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MILLIWATT ISOTOPE POWER SOURCE FOR MICROSPACECRAFT

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Abstract

Miniature spacecraft offer the potential to greatly reduce mission costs, but today there is no flight qualified power source that could operate a microspacecraft during a journey to the outer planets. This paper describes the Milliwatt Isotope Power Source (MIPS), a concept capable of reliable, long term electrical power generation in the milliwatt range. Utilizing existing Radioisotope Heater Unit (RHU) heat source technology and proven thermoelectric energy conversion module technology, a MIPS package about the size of a D-cell battery could deliver about 30 milliwatts of electrical power for several decades and weigh 70 grams. Such a power source could be used to power miniature instruments such as seismometers, propel a microrover or provide decentralized power aboard a more conventional spacecraft. Also, reliance on flight-qualified heat source technology and the small radioisotope inventory required are attractive safety considerations.

INTRODUCTION

Advances in modern electronics, very large scale integration (VLSI) and miniaturization will significantly benefit spacecraft design. Miniature spacecraft can be launched on small rockets, as opposed to more expensive Shuttle or Titan-Centaur launchers. Because of their small mass they can be sent on more direct trajectories, reducing mission duration time and operations costs. Microinstruments such as X-ray telescopes, imaging spectrometers, seismometers, and scanning calorimeters are all under consideration for microspacecraft as well as deployable microstations. Missions such as Asteroid Investigation with a Microspacecraft (AIM), Mars Environment Survey (MESUR) and microrover in particular are expected to benefit from these advances.

The technology to make microinstruments is rapidly advancing, but the availability of power may be a limiting factor. This paper describes miniature thermoelectric conversion technology suitable for power generation in the milliwatt range. Modern thin film techniques are also discussed as a possible alternative for microwatt range devices consistent with the voltage levels needed. Similar techniques have been developed in the former Soviet Union which allow, for example, 100 or more thermocouples to be packed into an array of 1mm x 1mm. An additional benefit of the MIPS may be the possibility of using other, less toxic isotopes. Such an approach would substantially reduce the manufacturing and launch approval costs of a MIPS.

APPLICATIONS

The MIPS could be utilized in a variety of autonomous science packages. For example, a microseismometer is being developed that requires less than 1 watt to operate. The next generation of seismometers is expected to consume no more than 0.1 W. Seismometers require power sources that can last for years due to sporadic nature of seismic events. An alpha-proton-x-ray spectrometer that is being developed for small rovers to investigate rock composition would require about one third of a watt of power, which again is within the range of a MIPS. The next generation of cameras using principles of active pixel sensors could operate on only a fraction of a watt.

There is also a number of microspacecraft instruments and subsystems that could operate using distributed instead of centralized power. Instruments such as magnetometers that must be located on extended booms are perfect candidates for distributed power.

The Mars Environment Survey (MESUR) mission could utilize a MIPS in many different ways. The lander could deploy its instruments away from its contamination zone if they had autonomous power. A MIPS could also be carried on a microrover released by the lander. A MIPS on board the rover would eliminate the need for a power cord tether and increase the mission life from the present 3-4 days to years. Because the power requirements of small rovers extend beyond fractions of a watt towards the 3-4 watt range, a suitable battery (such as $Li\text{-}TiS_2$) would be necessary to operate the rover. The MIPS would trickle-charge the battery, which in turn would be used for propulsion and operation of science instruments. A small 40 gram, 1 amp-hour battery could propel a microrover a few hundred meters in a day, followed by a three day charging cycle, followed by a day of scientific measurements and data transmission, followed by another charge cycle. This sequence could be repeated for 2-3 years enabling substantial terrain coverage with even fewer landers than is currently planned for MESUR.

Small RTGs are superior in many ways to other power options from the technical point of view. But they are considered to be expensive due to the cost for space qualification of their radioisotope sources, costs for launch approval and compliance with the National Environmental Policy Act, which includes the Environmental Impact Statement. However, a closer inspection of the launch approval laws imposed on launching of radioisotope sources, reveals that they omit RHU type sources as well as sources that contain less than 20 curies of radioactivity. These considerations make the RHU attractive as a heat source for the MIPS. Smaller units could fit under the limit of 20 curies and thus avoid many legal RTG costs.

BENEFITS

Future space missions are expected to be cheaper, faster, better. One of the key elements that make space missions expensive are costly launch vehicles. As missions become more ambitious in their reach for the outer regions of the solar system, the launch vehicles for standard size spacecraft also become bigger and more expensive. Shrinking the spacecraft allows using boosters that are smaller and less costly. For example, being able to launch a payload on an Atlas II as opposed to a Titan IV may result in launch cost savings of hundreds of millions. In addition, smaller spacecraft may translate into shorter trip times. For example, a small spacecraft appears required to reach Pluto before the collapse of its atmosphere. The next opportunity to study the atmosphere of Pluto will not occur for 200 years when Pluto is again warmed by the sun.

Solar arrays are not an ideal power source for small spacecraft, because the area of a spacecraft structure is very limited for body mounted panels. Spacecraft designers prefer to avoid deployable arrays because of the lower reliability, greater size, battery mass, thermal problems and vibrations. Deployable arrays also put greater demands on the Attitude, Articulation and Control System (AACS). Because of a higher inertia of the spacecraft the amount of propellant necessary for control increases, causing the spacecraft mass to escalate. Solar array panel size becomes prohibitively large for outer planet missions because of low insolation and low intensity low temperature (LILT) effects.

Many autonomous robotic packages cannot be outfitted with solar panels because of large size, difficulties in array orientation, or damage due to dust. For small packages, such as miniature seismographers, mineral scouts, and in-situ meteorological sensors, the only existing power sources are lithium batteries that can last only for several hours. Availability of a MIPS would alleviate all the above problems.

CONCEPTUAL DESIGN

The two primary technical concerns for the design of low power level RTG's are 1) heat source selection and 2) thermopile design. Mature technologies are available for both heat source and thermopile development and indeed RTG's have been designed and built to provide power levels ranging from ~3 μW_e up to several hundred watts. By utilizing existing technologies, small, light weight RTGs suitable for providing virtually any required power level can be designed. The following sections outline some of the available heat source and thermopile technologies.

Heat Source Considerations

This section describes key background and discusses considerations in designing a suitable heat source.

Radioisotope-based cardiac pacemakers probably represent the most mature, very low power level RTGs. Using Pu-238 as a heat source to provide ~3 μW_e up to ~500 μW_e, these devices have been implanted in a few thousand patients and are typically designed to withstand worst-case accident scenarios as well as high temperatures, so that the RTG might survive cremation conditions intact. These devices work well and still represent the only pacemaker technology which can outlive the patient, but concerns about disposal after the patients death have resulted in a limited market. For applications requiring power in the 75-500 mW_e range, such as navigational buoys and underwater cable repeater units, RTGs with 3-5% efficiency have been developed and deployed also utilizing a Pu-238 heat source.

While these reliable and robust heat sources should be examined further, they are not currently space qualified and are currently much heavier than desired. A particular concern for space RTGs is demonstrating worst case re-entry survivability, which can typically be achieved but the cost is high. It is desirable, therefore, to maintain a close heritage to existing technology and fortunately an appropriate heat source is available.

The Light Weight Radioisotope Heater Unit (LWRHU) is a second generation heat source designed to provide 1 W of thermal power in a package roughly the size of a D-cell battery, as shown in Figure 1. The entire unit is a right circular cylinder 3.2 cm high, 2.6 cm in diameter and weighs 40 grams. The graphite heat shield and thermal insulation package is sufficient to maintain the integrity of the fuel pellet even under worst case re-entry conditions. A large number of these units were used to provide local heating on the Galileo spacecraft and are baselined for use on the upcoming Cassini mission.

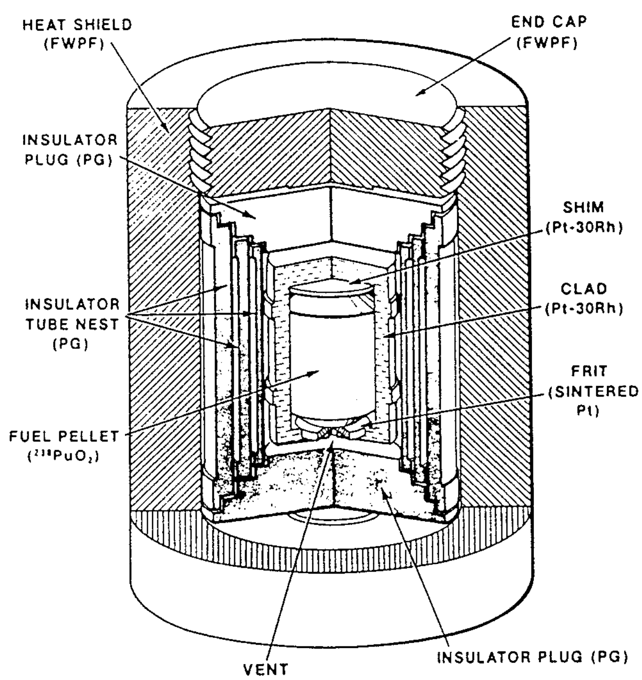

FIGURE 1. Light Weight Radioisotope Heater Unit (from Tate 1982).

The LWRHU is nearly ideally suited for use as a low power RTG since only minimal design modifications should be required. In the current design, the fuel pellet clad (see Figure 1) operates at about 405 K when the outer surface is at about 320 K. In order to produce a reasonable efficiency the bulk of the heat must be forced to flow through a thermopile for conversion to electricity. This problem becomes increasingly severe as the power level decreases because the cross-sectional area of the thermopile decreases more rapidly than the surface area of the fuel pellet. Thus, it becomes increasingly difficult to force the heat to flow through the thermopile.

The thermal resistance of the insulation tube nest and end plugs will therefore have to be increased substantially compared to the current LWRHU design. This is not a fundamental problem, however, since a variety of low power level RTGs have already demonstrated satisfactory solutions to the thermal design problems, as discussed above. Moreover, the heat shield design can be retained entirely so safety concerns should be minimized.

Detailed designs, of course, depend on specific mission requirements but some possible options can be discussed here. Figure 2 shows the primary modification, which involves replacing one of the thermal insulation plugs with a thermopile integrated into a high thermal resistance package. It should be possible to increase the thermal resistance of the insulator tube nest and plug assemblies, for example, by modifying the number and geometry of the layers in the tube nest. If necessary, a metal foil (Mo, for example) insulation package could be developed to provide much higher thermal resistance values.

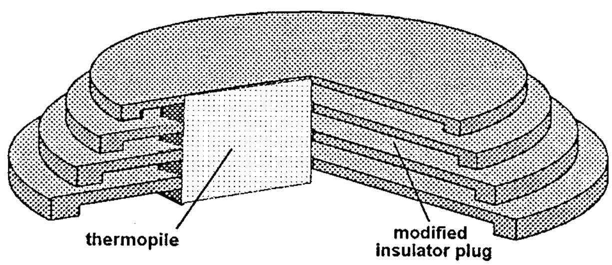

FIGURE 2. Modified Insulator Plug and Thermopile Assembly to Enable Power Generation From an RHU.

Finally, alternatives to the plutonium-238 (half-life of 87.8 years) radioisotope fuel should be considered, especially strontium-90 (half-life of 27.7 years) and even Cobalt-60 (half-life of 5.3 years), particularly for applications that may not require extremely long service life. Lifetime, cost, availability and radiation environment vary considerably depending on the primary isotopic fuel and these factors must be compared to mission requirements to ensure that the widest possible range of anticipated missions can be serviced.

In summary, several satisfactory options for heat source are available. The optimum choice requires better definition of possible mission requirements and then a more careful examination of the various trade-offs, but there can be little doubt about feasibility.

Thermopile Considerations

The following section discusses issues concerning thermopile materials, geometry and fabrication.

At first consideration, thermoelectric devices may seem ill-suited for low power applications because the voltage output of a single thermocouple is seldom more than a few tenths of a volt and often less than 0.1 V. DC-to-DC conversion efficiencies fall off rapidly at such small voltages and outputs in the range of 3-10 V are typically more desirable. Fortunately, thermoelectric technology offers many design options which can place 100 or more thermocouples in a single 'thermopile,' easily capable of providing the required voltages, even at low power levels.

While the output voltage of a thermoelectric device depends on the number of series-connected thermocouples in the device, the total electrical *power* output does not. The electrical power output depends on three factors:

- the heat input,
- the temperature range across the device, and
- the thermoelectric materials used to construct the device.

Thus, the power output and voltage output are essentially independent. The voltage can be any integral multiple of the voltage of a single couple assuming only that appropriate fabrication techniques are available.

For a given heat source the available thermal power is known, say about 1 W_{th} such as for the LWRHU. Quite generally, the efficiency and power output will increase with increasing temperature drop across the device. The upper operating temperature is then chosen a large as possible, consistent with materials limitations and appropriate safety margins. The lower operating temperature is typically determined by the available heat sink and for these low power RTGs can be expected to be less than 100 K. The choice of thermoelectric material, then, will essentially determine the operating temperature and power output of the device. There are three primary families of thermoelectric materials which are mature enough to be considered for the present application:

- silicon-germanium (SiGe) alloys, useful up to 1300 K,
- lead telluride (PbTe), useful up to about 900 K, and
- bismuth telluride (Bi_2Te_3), useful up to about 600 K.

Viable thermopiles have been built out of each of these materials and designs capable of 3-5% efficiency probably can be developed for each of the possible choices. Although other thermoelectric materials should be considered more carefully, bismuth telluride (Bi_2Te_3) appears to be the material of choice for use in a MIPS. General Atomics, for example, has built thermopiles from Bi_2Te_3 which deliver 115 mW_e to a load at 6 V with about 3% conversion efficiency. The thermopile consists of about 80 thermocouples, 1.5 cm long and about 0.058 cm by 0.058 cm cross-section. A similar thermopile built for cardiac pacemakers delivered 40 μW_e at 1 V using thermocouples 0.015 cm by 0.015 cm in size. Bismuth telluride-based thermopiles operate at lower temperatures, which makes design of the thermal insulation package easier due to the much lower contribution from radiation losses.

Lead telluride thermopiles operate at an intermediate range of temperatures and offer a slightly different mix of advantages. SiGe offers some advantages in terms of fabrication ease and allowing larger operating temperatures. Thermopiles suitable for producing power levels at least as low as about 15 mW_e at several volts should be possible using trivial variations on techniques now being developed at General Electric for use in the Modular-RTG (MOD-RTG), the next generation of RTGs suitable for Voyager-scale missions. The MOD-RTG multicouple technology is designed to operate at a hot side temperature of about 1325 K. Although the full mission life has not yet been demonstrated at the design conditions, by lowering the operating temperature to 1000-1100 K for the present applications, any concerns about lifetime are eliminated and the MOD-RTG multicouple technology can be considered as already demonstrated. 3-5% efficiency should be easily achievable with this either of these technologies.

Alternate fabrication techniques can also be considered. Sandia has built milliwatt RTG's using SiGe and thin-film techniques can conceivably be used to fabricate practically the entire thermopile, as shown schematically in Figure 3. If power levels well below 1 mW_e are required, reasonably efficient thermopiles can be fabricated using similar thin-film techniques, while still retaining reasonable voltages and efficiencies. Such a thermopile might measure about 1 cm by 1 cm by 0.005 cm and look something like a microchip, as suggested in Figure 3. For power levels above about 10 mW_e, conventional thermopile fabrication techniques are preferred, but at very low power levels the 'microchip thermopile' may become attractive.

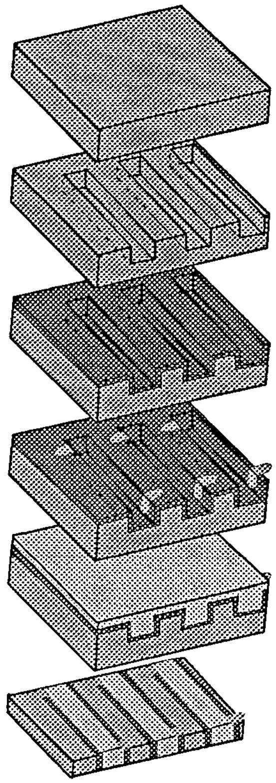

FIGURE 3. Schematic Method for Fabricating a Thin-Film SiGe Thermopile.

As with the heat source, there are several viable technology options for low power level thermopiles. The optimum choice requires only better definition of mission requirements and more detailed analysis of specific options.

CONCLUSIONS

A concept for a Milliwatt Isotope Power Source (MIPS) about the size of a D-cell battery has been described based on proven heat source and thermoelectric energy conversion technology. A MIPS could provide continuous milliwatt power levels for several decades or, coupled with a charging circuit and battery, power levels of a few watts on a regular basis for the lifetime of the available battery technology. The MIPS is thought to have a wide range of potential applications in areas such as microinstruments, microrovers and as a decentralized power source for conventional spacecraft.

Acknowledgments

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