar Probe, Pluto flyby, Comet Nucleus Sample Return, etc.) by DoE's evolutionary successor, the Mod RTG [2]. This unit employs the new 1300 K Si/Ge/GaP multicouple, which produces higher output voltage and allows modularity and improved packaging.

The RTG has demonstrated reliability well-suited for the requirements of these missions. Its thermoelectric conversion system, which has no moving parts to break or wear out, is made up of multiple series-parallel strings of redundant elements which accommodate failure of any element in the string with only partial degradation. No open circuit failures have ever been recorded: counting all the RTG powered missions flown to date, over 70 years of successful flight experience have been accumulated. For the converter, it translates to 442 million unicouple operating hours, demonstrating a reliablity in service measured in decades [3].

For missions where simplicity and reliability are needed most, the RTG has proven to be the simplest and most reliable power source. However, its thermoelectric conversion is not very efficient (typically 6 to 7 percent), so an RTG needs hundreds of thermal watts heat source in order to produce a few useful electrical watts, the rest of which must ultimately be disposed of as waste heat. Waste heat is a burden on the user since it must be continuously removed, placing a substantial auxiliary cooling requirement on the spacecraft during launch and transit.

The radioisotope inventory needed to produce this heat (roughly 30 Curies per thermal watt) is expensive, since the low emission spectrum and long half-life Plutonium isotope used in GPHS costs more than $1,000/g from the producer [4]. Each GPHS is loaded with 448 g of active isotope; counting the costs of production, encapsulation and assembly into heat source modules, the resulting mission user cost is about $6,000 a thermal watt.

Large radioisotope inventory translates to safety concerns since the amount of isotope launched aboard a spacecraft determines the "source term" generated in the event of an accident [5,6]. To a first approximation, the numerically calculated risk versus on-board inventory is a linear relationship—the more isotope carried, the greater the risk. These risks have been considered acceptable for the radioisotope powered missions carried out to date, but it would be desirable to reduce or eliminate that risk.

Where no alternatives to isotope power are available there is strong incentive to at least reduce the amount of isotope that is required. This can be accomplished by developing a power source with more efficient conversion. At present, the most efficient converters of thermal energy are dynamic heat engines. When energized by an isotope heat source, the resulting power plant is known as a dynamic isotope power system, or DIPS. DIPS requires less isotope per delivered electrical watt because heat engines are three to five times more efficient than thermoelectrics. But DIPS also introduces the complication of moving parts.

Historically, DIPS development has focused on turbomachinery-based heat engines because they are mechanically simple with potentially high reliability, and have significant advantages of scaling to higher power levels (kilowatts and above), a regime where generator weight and amount of on-board isotope heat source required is so burdensome as to completely rule out RTG's.

However, a turbomachinery based DIPS cannot compete effectively with RTG's for multihundred-watt missions—they are too large and too heavy. Power system studies done for the military BSTS satellite [7,8] showed that a Brayton DIPS would be heavier than Mod RTG's whenever power requirements less than 2 kWe were considered. Similar design studies done for the Low Power Brayton DIPS (LPD) [9], proposed as a replacement for two independent RTG units aboard an interplanetary robotic spacecraft—a direct multihundred-watt application in this instance—showed that LPD would be heavier than Mod RTG units below 1 kWe, and heavier than GPHS RTG's when power levels below 650 We were considered (figure 2).

The fundamental reason for this is the poor scaling of turbmachinery to lower power levels due to fixed losses including tip clearance. Generally speaking, turboalternator unit sizes below 500 W are considered impractical because of scaling effects on overall converter efficiency [10].

SMALL STIRLING DIPS

The Stirling engine, particularly the more recently developed free piston stirling engine (FPSE) combined with a linear alternator (LA), is a better converter choice for multihundred-watt isotope power. The FPSE/LA is quite different from the kinematic machinery developed under earlier isotope Stirling programs. It is mechanically simple, with only two moving parts and it is hermetically sealed, with no oils or other organic materials inside to degrade or contaminate. Since its vibrations are single frequency (reciprocating parts 60 to 100 Hz) they are relatively easy to attenuate or tune out.

Currently being developed for space power by NASA under the CSTI High Capacity Power program, FPSE/LA's development has focused on a multi-kWe converter for reactor power conversion [11] which will demonstrate compact physical size, high power density (7 kg/kWe), and a continuous service life exceeding 60 000 hr. Efficiencies of 20 percent have already been demonstrated at a temperature ratio of 2.2.

This engine represents a significant scale-up from the technology of earlier machines which were mainly multihundred-watt.

Unlike turbomachinery converters the FPSE scales easily over a wide range of unit sizes. Published performance data from various FPSE units previously built and tested [12 to 17], plotted in figure 3, demonstrates surprisingly consistent performance over a unit output power range from 5 W to 12.5 kW—roughly four orders of magnitude. Clearly the FPSE can be scaled from multi-kWe down to multihundred-watt unit sizes without losing its performance. Data published by a developer [18] indicates that specific weight of a multihundred-watt FPSE/LA power module should lie within the range 10 to 12 kg/kWe at temperature ratios typical of dynamic isotope power systems (2.5 and above). This evidence supports the proposition that a multihundred-watt converter derived from the CSTI space engine could produce a small Stirling DIPS that is competitive in size and weight.

The key to small Stirling DIPS is thermal integration of FPSE heater head with GPHS, which is the only space qualified isotope heat source available. Approximately 250 thermal watts each, the GPHS modules are designed for radiative coupling to a conversion system. The FPSE heater head can be heated directly by clustering the blocks around it as shown in figure 4, eliminating the need for a separate heat source assembly (HSA) and intermediate heat transfer loop. Since every GPHS block must have an unobstructed view of the heater head, 750 We is about the largest size unit that can be integrated in this fashion. At this size and below, significant savings in packaging and insulation weight can be achieved.

Data from a recent comparison of small Brayton and Stirling DIPS (major components, but without power conditioning or integration hardware) for distributed planet surface applications [19], shown in figure 5, illustrates the improvement in specific power that can be achieved when intermediate heat exchange and transport (insulated ducts, heat pipes, pumped loops) components are no longer needed. Coupled with the superior performance of FPSE at hundred-watt unit size, there appears a reasonable incentive to develop multihundred-watt isotope versions of this engine.

Since the concept was first identified [20], the potential of combining small free piston Stirling engines with isotope heat sources using direct integration has been explored. Design studies carried out at the NASA Lewis Research Center and the University of Florida have established concept feasibility. To date, a dual engine concept (figure 6) has been pursued. In these studies, various configurations of GPHS and insulation packages surrounding an opposed pair of FPSE heater heads were considered. Extensive thermal modeling was then carried out to simulate the GPHS heat source and its integration into various heat source/heater head geometries, using the analysis codes TRAYSYS and SINDA [21]. GPHS thermal models were correlated with data supplied by GE and DOE Mound Labs (developers of the GPHS). Modeling simulated various radiatively coupled configurations, using heater head data from the NASA Stirling Technology Branch. The analysis confirmed feasibility of direct integration. For heater head temperature of 1050 K, the GPHS fuel clad could be maintained within its operating limits under a variety of conditions including shutdown of one engine.

From the heat source/heater head geometries studied a preliminary dynamic isotope power system configuration, including heat source assembly, insulation package, converter and downstream components including power conditioning, emerged. Characterizations of these designs (table II) indicated that a multihundred-watt small Stirling DIPS should have dimensions similar to the DOE Mod RTG and exhibit a specific power of 7 to 8 W/kG. This is essentially the same size and weight as Mod RTG, but requiring one third the radioisotope.

The characterization has so far been preliminary. Efforts are now underway to improve the system definition and produce a conceptual design which has sufficient level of detail to address not only electrical power production from GPHS but also basic spacecraft isotope power system critical requirements such as isotope safety during launch and transit, re-entry, installation onto user vehicle and delivery of useable power to the spacecraft bus; continuous operation within the mission environment, life and reliability, and compatibility with on board users including vibration and electromagnetic disturbances. Design considerations peculiar to power systems that incorporate nuclear materials are also being addressed. These include loading of GPHS modules into the unit, its subsequent assembly, ground handling and storage, attachment and connections to the vehicle prior to launch.

The design definition is being carried out to a level of detail sufficient to show how each requirement will be met, and to establish firm subsystem and component requirements for the Heat Source/Heater Head Assembly, FPSE/LA Converters, cold end rejection loop and radiator, and electrical power conditioning and controls (PC+C) leading to critical hardware definition.

To ensure that the design addresses major concerns from a user standpoint, the Jet Propulsion Laboratory Spacecraft Power Systems section (engineering matrix support for JPL's deep space and planetary flight projects) has furnished a detailed set of mission and user vehicle requirements. They are referenced to the Cassini mission, using the Mariner Mk II spacecraft as the reference vehicle.

Present efforts at NASA Lewis are focussing on engine configuration and the thermal, mechanical and electrical integration of the FPSE/LA to other subsystems. Design assistance for the integrated heat source/heater head assembly containing GPHS modules is being provided by DoE's E.G.+G. Mound Laboratory (developers of GPHS).

The design will provide not only a credible estimate of hardware physical attributes but also a preliminary assessment of life and reliability that could be expected. This will permit competitive comparisons to other advanced concepts, and enable potential users to independently evaluate small Stirling DIPS as a low cost alternative to RTG's.

CONCLUSION

For the foreseeable future, the most likely missions for radioisotope power sources are long duration robotic missions at power levels of hundreds of watts. RTG's are normally considered for these missions but they require large amounts of isotope heat source which is hazardous, hard to obtain, and expensive. Because a dynamic system requires significantly less isotope to produce power, it could reduce the costs, and possibly the risks, to the mission. It has to be small enough, light enough, and reliable enough to replace the RTG.

It is possible to build a multihundred-watt DIPS by combining GPHS heat sources with the free piston space Stirling engine technology currently being developed. The high power density space engine, which can be scaled down to multihundred-watt unit size, is directly integrated with GPHS heat source through direct radiative coupling with FPSE heater head, thus avoiding intermediate heat transfer devices and minimizing heat losses. Detailed thermal analysis has shown the concept to be feasible, and preliminary system characterization shows it to be attractive—on a per electrical watt basis it is equivalent in size and weight to the next generation Mod RTG, but requires less than a third the radioisotope. If long term reliability of the small free piston Stirling space engine can be demonstrated, a small Stirling DIPS can provide a low cost alternative.

Because the small FPSE appears to have the potential to fit the mission requirements of this new application, and because the potential is too attractive to ignore, efforts are now underway to further develop and critically examine the small Stirling DIPS concept.

REFERENCES

[1] M. Shirbacheh, "The Proceedings of the Radioisotope Power Systems Requirements Workshop," Jet Propulsion Laboratory, Pasadena, CA, June 1990.

[2] R. Hartmann, "Modular RTG Technology Status," Proc. 25th IECEC, Vol. 1, AIChE, 1990, pp. 235-238.

[3] E. Skrabek, "Performance of Radioisotope Thermoelectric Generators in Space," Proc. 7th Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 1990.

[4] USDoE Office of Space/Defense Energy Projects.

[5] R. Englehart, "Mechanics of Space Nuclear Safety," Space Nuclear Power Systems, Vol. 2, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Co., 1984, pp. 497-503.

[6] G. Bennet, et al., "Development and Implementation of a Space Nuclear Safety Program," Space Nuclear Power Systems, Vol. 6, M.S. El-Genk and M.D. Hoover, eds., Orbit Book Co., Malabar, FL, 1987, pp. 59-92.

[7] G. Bennett, J. Janzen, J. Lombardo and A. Mehner, "The Dynamic Isotope Power System Technology Program," Proc. 23rd IECEC, Vol. 3, ASME, 1988, pp. 131-136.

[8] R. Brandewie, "Lockheed Missiles and Space Company BSTS Power System Definition Study," Rev. 1, RI/RD86-188, Rocketdyne Div., Rockwell International Corporation, Canoga Park, CA, July 1, 1986.

[9] W. Determan, D. Chung, A. Stadnik, and R. Johnson, "Low Power DIPS for Interplanetary Missions," Proc. 25th IECEC, Vol. 1, AIChE, 1990, pp. 210-215.

[10] R. Johnson and A. Stadnik, "Dynamic Isotope Power Systems (DIPS) for Space Exploration—Technical Information," Rockwell International Rocketdyne Division document BD 90-27, prepared for USDOE under Contract No. DE-AC03-88NE32129, Canoga Park, CA, May 1990.

[11] J. Dudenhoeffer, "Programmatic Status of NASA's CSTI High Capacity Power Stirling Space Power Converter Program," Proc. 25th IECEC, Vol. 1, AIChE, 1990, pp. 40-46. (Also, NASA TM-103142.)

[12] M.A. White, et al., "Fully Implantable Stirling Engine for Artificial Heart Power," Proc. 17th IECEC, Vol. 4, IEEE, 1982, pp. 1778-1783.

[13] D. Berchowitz, "The Development of a 1 kW Electrical Output Free Piston Stirling Engine Alternator Unit," Proc. 18th IECEC, Vol. 2, AIChE, 1983, pp. 897-901.

[14] R. Berggren and T. Moynihan, "Free Piston Stirling Engine Experimental Program: Part 1-Baseline Test Summary," ANL-CT-83-7 Part 1, Argonne National Labs, June 1983.

[15] J. Schreiber, S. Geng, and G. Lorenz, "RE-1000 Free Piston Stirling Engine Sensitivity Test Results," NASA TM-88846, 1986.

[16] N. Lane, D. Berchowitz, D. Shade, and A. Karandikar, "Development of a High Frequency Stirling Engine-Powered 3 kWe Generator Set," Proc. 24th IECEC, Vol. 5, IEEE, 1989, pp. 2213-2218.

[17] J. Cairelli, S. Geng, and R. Skupinski, "Results from Baseline Tests of the SPRE I and Comparison with Code Model Predictions," Proc. 24th IECEC, Vol. 5, IEEE, 1989, pp. 2249-2256.

[18] G. Dochat and M. Dhar, "Free Piston Stirling Engine System Considerations for Various Space Power Applications," Proc. 8th Symposium on Space Nuclear Power Systems, Albuquerque, NM, Jan. 1991.

[19] D. Bents et al., Comparison of Dynamic Isotope Power Systems for Distributed Planetary Surface Applications, Proc. 8th Symposium on Space Nuclear Power Systems, Albuquerque, NM, January 1991.

[20] D. Bents, Preliminary Assessment of Rover Power Systems for the Mars Rover Sample Return Mission, Space Power Vol. 8, No. 3 1989.

[21] T. McComas, Thermal Analysis of a Conceptual Design for a 250 We GPHS/FPSE Power System, Department of Nuclear Engineering, University of Florida 1990.

TABLE I.—MISSIONS THAT WILL REQUIRE RADIOISOTOPE POWER SOURCES

Mission	Proposed launch date	Classification	Mission duration, years	EOM power level, W
Craf	1995	Code S strategic plan	7.5	461
Cassini	1996	Code S strategic plan	10.5	480
Pluto flyby	1998	Solar system exploration	14 to 16	500 to 600
Solar probe	2000	Code S strategic plan	8	500
Mars rover sample return	2001	SEI precursor	4	500
Comet nucleus sample return	2002	Solar system exploration	8	500 to 700
Lunar site survey rover	2002, 2006, & 2010	SEI precursor	5	500
Neptum orbiter and landers	2003	Solar system exploration	20	500 to 700
Multiple asteroid orbiter grand tour (w/Landers)	2005	Solar system exploration	10 to 12	500 to 700
Mars site survey rover	2005, 2007, 2009, 2015, & 2024	SEI precursor	5	400
Jupiter grand tour (Orbiter and Landers)	2006	Solar system exploration	10 to 12	500 to 700
Interstellar probe	circa 2010	Space physics	20 to 25	200 to 500
Polar heliospheric probe	post 2010	Space physics	35	200 to 500

Table II.—

(a) 240 W system comparison

	Power source mass, kg	Power source envelope		Radiator temperature	Number of GPHS blocks required	Isotope fuel required, kg
		Diameter, cm	Length, cm			
GPHS-RTG	45.3	42	110	540	18	8.1
MOD-RTG	31.2	38	70	598	12	5.4
Small Stirling DIPS	33.8	27	100	375	4	1.8

(b) 480 W system comparison

	Power source mass, kg	Diameter, cm	Length, cm	Radiator temperature	Number of GPHS blocks required	Isotope fuel required, kg
GPHS-RTG	90.6	42	220	540	36	16.1
MOD-RTG	62.4	38	130	598	24	10.7
Small Stirling DIPS	59.8	27	120	375	8	3.6

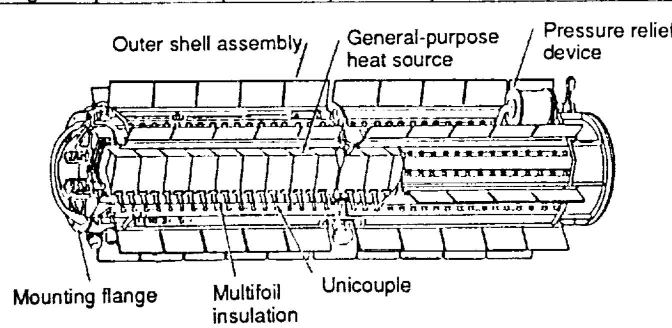

Figure 1.—General-purpose heat source – RTG.

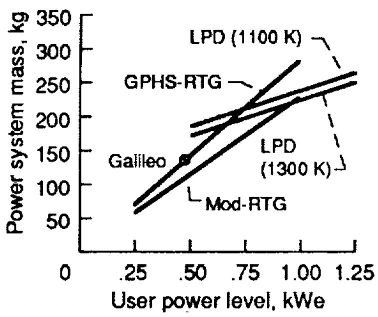

Figure 2.—Low-power DIPS versus RTG system masses (from ref. 9).

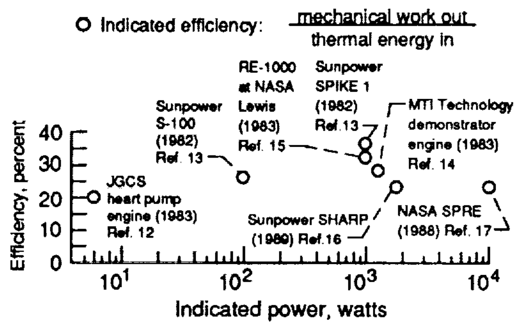

Figure 3.—Measured performance of selected free piston Stirling engines of various unit sizes.

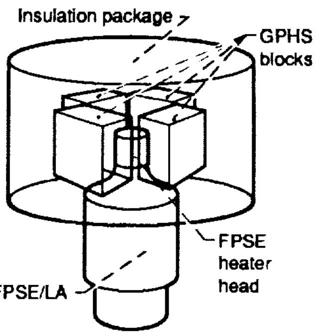

Figure 4.—Direct heat source/heater head integration.

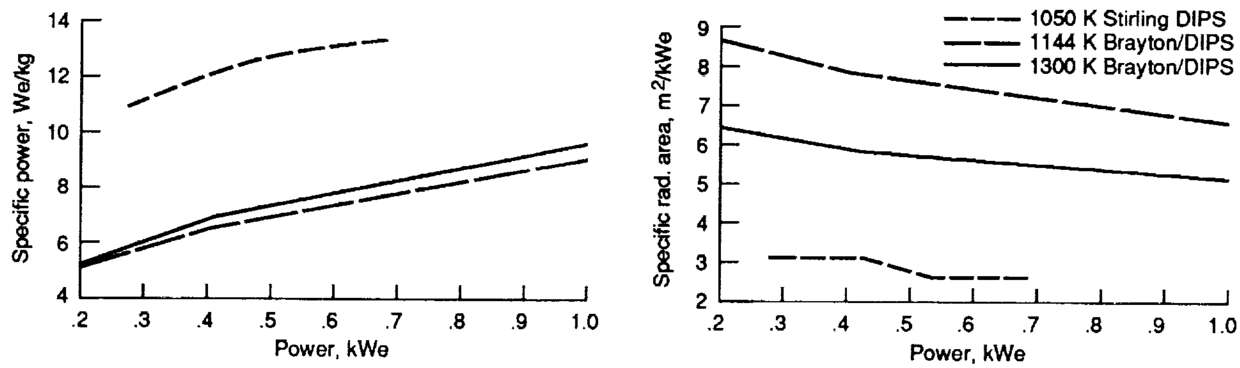

Figure 5.—Multihundred watt unit comparison. Stirling DIPS (direct integration) versus mass optimized Brayton DIPS (single PCU). Data from ref. 19.

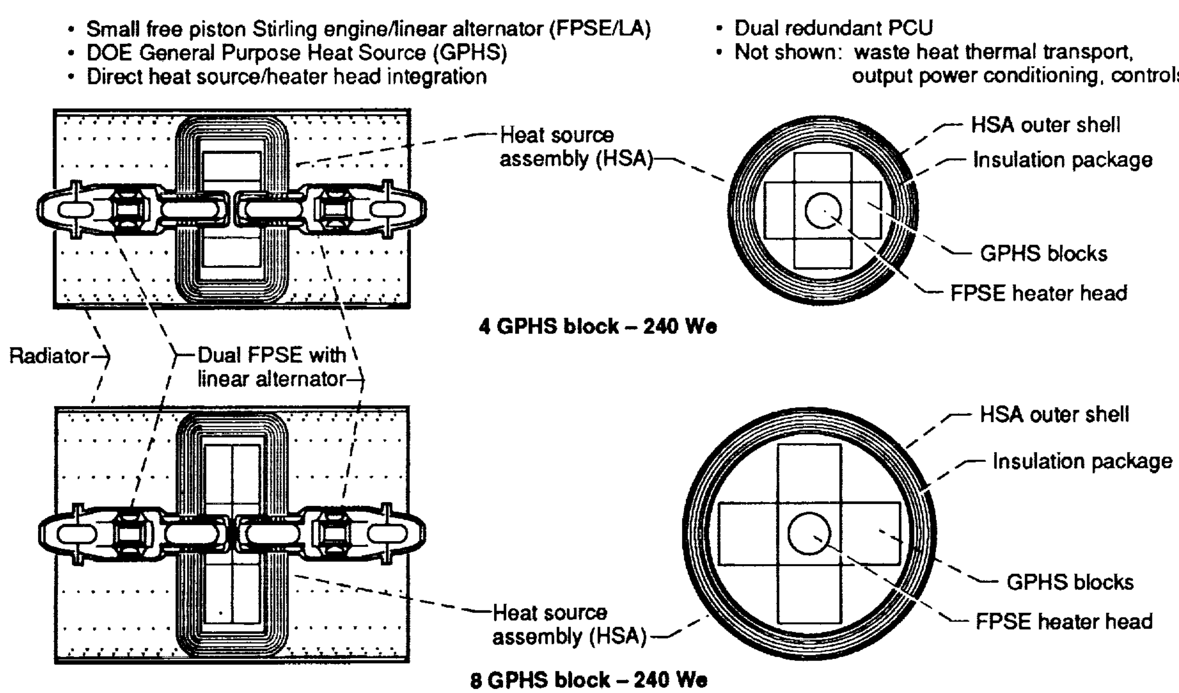

Figure 6.—Multihundred watt Stirling DIPS configuration.

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM -104401	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Design of Multihundredwatt DIPS for Robotic Space Missions		5. Report Date
		6. Performing Organization Code
7. Author(s) D.J. Bents, S.M. Geng, J.G. Schreiber, C.A. Withrow, P.C. Schmitz, and T.J. McComas		8. Performing Organization Report No. E -6216
		10. Work Unit No. 590-13-11
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135 - 3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546 - 0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 26th Intersociety Energy Conversion Conference cosponsored by the ANS, SAE, ACS, AIAA, ASME, IEEE, and AIChE, Boston, Massachusetts, August 4-9, 1991. D.J. Bents, S.M. Geng, J.G. Schreiber, and C.A. Withrow, NASA Lewis Research Center. P.C. Schmitz, Sverdrup Technology, Inc., Lewis Research Center Group, 2001 Aerospace Parkway, Brook Park, Ohio 44142 (work funded by NASA Contract NAS3-25266). T.J. McComas, Nuclear Engineering Department, University of Florida, Gainesville, Florida 32601. Responsible person, D.J. Bents, (216) 433-6135.

16. Abstract

Design of a Dynamic Isotope Power System (DIPS) based on the DOE General Purpose Heat Source (GPHS) and small free piston Stirling engine (FPSE) is being pursued as a potential lower cost alternative to radioisotope thermoelectric generators (RTG's). The design is targeted at the power needs of future unmanned deep space and planetary surface exploration missions ranging from scientific probes to SEI precursor missions. These are multihundredwatt missions. The incentive for any dynamic system is that it can save fuel, reducing cost and radiological hazard. Unlike a conventional DIPS based on turbomachinery conversion, however, the small Stirling DIPS can be advantageously scaled to multihundred watt unit size while preserving size and weight competitiveness with RTG's. Stirling conversion extends the range where dynamic systems are competitive to hundreds of watts—a power range not previously considered for dynamic systems. The challenge of course is to demonstrate reliability similar to RTG experience. Since the competitive potential of FPSE as an isotope converter was first identified, work has focused on feasibility of directly integrating GPHS with the Stirling heater head. Extensive thermal modeling of various radiatively coupled heat source/heater head geometries has been carried out using data furnished by the developers of FPSE and GPHS. The analysis indicates that, for the 1050 K heater head configurations considered, GPHS fuel clad temperatures remain within safe operating limits under all conditions including shutdown of one engine. Based on these results, preliminary characterizations of multihundred watt units have been established. The indicate that, per electrical watt, the GPHS/small Stirling DIPS will be roughly equivalent to Mod RTG in size and weight but require only a third the amount of isotope fuel. Effort is currently underway to produce a more detailed reference conceptual design. The design addresses system level issues such as mission environment, user vehicle integration, launch and transit for a typical planetary spacecraft, in addition to basic requirements associated with launch safety, assembly and loading, ground handling and storage. The emerging design will be the basis for showing how these requirements can be met, will permit further specification of components, and enable potential users to independently evaluate the small Stirling DIPS as an alternate power source.

17. Key Words (Suggested by Author(s)) Spacecraft power supplies; Nuclear auxiliary power units; Mars sample return missions; Nuclear electric power generation	18. Distribution Statement Unclassified - Unlimited; Subject Category 20

19. Security Classif. (of the report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161

PAGE 7 INTENTIONALLY BLANK

PRECEDING PAGE BLANK NOT FILMED