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Design of Small Stirling Dynamic Isotope Power System for Robotic Space Missions

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DESIGN OF SMALL STIRLING DYNAMIC ISOTOPE POWER SYSTEM FOR ROBOTIC SPACE MISSIONS

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Abstract

Design of a multihundred-watt Dynamic Isotope Power System (DIPS) based on the U.S. Department of Energy (DOE) General Purpose Heat Source (GPHS) and small (multihundred-watt) free-piston Stirling engine (FPSE) technology 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 Space Exploration Initiative precursor missions. Power level for these missions is less than a kilowatt. Unlike previous DIPS designs which were based on turbomachinery conversion (e.g. Brayton), this small Stirling DIPS can be advantageously scaled down to multihundred-watt unit size while preserving size and mass competitiveness with RTGs. Preliminary characterization of units in the output power ranges 200-600 We indicate that on an electrical watt basis the GPHS/small Stirling DIPS will be roughly equivalent to an advanced RTG in size and mass but require less than a third of the isotope inventory.

INTRODUCTION

Within the context of today's civil space agenda there are about twenty missions where radioisotope power sources will be required. These include all the deep space and outer planet missions presently in the Office of Space Science and Applications (OSSA) strategic plan plus those proposed by the solar system exploration and space physics subcommittees (Boain 1991), and the many robotic planetary surface missions considered as precursors to later human exploration (Petri et al. 1990). Almost all the missions (summarized in Table 1) are unmanned. From the known mission characterizations and the capabilities of vehicles and spacecraft involved, none of the unmanned missions will require more than 700 W. Dates listed for the missions are only estimates; most of them will not take place for 10 years or more. Although there is an eventual requirement for multi-kilowatt power to support manned missions (construction and operation of a lunar base, for example), the manned missions are not anticipated to take place until most of the unmanned missions have been completed. The unmanned missions are remote robotic missions, to 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 presently available to meet these requirements is the radioisotope thermoelectric generator (RTG) developed for NASA by the Department of Energy (DOE). The RTG is built around the space-qualified General Purpose Heat Source (GPHS), also furnished by DOE. The present day GPHS RTG is basically an array of radiatively coupled thermoelectric (TE) cells enclosing a stack of GPHS blocks as shown in Figure 1. This power source is the result of years of evolutionary development and flight experience. The GPHS RTG is next scheduled for service on the Cassini mission, but it may be superceded for later missions (Solar Probe, Pluto flyby, Comet Nucleus Sample Return etc.) by an advanced modular RTG design known as Mod RTG (Hartmann 1990). Mod RTG represents the next step in evolutionary development from the present state-of-art GPHS RTG. RTG's have demonstrated outstanding reliability. Their thermoelectric conversion system 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

TABLE 1. Missions That Require Radioisotope Power Sources

	Proposed Launch Date	Mission Duration	Estimated End of Mission Power Level
NASA Space Science Missions			
Cassini	1998	10.5 yrs.	480 W
Solar Probe	post 2000	8 yrs.	500 W
Solar System Exploration Missions			
Pluto Flyby	1998	14–16 yrs.	700 W
Neptune Orbiter	2002	20 yrs.	30 W
Mars Rover Sample Return	2001	4 yrs.	500 W
Solar Probe	2001	8 yrs.	337 W
Uranus Orbiter	2007–11	14–16 yrs.	700 W
Comet Nucleus Sample Return	2007–11	8 yrs.	500 W
Space Physics Missions			
Interstellar Probe	circa 2010	20–25 yrs.	200–500 W
Polar Heliospheric Probe	post 2010	35 yrs.	200–500 W
Space Exploration Initiative (SEI) -- Precursor Missions			
Lunar Site Rover (2 mission)	1997	1–2 yrs.	100–300 W
Mars Environment Survey (MESUR)	1998	5 yrs.	15 W
Lunar Surface Telescope Package	1998	5 yrs.	200–500 W
Lunar Comm. Network (4 missions)	1998 and 1999	>10 yrs.	100 W
Mars Rover Sample Return	post 2000	4 yrs.	500 W
Mars Site Survey Rover	post 2000	5 yrs.	400 W
Manned Missions			
Unpressurized Lunar Rover	post 2000	960 hrs.	2–5 kW
Pressurized Lunar Rover	post 2000	96 hrs.	12 kW
Lunar Excursion Vehicle Servicer	post 2000	1 yr.	10 kW

accumulated (Skrabek 1990). However, their thermal to electric conversion system is not very efficient (typically 6 to 7 percent). As a result, a significant cost penalty must be paid, since the low emission and long half-life plutonium isotope used in the GPHS, originally available as a byproduct from nuclear weapons production, is very expensive to produce and remaining stocks are limited. No production capability presently exists. The price paid by the government for new supplies of this material will range from \$1200/gm PuO_2, as quoted for this material by the Commonwealth of Independent States (CIS) for sale from their existing stock (DOE Correspondence 1991), to over \$8000/gm PuO_2 if new domestic production were initiated (Prospector II Workshop 1992). Each GPHS is loaded with 448 gm of active PuO_2. Counting the costs of production, encapsulation and assembly into heat source modules, the resulting mission user cost is estimated to be between \$6000 and \$18,000 per thermal watt. For an RTG, this translates to roughly \$100,000 to

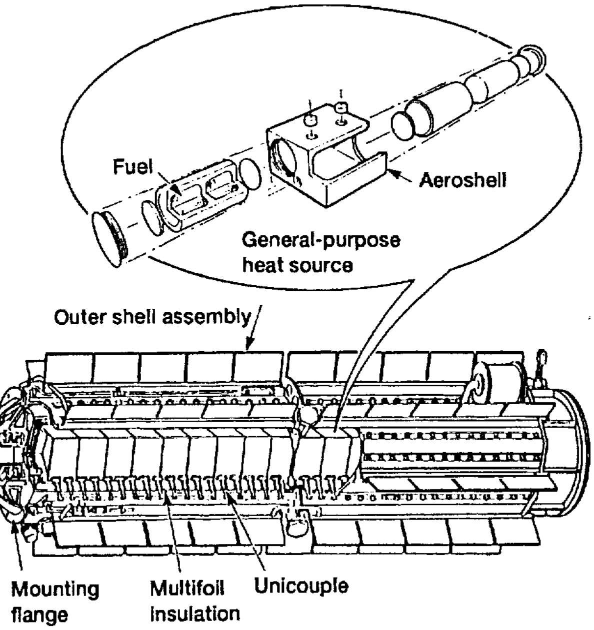

Figure 1.—General-purpose heat source - RTG.

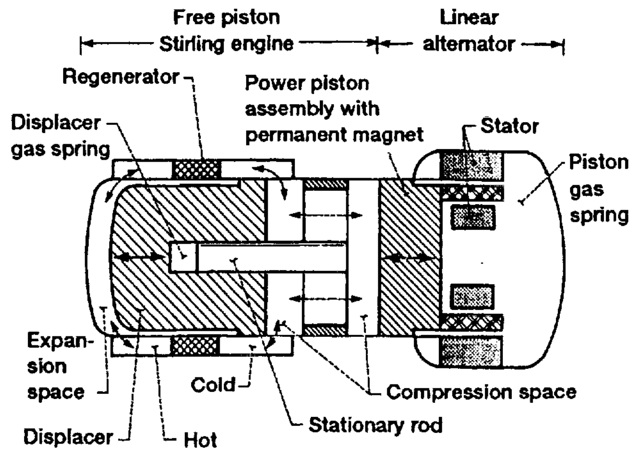

Figure 2.—Free piston Stirling engine/linear alternator.

$300,000 per electrical watt. The radioisotope inventory carried by RTGs (463 Ci per electrical watt) also translates to significant safety concerns (Englehart 1984, and Bennett 1987). To a first approximation, the numerically calculated risk versus on-board inventory is a linear relationship (i.e. the more isotope carried, the greater the risk). These risks have been considered acceptable for the radioisotope powered missions carried out to date but the desire to reduce or eliminate that risk has long been recognized (Aftergood 1988).

<u>Dynamic Isotope Power Systems (DIPS)</u>

Where no alternatives to isotope power are available there is a strong incentive to 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. A DIPS requires less isotope per delivered electrical watt because heat engines are 3 to 5 times more efficient than thermoelectric converters. DIPS development for space, historically aimed at multi-kWe missions that were anticipated for the post-Apollo era, focused on turbomachinery-based heat engine converters, primarily the closed Brayton cycle. Turbomachinery is mechanically simple, with potentially high reliability, and scales advantageously to higher power levels. For multi-kWe missions, a turbomachinery based DIPS is significantly lower in mass than the equivalent amount of RTG's. However, the turbomachinery based DIPS is not an effective competitor with RTG's for multihundred-watt missions. The fundamental reason for this is that turbomachinery does not scale well to lower power levels due to fixed losses such as bearing loss, windage, turbine tip clearance, etc (Johnson and Stadnik 1990). Generally speaking, turboalternator unit sizes below 500 W are considered impractical because of scaling effects on overall converter efficiency.

<u>Small Stirling DIPS</u>

The Stirling engine, particularly the more recently developed free-piston Stirling engine (FPSE) combined with a linear alternator (LA), is the better converter choice for multihundred-watt missions. As Figure 2 illustrates, the FPSE/LA is quite different from the kinematic machinery developed under earlier isotope Stirling programs (Lehrfeld and Richards 1980). It is mechanically simple, typically with only two moving parts, and it is hermetically sealed. Suspended on linear gas bearings or flexures, its moving parts do not contact. The Stirling engine's vibrations (moving parts reciprocate at 60 to 100 Hz) are essentially single frequency and can be easily attenuated or tuned out. Although its invention is relatively recent (1962), the FPSE has been developed and used for a wide variety of applications accumulating a considerable background of test and operational experience at power levels ranging from 5 W to 2 kW (Ross and Dudenhoeffer 1991). Run in reverse as cryocoolers for surveillance sensors, free piston Stirling machines have already seen operational use in space. This experience indicates potential to achieve, as an isotope engine, the high reliability that is required for decades of unattended remote operation. This is of paramount importance, since the FPSE/LA must inevitably be compared to RTG thermoelectric converters which have accumulated years of flight experience.

Unlike turbomachinery, an FPSE can be advantageously scaled from multi-kilowatt unit size to hundred-watt unit size and below. Published performance data from various FPSE units previously built and tested, plotted in Figure 3, demonstrate consistent performance over a range of unit sizes as large as the 10 plus kilowatt NASA SPRE (Cairelli and Geng 1988), to the kilowatt class Sunpower SHARP engine (Lane 1989), the MTI Technology Demonstrator (Bergren and Moynihan 1983), the NASA RE-1000 (Schreiber, Geng and Lorenz 1986) and SPIKE engines (Berchowitz 1983), to hundred watt class units such as the Sunpower S-100 (Berchowitz 1983), down to as small as the 5 W units developed to power an artificial heart (White 1982). The data is consistent over a range roughly four orders of magnitude.

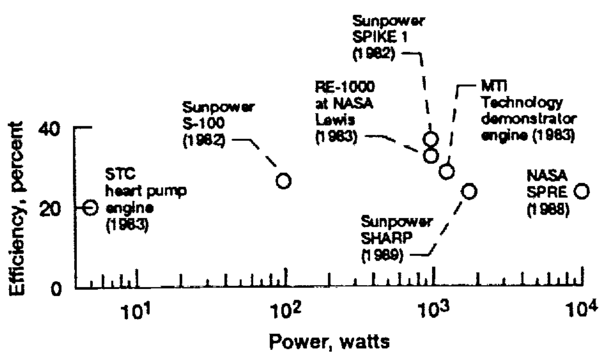

Figure 3.—Measured performance of selected free piston Stirling engines of various unit sizes.

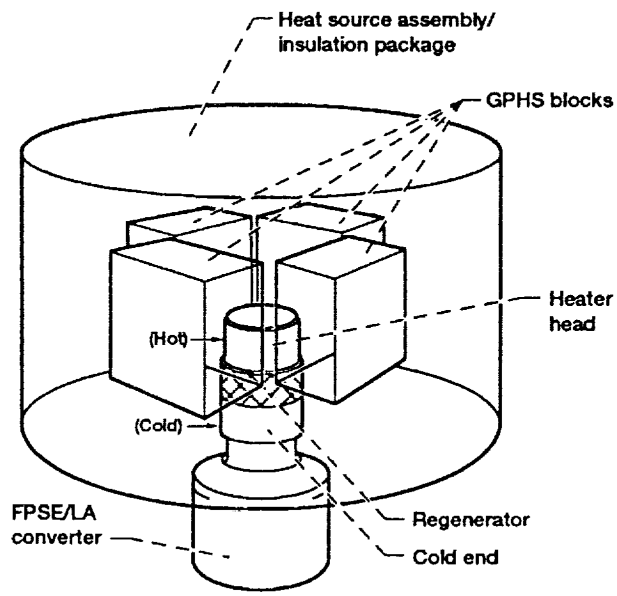

Figure 4.—Small free piston Stirling DIPS; direct integration, heat source to heater head.

The other attractive feature of the FPSE is its ease of thermal integration with GPHS at multihundred-watt unit size. Approximately 250 thermal watts each, the GPHS modules are designed for radiative coupling to a conversion system. For a multihundred-watt Stirling DIPS unit, 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. Previous work (Bents 1991, McComas and Dugan 1991) has shown the feasibility of direct integration. In these studies, which investigated the potential of combining small free-piston Stirling engines with isotope heat sources using radiative coupling, various configurations of GPHS and insulation packages surrounding an opposed pair of FPSE heater heads were considered. Thermal modeling was then performed to simulate the GPHS heat source and its integration into various heat source/heater head geometries, using the analysis codes TRAYSYS and SINDA. The analysis showed that heater head operating temperatures of 1000-1050K can be maintained while keeping the GPHS fuel clad temperatures within acceptable limits (less than 1600K to inhibit grain growth). Since each individual block GPHS block must have an unobstructed view of the heater head, geometric considerations limit the largest size unit that can be integrated in this fashion to about 600 We. However, significant mass savings is achievable for these smaller units.

Development of the direct integration concept, as shown in Figure 4, leads to the small Stirling DIPS configuration shown in Figure 5. Again the GPHS cluster is radiatively coupled to the FPSE heater head thus avoiding heavy intermediate heat exchange and transport components (insulated ducts, heat pipes, pumped loops etc.). Cylindrical in form, this small DIPS integrates the HSA, converters and downstream components inside a cylindrical heat pipe radiator which serves as the unit's mounting structure and outer envelope (the unit is attached to the spacecraft via compliant mounts). Two redundant converters are used; that is, in the event that one converter fails, the remaining converter absorbs the entire HSA heat load. These converters, which individually employ dual opposed power pistons for minimum vibration, mount into opposite ends of the HSA facing each other to further cancel vibration forces.

More detail can be seen in Figure 5(a) which shows general flow paths for heat from the GPHS cluster into the FPSE hot end, and waste heat from the converter cold end back out to the radiator. The HSA outer shell contains an imbedded network of heat pipes. These heat pipes couple the radiator drum segments (attached to its exterior circumference via an equalizer network) to the converter mounting sleeve (conductively couples to the FPSE cold end). The equalizer ensures that both halves of the cylinder radiate waste heat regardless of whether one or both engines are working.

Characterizations of the small Stirling DIPS concept shown in Figure 5, which include heat source assemblies, insulation packages, converters and downstream components, are presented in Table 2. Six point designs (unit sizes from 200 We to 600 We) are summarized. These designs were performed to robotic deep space platform requirements furnished by the Jet Propulsion Laboratory. Of the two 200 We designs, one is mass-optimized, and the other minimizes isotope useage. Performance is calculated for 12 years after beginning of life (BOL). Total DIPS unit mass and number of GPHS blocks used are also plotted in Figure 6 for comparison with estimates for state of art (GPHS) and advanced (Mod) RTG units based on published specific mass data (Hartmann 1990) shown at the bottom of Table 2. Shaded areas are bounded by BOL and 12 year performances. The characterizations indicate that a small Stirling DIPS will have physical dimensions and mass similar to Mod RTG, with specific powers ranging from 5.43 to 8.71 We/kg. But the isotope consumption, as evidenced by the number of GPHS modules required to produce equivalent electrical power, is only 20 to 30 percent of the RTG requirement.

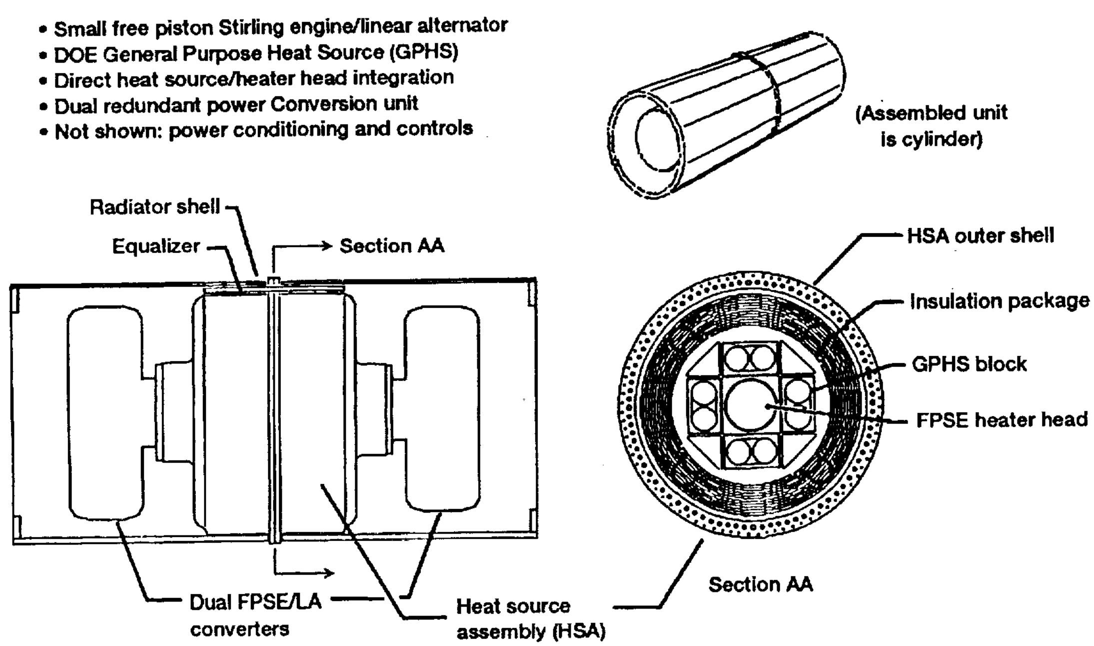

Figure 5.—Small Stirling DIPS unit configuration; cutaway view.

TABLE 2. Small Stirling DIPS, with Comparison to GPHS RTG and Mod RTG

Performance/Envelope Specification						
Output power, We[a]	200	200	300	400	500	600
Number GPHS blocks used	3	4	5	7	9	10
Envelope (cylinder)						
outer diameter, cm	25.6	29	32	37	40	40
length, cm	465	42	160	192	137	347
Heat Source Assembly (HSA) mass breakdown, kg						
GPHS blocks	4.36	5.82	7.27	10.2	13.09	14.55
Insulation package	2.63	3.17	3.71	4.81	5.21	4.9
Container with mounts	3.69	2.52	3.93	3.95	6.34	6.51
Conversion and Heat Rejection mass breakdown, kg						
Dual FPSE/LA converters	6.15	6.15	8.86	12.32	13.54	15.51
Radiator[b]	7.5	0.76	3.23	4.47	3.5	8.77
Power conditioning	10.02	10.02	11.28	12.32	13.22	14.03
Structure	3.43	2.84	3.83	4.71	5.5	6.43
Total Mass, kilograms	37.77	31.28	42.12	51.76	60.37	70.7
Specific Power, We/kg[a]	5.43	6.56	7.3	7.92	8.49	8.71

RTG data (from Hartmann 1990)	GPHS-RTG	Mod-RTG
Performance/Envelope Specification		
Output power, BOL We	285	340
estimated 12 years after BOL	220	262
Number GPHS blocks used	18	18
Envelope (cylinder with fins)		
outer diameter, cm	42.2	33
length, cm	114	108
Mass, kg	56.1	42.2
Specific Power, BOL We/kg	5.08	7.9
Specific Power 12 years after BOL, We/kg	3.92	6.1

[a]Specified 12 years after BOL.
[b]262 K maximum sink temperature.

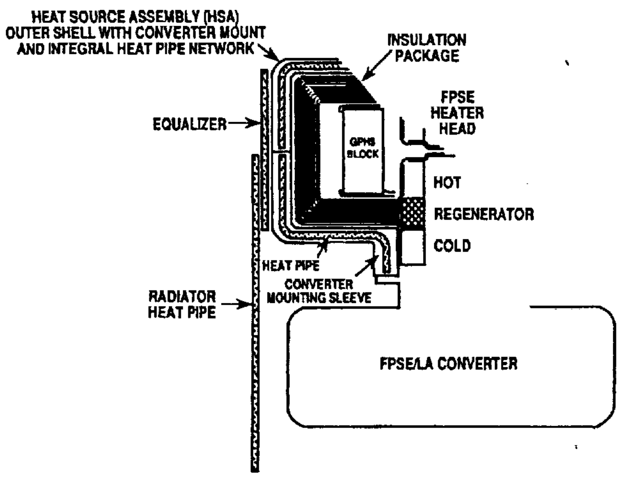

Figure 5a.—Small Stirling DIPS heat source/heater head integration and thermal management.

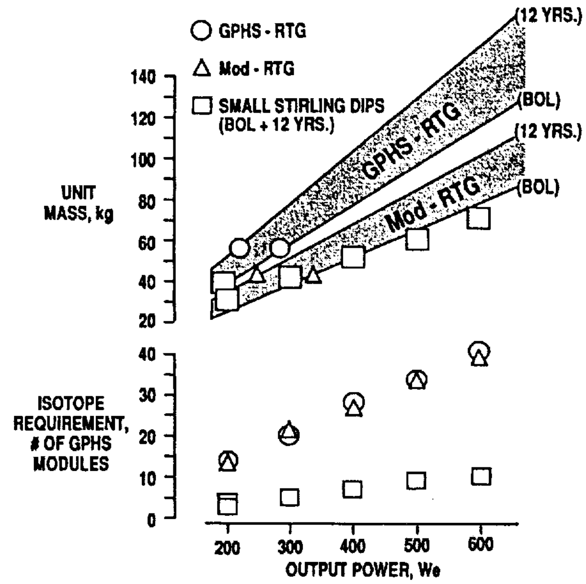

Figure 6.—Small Stirling DIPS for deep space platforms. Comparison of unit mass and isotope requirement with RTG's.

CONCLUSION

For the forseeable future, the most likely missions for radioisotope power sources are long duration robotic missions at power levels in the multihundred-watt range. RTG's are normally considered for these missions but they require large amounts of isotope heat source which is hard to obtain, hazardous, 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 sufficiently small, light, and reliable, however, in order to replace the RTG.

It is possible to build a multihundred-watt DIPS by combining GPHS with the free-piston space Stirling engine technology now being developed. The FPSE/LA, which can be built as a practical converter in the hundred-watt unit size, is directly integrated with the GPHS heat source through radiative coupling to the FPSE heater head, thus avoiding intermediate heat transfer devices, and minimizing system mass. Thermal analysis has shown the small Stirling DIPS concept to be feasible, and preliminary system characterizations show it to be attractive. On a per electrical watt basis it is equivalent in size and weight to the RTG, but requires less than one third the radioisotope. If long term reliability of the small free-piston Stirling space engine can be demonstrated, small Stirling DIPS can provide a low cost alternative to RTG's for these missions.

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