RTG* OPTIONS FOR PLUTO FAST FLYBY MISSION

* Radioisotope Thermoelectric Generator

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**44th CONGRESS OF THE
INTERNATIONAL ASTRONAUTICAL FEDERATION**
October 16-22, 1993 / Graz, Austria

RADIOISOTOPE THERMOELECTRIC GENERATOR OPTIONS FOR PLUTO FAST FLYBY MISSION

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Abstract

A small spacecraft design for the Pluto Fast Flyby (PFF) mission is under study by the Jet Propulsion Laboratory (JPL) for the National Aeronautics and Space Administration (NASA), for a possible launch as early as 1998. JPL's 1992 baseline design calls for a power source able to furnish an energy output of 3963 kWh and a power output of 69 watts(e) at the end of the 9.2-year mission. Satisfying those demands is made difficult because NASA management has set a goal of reducing the spacecraft mass from a baseline value of 166 kg to ~110 kg, which implies a mass goal of less than 10 kg for the power source.

To support the ongoing NASA/JPL studies, the Department of Energy's Office of Special Applications (DOE/OSA) commissioned Fairchild Space to prepare and analyze conceptual designs of radioisotope power systems for the PFF mission. Thus far, a total of eight options employing essentially the same radioisotope heat source modules were designed and subjected to thermal, electrical, structural, and mass analyses by Fairchild. Five of these - employing thermoelectric converters - are described in the present paper, and three - employing free-piston Stirling converters - are described in the companion paper presented next.

The system masses of the thermoelectric options ranged from 19.3 kg to 10.2 kg. In general, the options requiring least development are the heaviest, and the lighter options require more development with greater programmatic risk.

INTRODUCTION

The planet Pluto and its large moon Charon orbit the sun with a period of 248 years, at distances of 30 to 50 Astronomical Units. Its remoteness from the Earth has impeded efforts to obtain clear images with even the best telescopes, and is the reason why it is the only planet in the solar system not yet explored by spacecraft. As a result, there is great interest in the scientific community in taking a closer look at Pluto, Charon, and Pluto's atmosphere by means of a spacecraft reconnaissance.

That interest is made more urgent by the imminent collapse of the planet's atmosphere. Pluto recently passed its perihelion and will not do so again until the year 2237. Because of extreme cold as the planet recedes from the Sun, its atmosphere will undergo condensation in the decade from 2010 to 2020. Until then we have a unique opportunity to study the atmosphere's chemistry, dynamics, hydrodynamic and solar wind interactions. To take advantage of that opportunity, which won't recur for over 200 years, JPL has been studying a Pluto Fast Flyby (PFF) mission for NASA [Stern 1993, Staehle et al. 1992a, and Staehle et al. 1992b]. As its name implies, the mission contemplates a spacecraft to "fly by" the planet rather than to orbit or land on it. This simplification permits major size, mass, and cost reductions, and greatly shortens the time for development of the spacecraft and for transit to Pluto, allowing arrival before atmospheric collapse. JPL is considering two spacecraft to be launched in the 1998-2000 time frame and arriving at Pluto after an eight-year direct flight (no gravity assist). The data recorded during the brief Pluto flyby would then be transmitted to Earth at the rate of eight hours per day, during a one-year post-encounter cruise.

The spacecraft size reduction made possible by this option is illustrated in Figure 1, which compares the size of an early (1992) JPL baseline design for PFF with the much larger spacecraft of preceding interplanetary missions (Voyager, Galileo, Cassini). That PFF baseline design had an estimated mass (including propellant) of 165 kg, but this was rejected by NASA which gave JPL a goal of reducing the spacecraft mass to about 100 kg.

Fig. 1 Comparative Size of PFF and Prior Spacecraft.

JPL's 1992 baseline design assumed an RTG power source to meet the power demand schedule summarized in Table 1. As can be seen, the controlling mission phase is the post-encounter down-link. Including 20% for contingencies plus 10% margin, it requires 69 watts(e) at the end of 9.2 years. The table shows a total energy demand of 3963 kWh for the mission.

Table 1 JPL's 1992 Baseline Power Demand Schedule for PFF.

Phase Duration (years)	Pre-Encounter 2.0		Encounter 0.05	Post-Encounter 1.0	
Activity Fraction of Phase Time	1. Cruise 0.952	2. Downlink 0.048	7. Downlink 0.67	8. Downlink 0.33	9. Cruise 0.67
Power (Watts):					
Telecom					
Transponder (x15V)	10.0	11.0	10.0	11.0	10.0
TCU (x15V)	5.0	5.0	5.0	5.0	5.0
Amplifier (8V)	—	12.0	—	12.0	—
Power					
Shunt Regulator (5V)	1.0	1.0	1.0	1.0	1.0
Power Converter	7.5	10.7	10.7	10.5	7.2
Power Control (28V)	1.0	1.0	1.0	1.0	1.0
Attitude Control (15V)	5.4	5.4	11.5	5.4	5.4
Computer (5V)	4.5	4.5	5.0	4.5	4.5
Memory (12V)	0.5	0.5	0.5	0.5	0.5
Propulsion (28V)	0.5	0.5	1.5	0.5	0.5
Thermal (10/28V)	1.0	1.0	1.0	1.0	1.0
Science (10/28V)	1.0	1.0	6.0	—	—
Total	37.3	53.6	33.7	52.3	35.1
Incl. 20% contingency	44.8	64.3	64.4	62.8	43.3
Incl. 20% contingency +10% margin	49.3	70.7	70.8	69.1	47.6
Average Power, W	49.4		47.4	54.8	
Energy Demand, kWh	3450		33	480	

There has been a lot of interest in exploring the possibility of performing the mission without radioisotopes. One specific proposal called for powering the spacecraft with an 8 kg primary lithium battery having an energy density of 0.42 kWh/kg. But the resultant energy output of 2.72 kWh would represent a reduction of 99.93% from the 3963 kWh postulated in JPL's 1992 baseline plan.

Even if one made the optimistic assumption that all of the pre-encounter energy demand could be eliminated by operating the spacecraft in a dormant (inactive) mode and that reliable startup after an eight-year cold coast could be achieved, that would still leave the energy required for the post-encounter down-link which cannot be reduced by transmitting faster at a higher power rate. Transmitting a given set of data takes the same energy, whether done fast or slow.

As shown in Table 1, the post-encounter down-link alone, even if everything else were zeroed out, would require an energy of 202 kWh. Thus, even under these very optimistic assumptions, adoption of the proposed lithium battery option would require a reduction of about two orders of magnitude in the amount of science data returned to Earth. Conversely, supplying 202 kWh with a lithium battery would require a battery mass of 480 kg, which greatly exceeds the allowable spacecraft mass.

The only small power system alternatives with high energy-to-mass ratios are solar and radioisotope systems. But at a distance of 30 A.U. or more, the incident solar-flux is at least three orders of magnitude lower than at Earth, necessitating very large solar arrays. In fact, it is unclear whether current solar arrays would function at Pluto at all, because of still unsolved Low-Intensity, Low-Temperature (LILT) effects on solar arrays. Thus, the PFF mission is likely to require the use of radioisotope power sources in spite of their higher cost and more complex launch approval requirements.

One possible way of significantly reducing the cost and mass of radioisotope power systems is to couple the isotope source to converters that are more efficient than the thermoelectric uncouples used in present RTGs. The difficulty of NASA's prescribed mass reduction goal is illustrated in Table 2, which presents the mass assumptions of JPL's 1992 baseline design and its subsequent revised mass goals.

Table 2 JPL Mass Assumptions (kg).

	Baseline	Goals	Δ
Spacecraft (Wet)	164.1	112.4	31%
Power System	23.5	12.5	47%
Shunt Regulator	1.0		
Discharge Controller	1.2		
Power Distribution	1.5		
Power Controller	0.5		
Power Converter	0.6		
Pyro Switching Unit	0.8		
Radioisotope Power Source	17.8	9.5 (5.8)	47% (62%)

As shown, these goals call for a reduction of 31% in spacecraft weight and 47% in power system weight. The baseline assumption of 23.5 kg for the power system included 5.7 kg for various power processing components, leaving 17.8 kg for the radioisotope power source. Assuming, for want of better information, that the prescribed 47% mass reduction applies equally to the power source and the power processing components would leave less than 10 kg as the revised mass goal for the radioisotope power source.

To support NASA and JPL, the Department of Energy's Office of Special Applications commissioned Fairchild Space and Defense Corporation to prepare conceptual designs for a variety of PFF power source options, to help clarify the available options and to provide reliable mass estimates and technology status assessments. The study results are designed to support informed trade-off decisions by program management. Eight options have been designed and analyzed thus far: five thermoelectric and three Stirling systems. The thermoelectric options are described in the present paper, and the Stirling options are described in the next paper presented [Schock 1993]. Additional studies of thermophotovoltaic and AMTEC options are planned in the future.

RADIOISOTOPE HEAT SOURCE

All five of the thermoelectric options analyzed by Fairchild are based on the General Purpose Heat Source (GPHS) modules [Schock 1980]. These are the same modules that were used in the RTGs flown on the Galileo and Ulysses missions after very extensive safety analyses and tests and after passing stringent safety reviews, and that are slated for launch on the upcoming Cassini mission.

*Fine-Weave Pierced Fabric, a 90%-dense 3D carbon-carbon composite
 **Carbon-Bonded Carbon Fibers, a 10%-dense high-temperature insulator
 ***62.5-watt $^{238}\text{PuO}_2$ pellet

Fig. 2 General-Purpose Heat Source Module (250 Watt)

As shown in Figure 2, each GPHS module has a maximum thermal power of 250 watts, and contains four $^{238}\text{PuO}_2$ fuel pellets encapsulated in iridium-alloy clads designed to contain or immobilize the fuel in case of accidents before, during, and after launch. The remaining module components are graphitic and are designed to protect the integrity of the iridium clads. There are two impact shells and one aeroshell made of fine-weave pierced fabric (FWPF), a very tough high-temperature material. There are two fuel capsules per impact shell and two impact shells per aeroshell. The impact shells help to prevent breach of the clads during impact, and the aeroshell serves as an ablator in case of inadvertent atmospheric reentry. Between the impact shells and the aeroshell is a high-temperature thermal insulator consisting of carbon-bonded carbon fibers (CBCF), to prevent overheating of the clads during the reentry heat pulse and overcooling and embrittlement of the clads during the subsequent subsonic atmospheric descent before earth impact.

THERMOELECTRIC UNICOUPLS

Of the five thermoelectric options studied, two employed unicouples and three used multicouples. The unicumple designs are identical to those used in RTGs flown on the LES 8/9, Voyager, Galileo, and Ulysses missions and slated for launch on the Cassini mission. These unicouples have demonstrated exceptional reliability and endurance. They have operated in space for up to 17 years, always far beyond their original design goal.

Fig. 3 Unicumple

As shown in Figure 3, each unicumple contains an n-doped and a p-doped SiGe leg, which are joined together by a SiMo hot-shoe to form the couple. The hot-shoe also serves as a heat collector to concentrate the heat which the heat source radiates across a

vacuum gap. There is no contact between the heat source and the thermoelectric couples. The cold ends of the thermoelectric legs are bonded to electrical and thermal conductors and to mechanical mounting hardware. The gap between the two legs is filled with quartz fibers, and their periphery is wrapped with quartz yarn.

UNICOUPLE RTG OPTION-1

The PFF Unicouple RTG designs are derivatives of the GPHS/RTGs used on the Galileo, Ulysses, and Cassini missions [Schock and Sookiazian 1979, Schock et al. 1991, and Hemler et al. 1993]. As shown in Figure 4, the GPHS/RTG contains a central stack of 18 GPHS modules, radiating their heat to a surrounding array of 572 SiGe unicouples that are embedded in a thermal insulation assembly consisting of 60 alternating layers of molybdenum foil and quartz cloth. The unicouples' cold ends are bolted to the inside of an aluminum RTG housing with eight radiator fins. The cold ends of the cantilevered unicouples are interconnected in two 143 x 2 series-parallel networks within the RTG housing.

Fig. 4 GPHS RTG

The stack of 18 heat source modules in the GPHS/RTG has a single set of four lateral supports at its midplane. There are no other lateral supports. The stack is primarily held together against lateral launch loads by large compressive preload forces applied to the end modules [Schock 1979]. The preload is applied by four spring-loaded support studs, one at each corner of each end module.

The first Unicouple RTG Option examined for PFF is essentially a shortened version of the GPHS/RTG. It was found that the 69-watt EOM power demand shown in Table 1 could be satisfied with 5 instead of 18 heat source modules and with 160 instead of 572 unicouples. The shortened heat source stack permitted elimination of the mid-span supports. The resultant RTG design is shown in Figure 5. Detailed mass analysis yielded an RTG mass of 19.3 kg, which is even higher than JPL's baseline estimate of 17.8 kg, and is far above the 9.5 kg design goal.

Fig. 5 Unicouple RTG Option 1

UNICOUPLE RTG OPTION-2

The second Unicouple RTG Option examined in the Fairchild study uses the same number of heat source modules and uncouples as the first option. It differs primarily in the design of the heat source support structure. It assumes one instead of four support studs at each end of the heat source stack, and employs a simpler and lighter spring load mechanism. The resultant RTG design is shown in horizontal cross-section in Figure 6 and in vertical cross-section in Figure 7.

Fig. 6 Unicouple RTG Option 2, Section BB.

Fig. 7 Unicouple RTG Option 2, Section AA.

The two figures also show typical BOM operating temperatures. The two critical temperatures are the iridium clad temperature, which must be below 1330 °C to avoid excessive grain growth, and the uncouple's hot-junction temperature, which was limited to 1000°C in previous flight units. As can be seen, neither of these limits is exceeded by the design.

Analysis of the Option-2 design depicted in Figures 6 and 7 yielded a mass of 15.4 kg compared to 19.3 kg for Option-1. This is a significant step in the right direction, but a detailed structural analysis is required to confirm that the five-module heat source stack will in fact stay together under lateral launch loads with only a single support stud at each end. The reason for the uncertainty is that a single stud acts more like a simple support whereas a quadruple stud acts more like a fixed support of the heat source ends.

To address this uncertainty, a detailed NASTRAN model was constructed and analyzed, with the results depicted in Figures 8 and 9. Taking advantage of symmetry about the heat source's midplane, the model consisted of 2.5 aeroshells plus a graphite load plate and an inconel support stud. The masses of the fuel capsules and impact shells were included in computing the inertial side loads, but their structural contributions were ignored. To be conservative, all loads were assumed to be carried by the FWPF aeroshells.

Fig. 8 Normal Z-Stresses (in psi) and Deformations of Heat Source and Support Elements Under 750-lb Axial Load and 40-G Side Load.

In the structural analysis, the heat source was subjected to a 40-G side load, which is a conservative assumption based on previous RTG flight systems and assumes that the qual test would be 50% above expected flight levels. With that side load, it was found that the stack would stay together with a 750-lb axial preload applied through a single stud. This is demonstrated in Figure 8, which shows the normal z-stresses in the aeroshells. Since the 40-G side load was applied in the -y direction, the critical results are the module interface stresses on the stack's y-face. As can be seen, these are all negative (compressive). Therefore, the stack will stay together under the assumed conditions.

Fig. 9 Von-Mises Stress (in psi) and Deformations of Heat Sources and Support Elements Under 750 lb Axial Load and 40-G Side Load.

Figure 9 shows the computed von-Mises stresses under the same conditions. As can be seen, all graphitic von-Mises stresses are well within the 3-ksi strength limit of FWPF graphite. Only the much stronger Inconel stud has stresses above 2 ksi.

THERMAL AND ELECTRICAL ANALYSIS

The next step in the study was to perform a thermal and electrical analysis of the RTG. These analyses must be performed in a coupled manner, since temperatures affect electrical performance while electrical currents affect temperatures because of Peltier cooling. Methods for performing the coupled analysis in an integrated manner have been described in earlier publications by the author [Schock et al. 1990]. The coupled analysis calculates the current, voltage, and power output of each uncouple in the RTG's series/parallel network.

Parenthetically, it should be noted that the thermal-analysis model used in the study included the effect of the spacecraft and antenna in obstructing the RTGs view of space (see Figure 1). That effect was found to be small, and should be even smaller in JPL's recently revised designs where the antenna has been moved to the bottom of the spacecraft and the RTG has been moved from the side to the top of the spacecraft.

Figure 10 shows the effect of RTG voltage on the BOM power output of the Option-2 Uncouple RTG, for thermal powers ranging from 225 to 250 watts per heat source module. As can be seen, the output power maximizes at an RTG voltage of about 19 volts. But the optimum is quite broad. In fact, the RTG could actually produce 28 volts if desired, but then it would not meet the EOM power goal.

Fig. 10 Effect of Voltage and Thermal Power on BOM Power Output of Uncouple RTG (Option 2).

Fig. 11 Effect of Voltage and Thermal Power on BOM Hot-Junction Temperature (Unicouple RTG Option 2).

Figure 11 shows the effect of RTG voltage and thermal power on the maximum hot-junction temperature at BOM. Increasing the RTG's voltage decreases its current and therefore its Peltier cooling rate, which raises the hot-junction temperatures for a fixed design. Note that at the optimum voltage (19V) all the hot-junction temperatures - even for the highest thermal power - are below 1000°C, the established experience base. For high voltages and high thermal powers the hot-junction temperature does exceed 1000°C, but that can be mitigated by employing longer radiator fins.

Fig. 12 Effect of Voltage and Radiator Fin Length on BOM Performance of Unicouple RTG, Option 2.

As shown in Figure 12, increasing the fin length from 7.5 to 12.5 cm lowers the hot-junction temperature by 14°C. This would have virtually no effect on the RTG's BOM power output, since the difference between hot- and cold-junction temperature remains essentially unchanged. However, it would raise its EOM power, because of slower thermoelectric degradation at reduced hot-junction temperatures, but probably not enough to justify the additional mass of the longer fins.

Fig. 13 Effect of BOM Thermal Power on EOM Output of Unicouple RTG, Option 2.

The effect of thermoelectric degradation and isotope decay on the power output of the RTG were computed using analytical techniques previously described by the author [Schock 1991a]. The results for an RTG with 7.5-cm fins are displayed in Figure 13. As can be seen, the 69-watt(e) goal at the end of the 9.2-year mission can only be met with the maximum BOM thermal power of 250 watts per GPHS module. But the fuel in the present U.S. inventory, which has been decaying since shutdown of Pu-238 production in 1983, is limited to 238 watts per module. However, the thermal power goal can be met with the higher-enrichment Russian fuel slated for delivery to the U.S. in time for the PFF mission. Even if the Russian fuel were not available, the EOM power goal can probably be achieved by retarding the thermoelectric degradation by lowering the RTG's hot-junction temperature during the eight-year cruise phase. This temperature reduction could be accomplished by lowering the RTG voltage during periods of low power demand, thereby increasing the output current and Peltier cooling rate [Schock 1991b and Schock 1992].

THERMOELECTRIC MULTICOUPLES

The remaining three thermoelectric options discussed in this paper are based on multicouples instead of unicouples. The Multicouple RTG designs are derivatives of the Modular Isotopic Thermoelectric Generator (MITG) design first proposed in 1981 [Schock 1981, Schock 1983a and Schock 1983b]. As shown in Figure 14, each multicouple has 40 thermoelectric legs instead of two. These are bonded to 20 SiMo hot-shoes and 21 W cold-shoes to form the multicouple's series-connected thermopile. The thermopile's hot end is glass-bonded to a ~5 cm-square graphite heat collector. Its cold end is glass-bonded to a graphite compliance pad which is brazed to a tungsten cold-stud used to bolt the multicouple to the RTG housing. The purpose of the low-modulus graphite is to avoid excessive stresses due to differences in thermal expansion coefficients.

Fig. 14 Multicouple (~2.1 Watt, 3.5 Volt).

As shown, each multicouple's power leads are at the center of its thermopile, and emerge through the tungsten cold-stud to the outside of the RTG. This may permit tapping off different output voltages from the same RTG, which could allow elimination of DC-to-DC converters with their large power loss (13.8 watts). Since each multicouple contains 20 series-connected unicouples, its optimum output voltage is ~3.5 volts instead of the uncouple's 0.18 volts. Each heat source module radiates its heat to eight multicouples instead of 32 unicouples, which reduces the number of thermoelectric devices by 75%. If connected in series, the eight multicouples surrounding each heat source module produce 28 volts, making possible a scalable modular RTG design.

The multicouples are embedded in 0.75 cm-thick thermal insulation consisting of 60 layers of 0.00075-cm Mo foils separated by ZrO_2 particles. This compares with the 2 cm-thick thermal insulation employing quartz cloth separators that are used in uncouple RTGs. The thinner insulation package significantly reduces the mass of the insulation and of the housing of the Multicouple RTG.

Multicouples have been under development for about ten years under DOE's Modular RTG program [Kelly et al. 1993], but they are still not as mature as unicouples. A typical test arrangement of a prototypic RTG module is depicted in Figure 15.

Fig. 15 8-Multicouple Test Assembly in Prototypic Generator Configuration.

Development tests have experienced major delays due to anomalous negative-bias effects. Those effects were subsequently shown to be caused by avoidable contaminants in the test assembly (such as, in electrical heaters) and not due to inherent flaws in the multicouple design. The latest multicouple tests have operated successfully for over 15,000 hours under negative bias, but have exhibited degradation rates that were twice as high as those of previously flown unicouples. (See Figure 16.) The higher degradation has been attributed to dopant diffusion from the hot-shoes into the p-legs. This problem is believed to be fixable and a program to demonstrate the fix has been negotiated, but is presently unfunded for budgetary reasons.

Fig. 16 Typical Multicouple Degradation Rate (Build-3, MC-7).

MULTICUPLE RTG OPTIONS

The first PFF Multicouple RTG Option is depicted in vertical cross-section in Figure 17 and in horizontal cross-section in Figure 18. This is a derivative of the MOD/RTG design [General Electric Company 1991], with five standard heat source modules supported by a single stud at each end of the stack (like in the Unicouple RTG Option-2), with forty multicouples mounted on the inside of a cylindrical aluminum housing with eight 7.5-cm fins.

Fig. 17 Multicouple RTG Option 1, Section AA.

Fig. 18 Multicouple RTG Option 1, Section BB.

The temperatures shown are for a thermal power of 250 watts per heat source module. As can be seen, the iridium clad and the hot-junction temperatures are both within their prescribed limits. The RTG has a mass of 13.4 kg compared to 19.3 kg and 15.4 kg for Unicouple Options 1 and 2.

Multicouple RTG Option-2 is a derivative of Fairchild's 1981 MITG design [Schock 1981]. Like the preceding design, it has five heat source modules, a single support stud at each end of the heat source, and 40 multicouples. As shown in Figures 19 and 20, its chief differences from Option 1 are the shape of the RTG housing and insulation package (square versus round), a lower-density housing material (Be or Mg versus Al), a lighter and more conductive radiator material (carbon-carbon versus aluminum), and fewer radiator fins (4 versus 8).

Fig. 19 Multicouple RTG Option 2, Section BB.

Fig. 20 Multicouple RTG Option 2, Section AA.

These differences resulted in a more compact and lighter design (12.2 kg versus 13.4 kg for the same number of heat source modules). The temperatures shown in the two figures are for a thermal power of 250 watts per GPHS module.

The Multicouple RTG designs were subjected to the same coupled thermal and electrical analyses as those described earlier for the Unicouple RTGs. The Multicouple RTGs were analyzed both for standard thermoelectric materials and for improved materials. The standard materials, which are representative of multicouples that have been extensively life-tested, have a figure-of-merit Z of $0.66 \times 10^{-3} \text{ K}^{-1}$. The improved material, which have a much smaller data base, have a Z of $0.70 \times 10^{-3} \text{ K}^{-1}$. Improved SiGe materials that exhibited substantially higher figures of merit have been made [Caillat et al. 1993], but their reproducibility has not yet been demonstrated and they were not used in our system studies.

The BOM performance of Unicouple RTGs ($Z = 0.58 \times 10^{-3} \text{ K}^{-1}$) and Multicouple RTGs is compared in Figure 21, which shows the effect of RTG voltage on BOM power for five 250-watt heat source modules. As shown, the BOM power maximizes at ~19 volts for Unicouple RTGs and ~30 volts for Multicouple RTGs. The maximum BOM power gain of the Multicouple RTG over the Unicouple RTG is 3 watts for standard materials and 8 watts for improved materials. But the chief advantage of the Multicouple RTG is that, for the same thermal power, it is 3.2 kg lighter than the Unicouple RTG.

Fig. 21 Comparative BOM Power of Unicouple RTG and of Multicouple RTG with Standard and Improved T/E Materials.

Fig. 22 Effect of Improved T/E Materials and Degradation Rate on EOM Power of Multicouple RTG.

As mentioned earlier, multicouples have exhibited twice the degradation rate of uncouples. While this problem is believed to be fixable, the program to demonstrate a fix is currently unfunded. The effect of degradation rate and of material properties on EOM power is illustrated in Figure 22. As can be seen, with the doubled degradation rate and the standard thermoelectric material the Multicouple RTG would fall 4 watts(e) short of meeting the desired 10% margin for the EOM power goal. But that goal could be met or exceeded either by the use of the improved materials or by lowering the multicouple degradation rate to that of uncouples.

Finally, the third Multicouple RTG Option is identical to the Option 2 design, except that the number of heat source modules is reduced from 5 to 4 and the number of multicouples is reduced from 40 to 32. These reductions may be possible because each multicouple's terminals are on the outside of the RTG housing. This permits more options in how the 3.5-volt multicouples are interconnected, and makes it possible to generate several different output voltages from the same RTG, to match the desired load voltages. This may enable elimination of the DC-to-DC converter, which is a major power consumer. As was shown in Table 1, the power converter consumes 10.5 watts(e), which corresponds to 13.9 watts(e) with the 20%

contingency allowance and the 10% margin. Thus, its elimination would reduce the critical power requirements from 69 watts to 55 watts(e), a reduction of 20% which exactly matches the reduction from 5 to 4 heat source modules. If feasible, this would shorten the RTG from 38 to 33 cm, and would reduce its mass from 12.2 kg to 10.2 kg.

CONCLUSION

While Multicouple RTG Options-1 and-2 are significantly lighter than the baseline RTG, Option-3 is the only one that almost meets NASA's PFF mass goal. Unfortunately, it is also the option requiring the greatest development effort and entailing the greatest programmatic risk. Uncouple RTG Option-2 would be much less risky, but its mass of 15.4 kg would require a slightly longer transit time to Pluto.

Further mass and cost reductions require departures from mature but inefficient thermoelectric converters and substitution of much more efficient advanced technologies, like Stirling engines, thermophotovoltaic systems, or AMTEC. Detailed system options based on free-piston Stirling engines are described in the next paper [Schock 1993], and future studies will examine radioisotope power system designs based on other conversion technologies.

Acknowledgments

The author takes pleasure in acknowledging the many valuable contributions to the above work of his Fairchild colleagues K. Sankarankandath (mechanical design), G. Summers and K. Iman (structural analysis), and T. Or and H. Noravian (thermal and electrical analysis), and the support of the Department of Energy's Office of Special Applications (R. Lange, Director).

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