FAIRCHILD
S P A C E

IECEC#910469

**UNIFORM FIN SIZES VERSUS UNIFORM FIN ROOT TEMPERATURES
FOR UNSYMMETRICALLY OBSTRUCTED SOLAR PROBE RTGs**

**Alfred Schock, Chuen Or, and Heros Noravian
Fairchild Space Company
20301 Century Blvd.
Germantown, MD 20874
(301) 428-6272**

**For presentation at the
26th Intersociety Energy Conversion Engineering Conference
Boston, Massachusetts
August 4-9, 1991**

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

UNIFORM FIN SIZES VERSUS UNIFORM FIN ROOT TEMPERATURES FOR UNSYMMETRICALLY OBSTRUCTED SOLAR PROBE RTGs

A. Schock, C. Or, and H. Noravian
Fairchild Space
20301 Century Blvd.
Germantown, Maryland 20874
(301) 428-6272

ABSTRACT

The Solar Probe will approach the sun within four solar radii or 0.02 AU. Because of that proximity, the spacecraft must be protected by a thermal shield. The protected umbra is a cone of 4 m diameter and 7.5 m height, and all temperature-sensitive flight components must fit within that cone. Therefore, the RTGs which power the Solar Probe cannot be separated from each other and from other payload components by deploying them on long booms, as was done on previous missions. Instead, the RTGs must be located near and thermally isolated from the spacecraft's payload. As a result, only about half of each RTG's circumference has a direct view of space. The other half is cooled indirectly, by means of a semi-cylindrical reflector. For a standard RTG design with uniform radiator fins, the unsymmetrical reflectors result in significant circumferential variations in the thermocouples' cold-junction temperatures, voltages, and currents. This can be avoided by varying the dimensions of the radiator fins, so as to produce a uniform set of fin root temperatures. The paper compares the performance of such variable-fin RTGs with that of uniform-fin RTGs. It derives the fin dimensions required for circumferential isothermicity, identifies a design that maximizes the RTG's specific power, and proves the practicality of that design option. However, detailed thermal and electrical analyses led to the somewhat surprising conclusion that (for a given thermal power) the nonuniform-fin design results in the same power output, at a higher maximum hot-junction temperature, as the standard uniform-fin design, despite the latter's nonuniform cold-junction temperatures.

INTRODUCTION

The paper deals with the integration of Radioisotope Thermoelectric Generators (RTGs) with the spacecraft for the Solar Probe mission under study at NASA's Jet Propulsion Laboratory (JPL). In response to a request for assistance from NASA and JPL, the US Department of Energy's Office of Special Applications commissioned Fairchild Space and Defense Corporation to carry out an RTG design study for that mission.

The Solar Probe mission [1] is designed to explore and resolve the fundamental nature of the solar corona. To do so, the probe will perform in-situ measurements at distances as close as four solar radii or 0.02 AU from the sun. The region of the inner heliosphere, from 4 to 65 solar radii, remains the last major unprobed region of our solar system. Its exploration is crucial for understanding the physics of the solar corona and of many fundamental astrophysical processes. In-situ measurements are needed because of the proximity of the low-brightness corona to the much brighter photosphere. Scientific objectives of the Solar Probe mission include measurement of the density, velocity, and composition of the thermal solar wind plasma, and of the magnetic fields, plasma waves, and energetic particles present in this unexplored region of the heliosphere.

To make it possible to reach a perihelion of 0.02 AU with available boosters, it is planned to employ gravity-assist flybys of both the Earth and Jupiter. The Jupiter gravity assist will also be used to lift the spacecraft out of the ecliptic plane into a polar orbit of the sun, as illustrated in Figure 1. The figure depicts an early JPL-generated mission plan calling for a 1998 launch and two solar flybys, the first in 2003 and the second in 2007. In more recent plans, these dates are delayed by about three years, but the general mission profile is otherwise unchanged.

Figure 1. Solar Probe Trajectory and Schedule

POWER SYSTEM

JPL specified a power output of at least 430 watts(e), not just at solar encounter but throughout the 9-year mission, since scientific observations will be made throughout the mission, not just near the two perihelia.

The JPL study team concluded that the mission does not lend itself to solar power, because the solar distance varies from 5 AU at Jupiter to 0.02 AU at perihelion, so that the solar intensity varies by a factor of 62,500. Therefore, they have baselined the use of RTGs for powering the spacecraft. RTGs in this power range have operated reliably for very long periods on previous space missions, such as the Voyager mission to Neptune and beyond.

The Fairchild study concluded that the Solar Probe power requirements can be met by two RTGs adapted either from the uncouple-based GPHS-RTG design [2] used for the recently launched Galileo mission or from the more advanced multicouple-based Mod-RTG design [3] under development by DOE. The Mod-RTG would yield a lighter and more compact system, but the GPHS-RTG is a very mature design that has been performance-proven and safety-qualified in extended ground and flight tests. Therefore, the GPHS-RTG design was selected for illustrative purposes in the present paper. However, the spacecraft integration concept and analytical approach described would be equally adaptable to the Mod-RTG option.

Figure 2. GPHS RTG

The 1.15 m-long GPHS-RTG is depicted in Figure 2. It contains a central heat source consisting of a stack of 18 General Purpose Heat Source modules [4]. The heat generated by isotope decay is radiated to an array of 576 thermoelectric uncouples, which are bolted to the RTG's cylindrical housing. The uncouples convert part of the heat to electricity, and reject the balance to the finned RTG housing, for radiation to space.

PRINCIPAL DESIGN PROBLEM

The primary difference between the Solar Probe RTGs and previous RTGs relate to their thermal environment. At the 0.02 AU perihelion, the solar intensity is 2500 times as high as in earth orbit. To prevent overheating, the spacecraft will be protected by a conical graphite shield of 4-meter base diameter and 7-meter height, as illustrated in Figure 3. Because of the spacecraft's proximity to the sun, the sun subtends an angle of about 30 degrees, so that its rays are far from parallel. As a result, the protected region behind the 4-meter-diameter heat shield is not a cylinder but a cone that is only 7.5 m long. All the other spacecraft components, including payload appendages and RTG radiators, must fit within the limited volume of that conical umbra.

Figure 3. JPL's Solar Probe Design Concept

RTGs have relatively low efficiencies, and most of their thermal power ends up as waste heat, to be radiated to space. Most previous RTGs have had an essentially unobstructed view of space. But that is not possible in the Solar Probe. Since everything must be located within the conical umbra, the large solar shield and the payload are necessarily close enough to the RTGs to obstruct their radiators. Moreover, a thermal shield is required between the RTGs and the

temperature-sensitive payload, particularly during the first two years of the mission, before the science platform is deployed. Therefore, the solar shield and the payload shield cause severe blockage of the RTGs' view of space. Coping with the heat rejection problem is the major challenge to the Solar Probe's RTG designer and system integrator, and is the principal focus of this paper.

HEATPIPE-COOLED RTG

One method of uniformly cooling the obstructed RTGs would be by wrapping heatpipes around each RTG's cylindrical housing to deliver the waste heat to a planar, one-sided radiator. This option largely decouples the RTG geometry from the radiator geometry. It would result in uniform cold-junction temperatures and essentially isothermal radiators. Because heatpipe radiators are much lighter than conductive radiators, they would optimize at substantially lower heat rejection temperatures and higher conversion efficiencies than conductive radiators.

However, these advantages are offset by the fact that in the temperature range of interest the experimental data base on heatpipes is quite limited and very poorly documented. The most successful test the author is aware of was a test of a copper/water heatpipe that ran for 16,000 hours at 190°C. Performance was stable, but post-test destructive examination revealed internal discoloration, which may be a harbinger of future problems.

Another drawback to the use of copper-water heatpipes (in contrast to alkali metal heatpipes) is that their operation is very sensitive to adverse gravitational effects. Depending on their orientation, this may preclude their operation before and during launch, which would necessitate use of an auxiliary cooling loop. Because of these drawbacks, a heat rejection scheme that does not require heatpipes is considered preferable, provided it does not result in excessive performance penalty.

REFLECTOR-COOLED RTG

One way of cooling obstructed RTGs without heatpipes is to use a semi-cylindrical or parabolic thermal reflector around the inward-facing side of each RTG. For the standard GPHS-RTGs that were launched on the Galileo and Ulysses mission and will be used on the CRAF/Cassini missions, this is illustrated in Figure 4 for two different reflector radii.

Two RTG orientations were investigated. In the horizontal orientation, illustrated in Figure 5, the two RTGs lie in a plane perpendicular to the spacecraft axis, just behind the heat shield; and in the oblique orientation, illustrated in Figure 6, the RTGs' long axes point at the deployed science platform to minimize the radiation flux at that location, by maximizing self-shielding of the RTGs. The radiation doses at the payload's science platform for the two orientations were

Figure 4. Semi-Cylindrical Reflector Options

analyzed, based on measured neutron and gamma dose rates at various radial and axial distances from the GPHS-RTG. The results of the analysis indicated that the oblique RTG orientation gives somewhat lower doses at the platform, but the difference is not large enough to be decisive. Either orientation appears to be acceptable, and the subsequent analyses apply to either one.

Figure 5. Reflector-Cooled RTG, Horizontal Option

Figure 6. Reflector-Cooled RTG, Oblique Option

There are, in general, two options for coping with the RTGs' obstructed heat rejection paths illustrated in Figures 5 and 6. One is to employ uniform, symmetrical RTGs and accept the resultant performance loss due to circumferential non-uniformity in uncouple temperatures, voltages and currents. The other is to vary the RTGs' fin dimensions so as to produce uniform uncouple temperatures, voltages and currents. This paper analyzes the two options, to determine which yields the higher specific power.

PRELIMINARY SCOPING STUDIES

To scope the problem, the analysis first applied a simplified model to the uniform-fin case illustrated in Figure 4. The simplified model confined its attention to the RTG housing, fins, and reflector. It assumed uniform heat input to the inside of the cylindrical RTG housing, and employed a two-dimensional $R\theta$ model of the finned RTG housing and the reflector. The RTG had eight fins of trapezoidal cross-section, with 0.060" fin roots, 0.015" fin tips, and 3" root-to-tip lengths. Detailed radiation-interchange analyses accounting for multiple reflections between the RTG housing, fins, and reflector were performed.

A range of reflector radii and emissivities was analyzed, with the results shown in Tables 1 through 3. Table 1 shows the effect of a semi-cylindrical reflector with a 10-inch radius and an emissivity of 0.85 on the temperature of the GPHS-RTG housing. As shown in

the table's right column, the obstructing reflector significantly increases the RTG housing temperatures. For a fixed RTG design, such a large increase in cold-junction temperatures would result in an unacceptable increase in the RTG's hot-junction temperatures and degradation rate. This could be avoided by lowering the fuel loading or by increasing the thermoelectric leg areas, but that would result in a substantial decrease in RTG efficiency and power.

Table 1. Effect of Obstruction by 10"-Radius Reflector on Housing Temperatures of Standard GPHS RTG

	Unobstructed RTG	Reflected RTG	ΔT
RTG Housing Temperatures, °C:			
Max.	264	382	118
Min.	264	307	43
ΔT	0	75	

In addition, the table's bottom line shows a circumferential temperature variation of 75°C, which implies a corresponding variation in optimum couple voltage and current. But all thermoelectric couples in parallel groups must produce the same output voltage, and all groups in series must deliver the same current. Therefore, most of the couples must necessarily operate off-optimum. Thus, a large temperature variation leads to additional degradation of the RTG's efficiency. Clearly, it would be desirable to reduce the circumferential temperature variation of the obstructed RTG.

One possible way of achieving this is to increase the radius of the semi-cylindrical reflector. Table 2 shows the effect of reflector radius on the RTG housing temperature. Radii of 10, 15, and 25 inches were analyzed. The results show that larger reflector radii do indeed yield significantly lower and more uniform cold-junction temperatures, and therefore higher conversion efficiencies. But very large reflector radii would be more difficult or impossible to accommodate in the limited volume of the conical umbra, without interference with the probe's payload. As a compromise, subsequent analyses assumed an illustrative reflector radius of 15 inches, but it is not yet certain that reflectors of that size can be accommodated on the spacecraft.

Table 2. Effect of Reflector Radius on Temperatures of Reflector and RTG Housing

Reflector Radius, inches	10	15	25
Reflector Temperatures, °C:			
Max.	329	205	97
Min.	226	147	73
RTG Housing Temperatures, °C:			
Max.	382	316	277
Min.	307	284	267
ΔT	75	32	10

Table 3 shows the effect of reflector emissivity on the temperatures of the reflector and the RTG housing. Systems with reflector emissivities ranging from 0.10 to 0.85 were analyzed. Surprisingly, it was found that the reflector emissivity has no effect on the RTG housing temperature, and virtually no effect on the reflector temperatures. This is fortuitous, because it eliminates the need for special surface treatments to produce high or low reflector emissivities. Additional analyses examined the effect of specular versus diffuse reflectors, and found essentially the same RTG temperatures for both.

Table 3. Effect of Reflector Emissivity on Temperatures of Reflector and RTG Housing

Reflector Emissivity	<u>0.1</u>	<u>0.5</u>	<u>0.85</u>
Reflector Temperatures, °C			
Max.	199	203	205
Min.	141	147	147
RTG Housing Temperatures, °C:			
Max.	316	316	316
Min.	284	284	284
ΔT	32	32	32

ANALYSIS OF OBSTRUCTED RTGs

The scoping-study results presented in Tables 1 through 3 permit only qualitative conclusions about the effect of the reflector on RTG power output. To obtain quantitative conclusions, a much more complex thermal and electrical analysis is needed.

Previous RTG analyses usually made the simplifying assumption that all of the thermoelectric couples in the generator's series-parallel network operate at the same hot- and cold-junction temperatures and at the same current and voltage. For unobstructed RTGs, such a simplified analysis is a useful initial design tool, since it permits closed-form solutions for the optimum area ratio A_n/A_p of the thermoelectric n- and p-legs and for the optimum output voltage. For these optimized parameters, it yields simple expressions for the maximum material efficiency of the thermoelectric couples, and for the required RTG design parameters [5,6].

But the above simplifying assumptions can introduce significant errors even for unobstructed RTGs, because all RTGs have appreciable axial temperature variations due to unavoidable end losses by radiation and by conduction through the heat source support structure. They are even less adequate for reflector-cooled RTGs with their highly unsymmetrical heat rejection paths. To analyze them, Fairchild developed a methodology and computer code to determine the performance of RTGs with circumferential as well as axial temperature, voltage, and current variations.

These analysis methods were described in detail in previous publications [7, 8]. The Fairchild computer code simultaneously performs integrated thermal, thermoelectric, and electrical analyses of the parallel-series-parallel thermocouple network in the RTG. For each iteration, the code uses each couple's hot- and cold-junction temperatures from the preceding iteration to compute its temperature-averaged thermoelectric properties, electrical current, and voltage, taking into account that all couples and circuit branches in parallel must produce the same voltage, and all couple groups in series must produce the same current. The code then uses the current of each couple to compute the heat input rate at its hot junction and the heat rejection rate at its cold junction, taking account of the Peltier effect, Ohmic dissipation, and the Thomson effect, and of the thermal power converted into electrical power in each couple. These rates are then inserted into a detailed thermal model of the RTG for the next iteration of the analysis. This cycle is repeated until convergence is achieved, at which point the RTG's performance parameters are computed. The validity of the method was demonstrated by the good agreement between its predictions and long-term test results.

ANALYSIS OF OBSTRUCTED UNIFORM-FIN RTG

The application of the code to the analysis of the obstructed uniform-fin Solar Probe RTG started with the construction of a 942-surface radiation-interchange analysis model. The model represented the housing and fins of the GPHS-RTG pictured in Figure 2 and the 15" semi-cylindrical reflector shown in Figure 8. The ITAS (Integrated Thermal Analysis System) code [9], which accounts for the effect of mutual reflections, was used to compute over 65,000 radiation interchange factors between all surface nodes that are within each other's view.

The computed radiation interchange factors were then inserted into a detailed thermal and electrical analysis model consisting of 1332 thermal nodes. The thermal power of the 18 stacked-up heat source modules was adjusted to account for fuel decay during the anticipated interval between the fuel encapsulation and the beginning of the mission (BOM).

Such detailed coupled thermal and electrical analyses were performed for a broad range of thermal power levels for both obstructed and unobstructed RTGs. The principal results for an RTG obstructed by a 15"-radius reflector and the comparative results for an unobstructed RTG are displayed in Figures 7 through 9. (The unobstructed units had axial temperature variations but no circumferential variation.)

Figures 7 and 8 respectively show the effect of the thermal power on the RTG power output and average hot-junction temperature. As can be seen, both relationships are essentially linear. The two figures show that, for a given thermal power, the obstruction by the reflector has practically no effect on the RTG's power output, but has a significant effect on its hot-junction temperature, which affects the degradation rate.

Figure 7. Effect of 15"-Radius Reflector on Power Output of GPHS RTG

Figure 8. Effect of 15"-Radius Reflector on Temperature of GPHS RTG

Figure 9 presents cross-plots showing the relationship between maximum hot-junction temperatures and BOM power outputs for unobstructed RTGs and for RTGs obstructed by reflectors of 10- and 15-inch radius. The performance of the obstructed and unobstructed RTGs should be compared for the same maximum hot-junction temperature, since that is what determines the RTG's degradation rate and lifetime. Previous SiGe flight units (LES 8/9, Voyager, Galileo) were designed for a maximum hot-junction temperature of 1000°C. For that temperature, Figure 9 shows that the RTG's power output is reduced by 23 watts (7.5%) for the 15" reflector, and by 52 watts (17.0%) for the 10" reflector. This confirms the high sensitivity of power output to reflector radius, and shows that even a 15" radius results in a significant performance penalty for the standard GPHS-RTG design.

Figure 9. Effect of Reflector Radius on BOM Power at Fixed Hot-Junction Temperature

VARIABLE-FIN RTG

To compensate for the RTG performance penalties shown in Figure 9, the possibility of compensating for the reflector's unsymmetrical blockage through the use of nonuniform fins was investigated. This concept is illustrated in Figure 10. As can be seen, small (or no) fins are used on the outward-facing, unobstructed side of the RTG, and much larger fins are used on the RTG's inward-facing side, which is most obstructed by the reflector.

Figure 10. Variable-Fin RTGs and Reflectors Integrated with Solar Probe

Detailed radiation-interchange and thermal-conduction analyses were performed for various combinations of root-to-tip fin heights and fin root thicknesses. These analyses showed that, with a 15-inch reflector radius, isothermal RTG housings can be obtained with practical fin dimensions.

By trial-and-error analyses, over 100 isothermal designs for various cold-junction temperatures were generated. For each cold-junction temperature and a prescribed hot-junction temperature of 1000°C, a combined thermal, thermoelectric, and electrical analysis was used to calculate the RTG output power at 30 volts. From these isothermal designs, solutions with the highest power-to-mass ratios for various power levels were selected. The selected solutions are described in Table 4, and plotted in Figure 11.

Figure 11 shows a plot of RTG weight versus BOL power, corresponding to the solutions from Table 4. Since these represent the minimum-weight solutions, the weight-versus-power curve of Figure 11 represents the lower envelope of all possible solutions. All other solutions lie above that curve.

Table 4. Minimum Weight Solutions for Isothermal RTGs (Variable Fin Dimensions)

Cold-Junction Temperature, °C	318	328	338	350
RTG Housing Temperature, °C	288	298	308	320
Fin Length, inch				
#1	8	8	8	7
#2, #8	6	5	4	4
#3, #7	3	3	2	2
#4, #6	2	1	0.5	0
#5	2	1	0.5	0
Fin Root Thickness, inch				
#1	177	094	046	031
#2, #8	144	077	042	015
#3, #7	118	034	023	015
#4, #6	015	015	015	0
#5	015	015	015	0
Fin Weight, lb	8.68	4.35	2.27	1.30
RTG Weight, lb	127.73	123.40	121.31	120.35
BOL Power, watt	281.5	277.9	274.4	270.2

Figure 11. Effect of BOL Power on Minimum Weight and Optimum Cold-Junction Temperature, Efficiency, and Specific Power of Isothermal RTG

In addition to weight and power, the tick marks at the top of the figure show the BOL efficiency, and the diagonal lines indicate the specific power. As can be seen, the specific power maximizes at the design that corresponds to a cold-junction temperature of 338°C. At lower cold-junction temperatures, the fractional fin weight increase exceeds the fractional power gain, and at higher cold-junction temperatures the fractional fin weight saving is less than the fractional power reduction. The optimum variable-fin design is depicted in Figure 12.

Figure 12. Optimum Fin Dimensions and Radiator Temperatures of Reflector-Cooled RTG with Isothermal Housing (Fin Thickness Quadrupled for Visibility)

For a Solar Probe RTG that is unsymmetrically obstructed by a semi-cylindrical reflector, we can employ either uniform fins yielding unsymmetrical cold-junction temperatures or nonuniform fins yielding axisymmetrical cold-junction temperatures. Detailed analyses to compare the effectiveness of those two options were performed for a reflector radius of 15 inches, using Fairchild's methods for the coupled thermal and electrical analysis of obstructed RTGs. The results of the detailed analysis for the uniform-fin option were displayed in Figure 9. For a consistent comparison, equally detailed analyses were performed for the nonuniform-fin design depicted in Figure 13. Those analyses confirmed that the use of the nonuniform-fin design eliminates the circumferential temperature variations, as predicted by the simplified analysis.

The overall performance of RTGs with uniform and nonuniform fins is compared in Figure 13. As can be seen, for the same thermal power, the two options yield essentially the same power output. But the maximum hot-junction temperature of the nonuniform-fin design is about 10°C above that of the uniform-fin design. This would significantly raise the thermoelectric degradation rate. For the same maximum hot-junction temperature (e.g., 1000°C), the output of the nonuniform-fin design is 7.5 watts(e) or 2.5% lower than that of the uniform-fin design. Thus, there would be no incentive to employ nonuniform fins instead of the standard design with uniform fins for this application.

Figure 13. Effect of Uniform and Non-Uniform Fins on Solar Probe RTG with 15" Radius Reflector

REFERENCES

- [1] W. Feldman, Chairman, 1989 Solar Probe Science Study Team, "Solar Probe Scientific Rational and Mission Concept," JPL-D-6797, Jet Propulsion Laboratory, November 1989.
- [2] A. Schock, and H. Sookiazian (1979) "Design Optimization of RTG for Solar - Polar Mission," Vol. 2, pages 1444-1454. Proc. of the 14th Intersociety Energy Conversion Engineering Conference, held in Boston, Massachusetts, August 1979.
- [3] A. Schock (1981) "Modular Isotopic Thermoelectric Generator," Vol. 1, pages 327-342. Proc. of the 16th Intersociety Energy Conversion Engineering Conference, held in Atlanta, Georgia, August 1981.
- [4] A. Schock (1980) "Design, Evolution, and Verification of the General Purpose Heat Source," Vol. 2, pages 1032-1042. Proc. of the 15th Intersociety Energy Conversion Engineering Conference, held in Seattle, Washington, 1980.
- [5] I.A. Ioffe, (1957) Semiconductor Thermoelements and Thermoelectric Cooling, Infosearch, London, 1957.
- [6] A. Schock, et al. (1989) "Mars Rover RTG Study," FSC-ESD-217-89/450A. Fairchild Space, Germantown, Maryland, November 1989.
- [7] A. Schock, C.T. Or, and E.A. Skrabek (1990) "Thermal and Electrical Analysis of Mars Rover RTGs, and Performance Comparison of Alternative Design Options," Trans. of the Seventh Symposium on Space Nuclear Power Systems, held in Albuquerque, New Mexico, January 1990.
- [8] A. Schock, T. Hamrick, and K. Sankarankandath (1990) "Design and Structural Analysis of Mars Rover RTG," in Trans of the Seventh Symposium on Space Nuclear Power Systems, held in Albuquerque, New Mexico, January 1990.
- [9] ITAS: Integrated Thermal Analysis Systems, Analytix Corporation, Timonium, Maryland 1990.