Small Radioisotope Thermophotovoltaic (RTPV) Generators

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Abstract. The National Aeronautics and Space Administration's recently inaugurated New Millennium program, with its emphasis on miniaturized spacecraft, has generated interest in a low-power (10- to 30-watt), low-mass, high-efficiency RTPV power system. This led to a Department of Energy (DOE)-sponsored design study by OSC (formerly Fairchild) personnel, who had previously conducted very encouraging studies of 75-watt RTPV systems based on two 250-watt General Purpose Heat Source (GPHS) modules. Since these modules were too large for the small RTPVs described in this paper, OSC generated derivative designs for 125-watt and 62.5-watt heat source modules. To minimize the need for new development and safety verification studies, these contained identical fuel pellets, clads, impact shell, and thermal insulation as the previously developed and safety-qualified 250-watt units. OSC also generated a novel heat source support scheme to reduce the heat losses through the structural supports, and a new and much simpler radiator structure, employing no honeycombs or heat pipes. OSC's previous RTPV study had been based on the use of GaSb PV cells and spectrally selective Infra-Red (IR) filters that had been partially developed and characterized by Boeing (now EDTEK) personnel. The present study was based on greatly improved selective filters developed and performance-mapped by EDTEK under an OSC-initiated subcontract. The paper describes illustrative small-RTPV designs and analyzes their mass, size, power output, system efficiency, and specific power, and illustrates their integration with a miniaturized New Millennium spacecraft.

INTRODUCTION

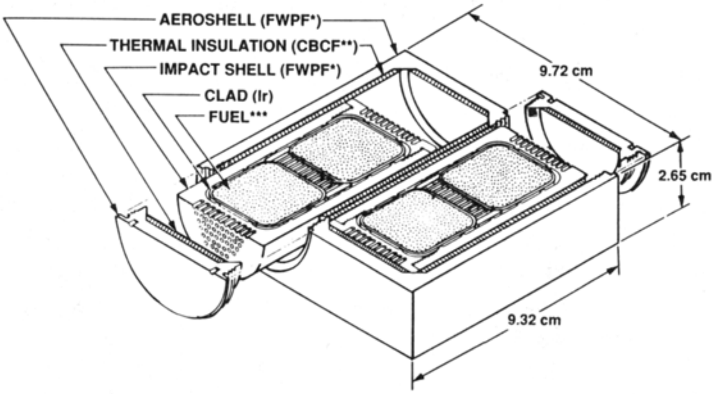
Revolutionary developments are occurring in the U.S. space program to enable the launchings of many small and inexpensive science missions instead of the infrequent and very expensive missions launched in recent decades. This requires drastic reductions in the mass and cost of spacecraft and payloads through use of advanced technologies, which are the goals of NASA's recently initiated New Millennium program. It also requires corresponding reductions of the payload's power demand and increases in power system efficiency and specific power, since power systems have traditionally constituted about one third the mass of the spacecraft.

Those space missions that require too much energy for reasonable sized batteries and that must operate where sunlight is inadequate for practical solar power systems can utilize radioisotope power systems. Such systems, employing thermoelectric converters, have been successfully used on dozens of space missions, where they have demonstrated excellent reliability and durability. But their efficiencies are too low to meet the objectives of the New Millennium program. This has led to NASA interest in much more efficient radioisotope power systems. There are three prime contenders that offer the possibility of tripling the efficiency of thermoelectric conversion systems at low power outputs: thermophotovoltaic (RTPV) systems, free-piston Stirling engines with linear alternators, and Alkali Metal Thermal to Electric Conversion (AMTEC) systems. The authors have conducted detailed studies [1,2,3,4,5,6] of 75-watt radioisotope power systems of the first two options for the Department of Energy, and have recently initiated a study of the third option. The studies of the first two options showed that both of the advanced systems would yield much higher efficiencies (and therefore reduced fuel requirements) than present Radioisotope Thermoelectric Generators (RTGs [7,8,9,10]), but that TPV systems promise much lower weights and higher specific powers than present-technology Stirling systems [5,6,10]. Recently, the NASA Administrator requested that DOE prepare a much smaller (20-watt) RTPV system design. DOE assigned that task to OSC, with the results reported in the present paper.

SMALL RTPV GENERATOR DESIGN

The previous study of a 75-watt(e) RTPV had employed a 500-watt radioisotope heat source consisting of two 250-watt General Purpose Heat Source (GPHS) modules [11] which DOE had developed and safety-qualified for various RTG missions (Galileo, Ulysses, Cassini). As shown in Figure 1, each GPHS module contains four 62.5 watt(t) PuO_2 fuel pellets encapsulated in iridium-alloy clads. The remaining module components are graphitic and are designed to protect the integrity of the iridium clads in case of accidents before, during, and after launch.

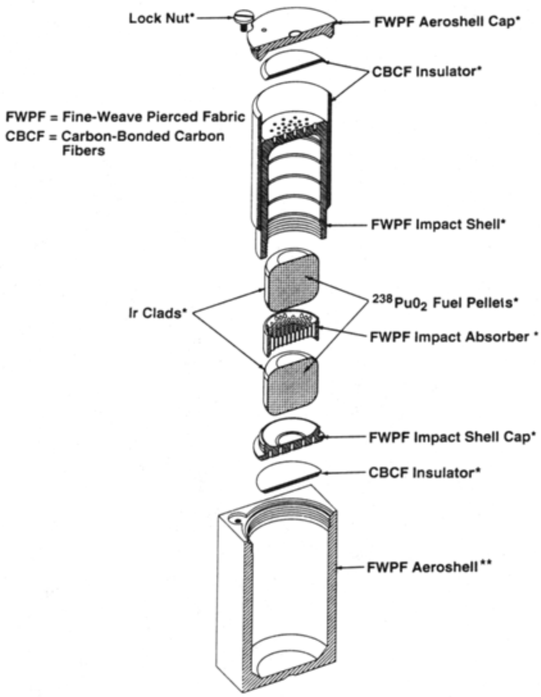
There are two impact shells and one aeroshell made of fine-weave pierced fabric (FWPF), a very tough high-temperature three-dimensional carbon-carbon composite. The aeroshell would serve as an ablator in the unlikely event of inadvertent atmospheric reentry, and the impact shells would help to prevent breach of the clads during subsequent Earth impact. 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 prior to earth impact.



*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} PuO_2 pellet

FIGURE 1. GPHS-General Purpose Heat Source Module (250 Watts) Sectioned at Mid-Plane.

The previously flown 250-watt GPHS modules are too big for a 20-watt RTPV generator. To minimize the need for new development and safety tests, OSC elected to base its design on a 125-watt heat source, containing identical fuel pellets, clads, impact shell, and thermal insulator, and employing the same aeroshell material and wall thickness as the 250-watt units, as shown in Figure 2.



* Identical to GPHS Module
** Identical Material and Wall Thickness

FIGURE 2. Exploded View of 125-watt Heat Source (Sectioned at Midplane).

HEAT SOURCE CANISTER AND SUPPORT SCHEME

As shown in Figure 3, the heat source is enclosed in a molybdenum canister. This is to prevent contaminants released by the hot heat source from reaching the gold filter and the gallium antimonide photovoltaic (PV) cells, which could degrade their performance. The outside of the canister is coated with tungsten, to minimize sublimation (only 10^{-6} monolayers in ten years) and the tungsten coating is roughened to enhance the generator's conversion efficiency, for reasons explained in previous reports [2,3,4]. Where the inside of the canister is in contact with the aeroshell it is lined with iridium , to prevent reaction between molybdenum and graphite.

The support scheme previously proposed for the 500-watt heat source would have led to excessive heat losses from the small (125-watt) heat source. To avoid this, OSC devised a heat source support scheme in which each end of the canister is supported by a single zirconia ball seated in spherical indentations on the outside of the high-temperature canister end caps and on the inside of the low-temperature aluminum housing of the generator. Thus, the heat source is supported both axially and laterally.

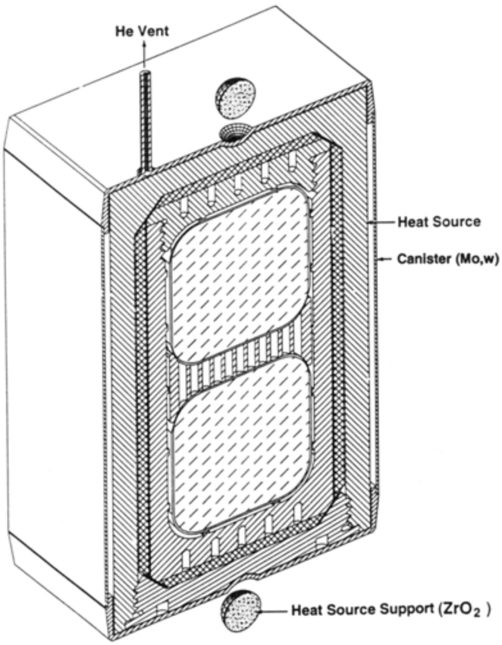


FIGURE 3. 125-Watt Heat Source Enclosed in Molybdenum Canister.

Figure 4 shows the high-temperature canned heat source inside the generator's low-temperature aluminum housing, and depicts the heat source support scheme. The canister's two end faces and its two inactive side faces are thermally insulated by a multifoil assembly (not shown), consisting of 60 layers of 0.008 mm W foils separated by ZrO_2 spacer particles, similar to those successfully used in previous long-duration thermoelectric converter tests. As shown, the helium generated by the fuel's alpha decay is vented to space through a semi-permeable vent plug.

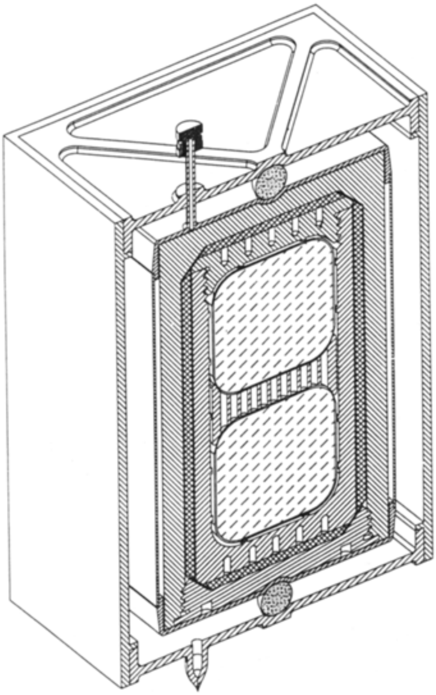


FIGURE 4. 125-Watt Heat Source in Al Converter Housing, Showing Low-Loss Support Scheme.

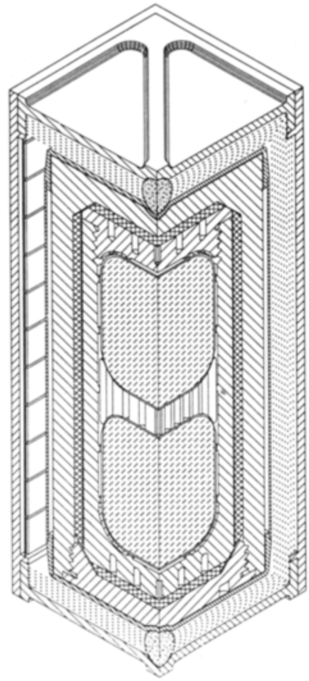


FIGURE 5. Quarter Section of 20-Watt RTPV Converter. (Showing Multifoil Thermal Insulation and PV Cells)

As indicated in Figure 5, the canister's two end faces and two of its four side faces are covered with the multifoil thermal insulation, and the other two side faces radiate heat to photovoltaic cells covered with spectrally selective infra-red filters (not shown), which are bonded to the inside of the aluminum housing.

Our analysis showed that 8.6% of the heat source's thermal power is lost through the multifoil insulation, and only 1.0 % passes through the ZrO_2 support balls. Thus, over 90 % of the thermal power is transferred to the PV cells.

As shown in Figure 6, each of the canister's two active faces radiates heat to a photovoltaic array of 6x11 closely spaced gallium antimonide cells, 7.9 x 8.4 mm each. The canister side walls and planar arrays of filtered PV cells are parallel to each other and closely spaced to provide a good view factor for radiative interchange. The spacing between the PV cells is the minimum necessary for the desired series-parallel connections. The cells on each face are bonded to a BeO substrate, which in turn is bonded to the generator's aluminum side wall.

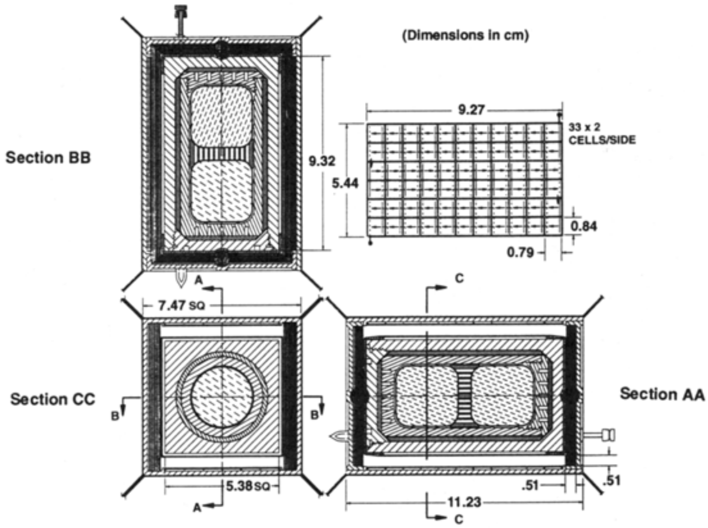


FIGURE 6. Sectioned Views of RTPV Heat Source and Converter, with 66 x 2 Series-Parallel Cell Network to Produce 28-Volt Output.

Each of the two cell arrays is covered with a spectrally selective infra-red filter [12,13], to permit the transmission of those wavelengths which can be efficiently converted to electricity by the PV cells, and the reflection of those wavelengths that cannot. Much of the reflected radiation is absorbed by the heat source canister, which then re-emits it with a full spectral distribution. Thus, the unused reflected energy is conserved, which reduces the energy to be supplied by the radioisotope heat source and greatly increases the efficiency of the generator. Hence, the selective filter is a vital element of this RTPV system.

Each of the generator's two PV cell arrays is covered with a resonant gold filter. The filter consists of a continuous thin gold film deposited on a transparent substrate (e.g., sapphire), about 54 x 93 mm, containing over two hundred million submicronic holes per cm^2 in its active regions (i.e., opposite each PV cell). The size, spacing, and geometry of the hole pattern determines the performance of the resonant filters.

The converter's 132 PV cells are arrayed in a series-parallel matrix. At each horizontal level, the cells are parallel-connected in groups of two, and these groups of parallel cells are series-connected to groups in adjacent horizontal levels. Thus, the generator consists of a 66 x 2 series-parallel network, for a total output of approximately 28 volts.

Heat Rejection System

The RTPV System needs much larger radiator fins than typical RTGs, because the PV cells must operate at much lower heat rejection temperatures to achieve their high efficiencies. For the previously published 75-watt design, the optimum radiator dimensions, i.e., the dimensions that maximize the system's specific power, were determined by detailed analyses.

Figure 7 shows an exploded view of the previous 75-watt generator [1, 3, 4] and of one of its four radiator fins, with typical dimensions. As shown, it had a large trapezoidal fin bonded to each side of the converter housing. The exploded fin view shows a central core consisting of an aluminum honeycomb with two embedded aluminum/ammonia heat pipes. To each face of the honeycomb core, two skins were bonded: an inner skin of aluminum which had minimal thickness over most of its length, but was thickened near the fin root to provide increased structural strength for resisting bending moments during launch; and an outer skin consisting of a graphitized carbon-carbon composite to provide high thermal conductance in the fiber direction. The graphite fibers were oriented in the vertical direction, normal to the heat pipes' axes. In that direction they have a thermal conductivity twice that of copper, at about one fourth its density [14]. The graphite skins served to distribute the heat from the heat pipes over the width of the fin, and also provided the fin with high-emissivity surfaces

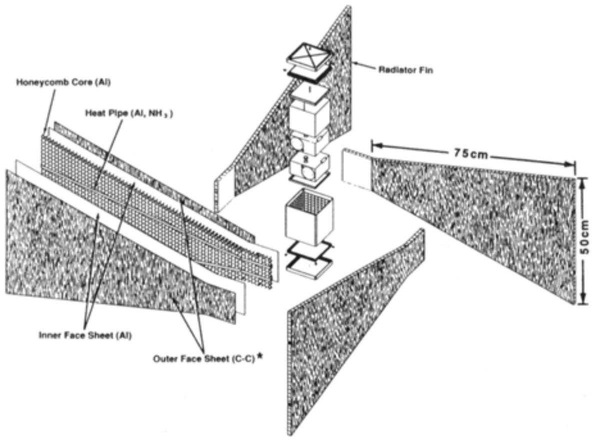


FIGURE 7. Exploded View of 75-Watt RTPV Generator and of Radiator Fin.

For the small RTPV generator, OSC was able to devise a much simpler radiator, with no honeycombs or heatpipes. As indicated by the cut-away view shown in Figure 8, it consists of 12 mutually stiffened trapezoidal fins, emanating at 45 degrees from the 12 edges of the converter housing. The mutual stiffening provided by neighboring fins greatly reduces the bending moments during launch vibration, and makes it possible to dispense with the previously shown honeycombs and with the embedded heat pipes. Each fin consists of a 0.020" aluminum core, bonded to high conductivity carbon-carbon face sheets. The dimensions shown are illustrative. Their optimization will be discussed shortly.

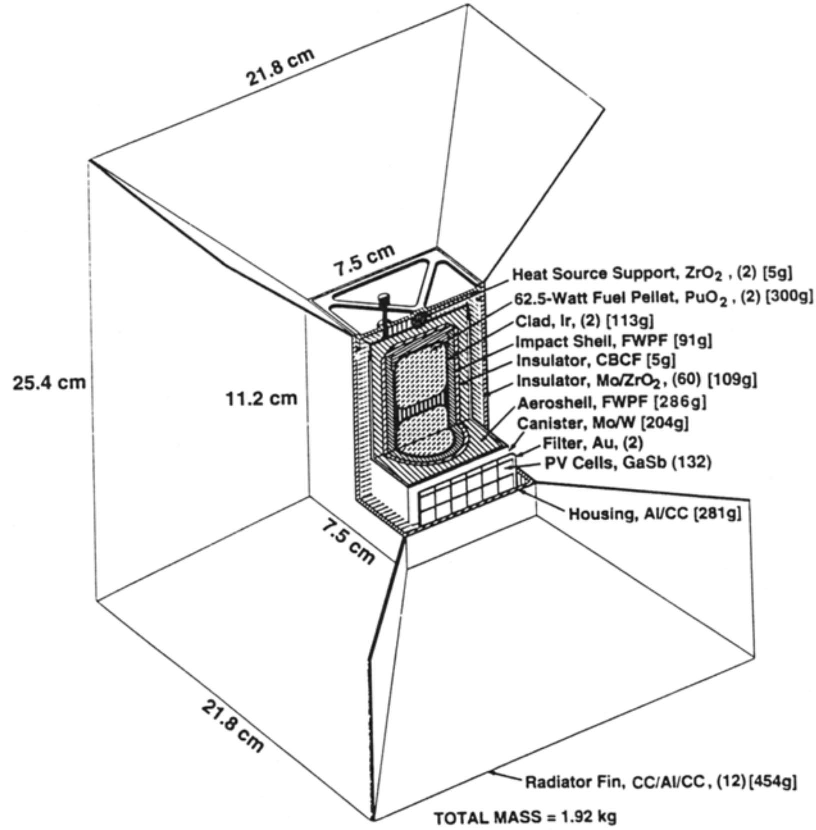


FIGURE 8. Small RTPV Radiator Configuration, Showing Mass Breakdown of Generator with Typical Radiator Height (25 cm) and Graphite Thickness (0.18 mm)

As can be seen for the illustrated dimensions the heat source and the radiator respectively comprise 52% and 24% of the generator's 1.92 kg mass.

Effect of Filter and Cell Improvements

As described in detail in previous publications [2,3,4], analysis of the RTPV generator requires three sets of wavelength-dependent data: the emissivity of the heat source canister, the quantum efficiency of the PV cell, and the reflectivity of the IR filter. For the latter two, OSC's previous study employed measured and projected performance models supplied to us by Boeing (now EDTEK) personnel in 1993 [2]. The effect of those models is depicted in Figure 9, which presents plots of the TPV converter's output power density versus input heat flux for the projected and measured filter and cell performance models (for an illustrative 0°C cell temperature). The figure also shows lines of constant conversion efficiency and the effect of heat flux on source temperature. As can be seen, for a given heat flux the projected filter and cell models yield much higher conversion efficiencies than the measured models. Therefore, OSC initiated a subcontract at EDTEK to develop improved filters and cells, and to demonstrate what performance improvements can actually be achieved.

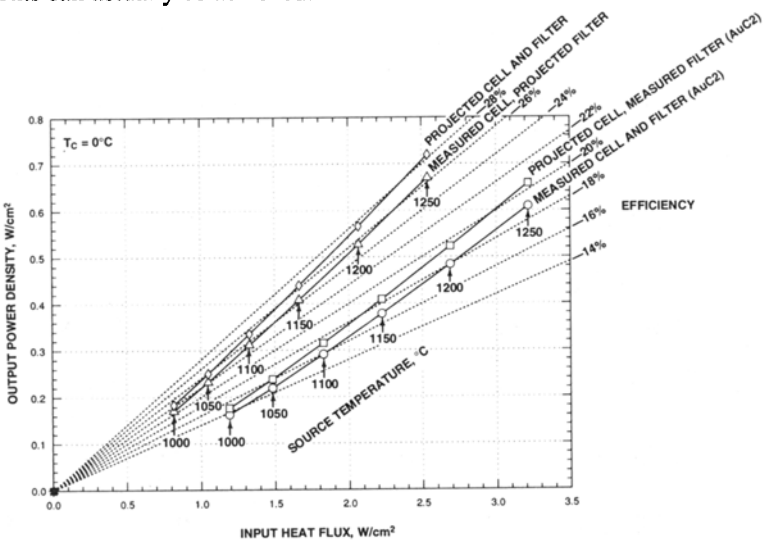


FIGURE 9. Effect of Projected Cell and Filter Improvements on Conversion Efficiency for Same Heat Flux.

In Figure 9 the differences between the first and second curves and between the third and fourth curves represent the effect of projected cell improvements; and the differences between the first and third curves and between the second and fourth curves represent the effect of projected filter improvements. Clearly, the efficiency gain produced by the projected filter improvement is much greater than that yielded by the projected cell improvement. Therefore, OSC requested that EDTEK give higher priority to filter improvement than to cell improvement.

The EDTEK subcontract started in the fall of 1994, and several of the filters made to date (May 1995) demonstrate very encouraging improvement over the filter measured in 1993 (AuC2). As shown in Figure 10, the performance of each of several new filters has already closed 75% of the gap between the 1993 measured and projected filter performances. This enhances our confidence that EDTEK's continuing filter and cell improvement studies [15] will suceed in achieving their projected performance goals.

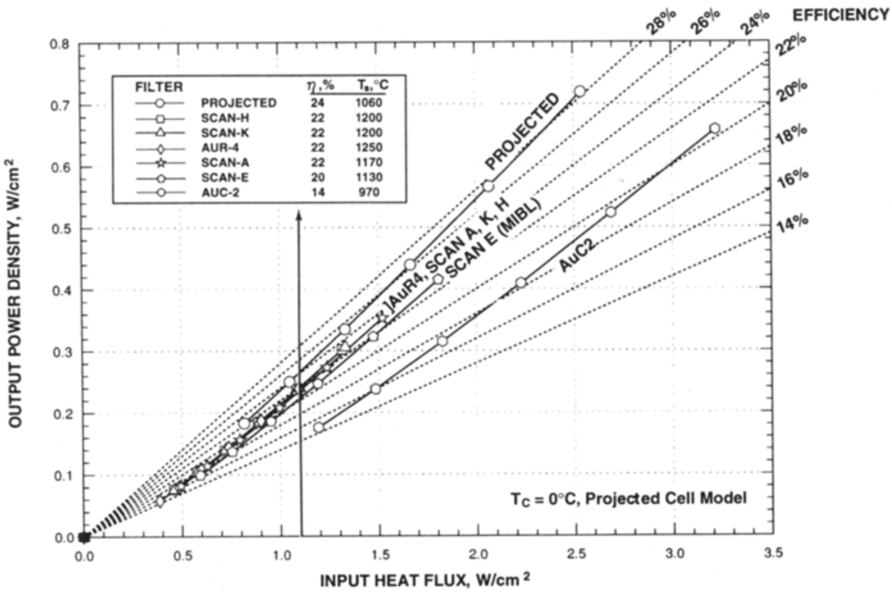


FIGURE 10. Comparison of Converters with Recent and Previous Filters.

Parametric System Analysis and Optimization

Analysis of the RTPV power system, including its heat rejection system, requires coupled optical, thermal, and electrical analyses. As described in detail in previous reports [2,3,4], these analyses were carried out by means of a thermal analysis code (SINDA [16]) that had been modified by OSC, and by a standard thermal radiation code (SSPTA [17]).

In the coupled analysis, the heat generation rate is known, but the heat source surface temperature and cell temperature are not. Therefore, the analysis must be carried out iteratively. In each iteration, the two thermal codes compute a new set of canister and cell temperatures, which are used as inputs in the next iteration. This iterative procedure is repeated until the modified code converges on a consistent solution.

For a fixed heat source thermal power and converter design, the only other system design parameters are the size of the radiator and the thickness of the high-conductivity carbon-carbon face sheets (see Figure 8). Increasing either of those parameters will lower the cell temperature, which increases the power output and efficiency. But this benefit is obtained at the cost of increased system mass. Thus, the system design requires a trade-off between system mass and performance (efficiency, power output). The goal of the optimization study is to determine the radiator dimensions which maximize the power system's specific power.

Effect of Graphite Skin Thickness

Let us first examine the effect of varying the graphite skin thickness on system characteristics for an illustrative 25 cm generator height and a converter with 90% active cell area. The effect of varying the graphite skin thickness from 0 to 1.0 mm is illustrated in Figure 11. The figure shows the effect of graphite skin thickness on system mass, cell temperature, output power, system efficiency, and specific power. In each of the three plots, the solid curve represents results based on measured values of SCAN-A filter transmittance and cell quantum efficiency, the dotted curve is based on SCAN-A filter and projected cell performance, and the dashed curve is based on projected values of the two.

As shown in Figure 11, for each performance model the initial addition of the graphite skins lowers the cell temperature which increases the output power and efficiency significantly, but after adding a surprisingly small thickness (typically 0.15 mm) further additions of graphite only increase the mass with little further increase of power or efficiency.

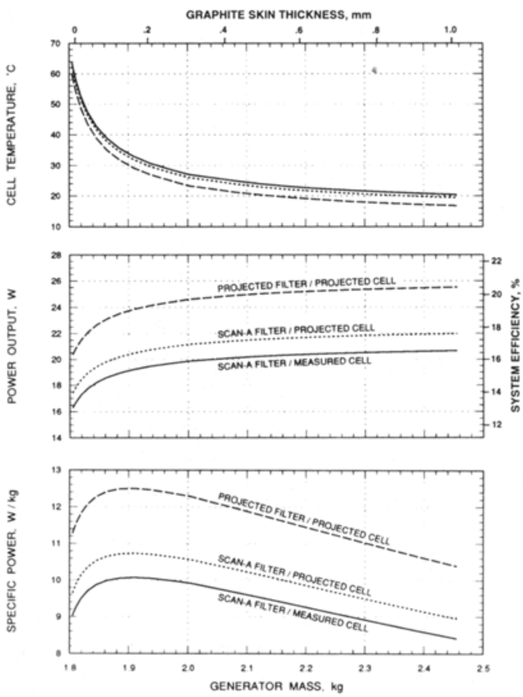


FIGURE 11. Effect of Graphite Skin Thickness.

Effect of Radiator Fin Dimensions

The results of parametric design studies are displayed in Figures 12 and 13. Both figures show curves representing the results of thermal, electrical, and mass analyses for generator heights ranging from 20 to 36 cm, with the graphite skin thickness as the implicit variable within each curve. Each point on each curve is the result of an iterative solution of the coupled thermal and electrical analyses, using the modified thermal analysis code described earlier.

Figure 12 shows plots of cell temperature versus generator mass. For each radiator size, the upper curve is based on the measured (SCAN-A) filter transmittance and the projected PV quantum efficiency model, and the lower curve is for the projected filter and cell characteristics. As can be seen, the larger fins lead to very low cell temperatures, but at substantially higher masses.

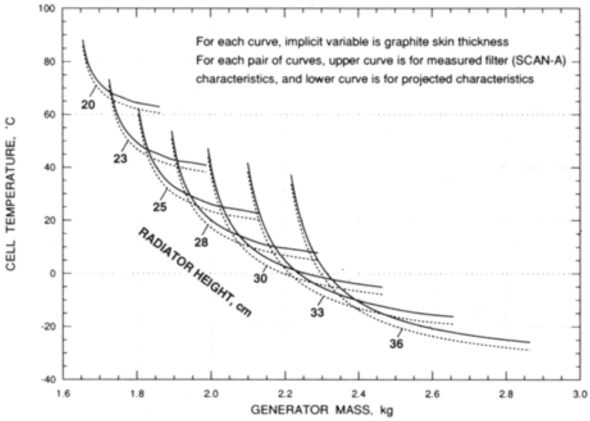


FIGURE 12. Effect of Radiator Height on Cell Temperature

The trade-offs between mass and performance for the measured and projected filters are summarized in Figure 13. For each radiator size, it presents curves of output power and system efficiency versus generator mass, with graphite skin thickness as the implicit variable. It also shows diagonal lines of constant specific power, which identify the radiator height that maximizes the generator's specific power.

For each filter and cell performance model, the figure shows a family of performance curves for different radiator dimensions and a tangent envelope curve, with indicated cell temperatures at their point of tangency. For each performance model, the corresponding envelope curve represents the highest specific power that can be achieved by optimizing the system's radiator geometry. For every point on the envelope, there is some combination of radiator height and graphite skin thickness that will achieve the indicated performance.

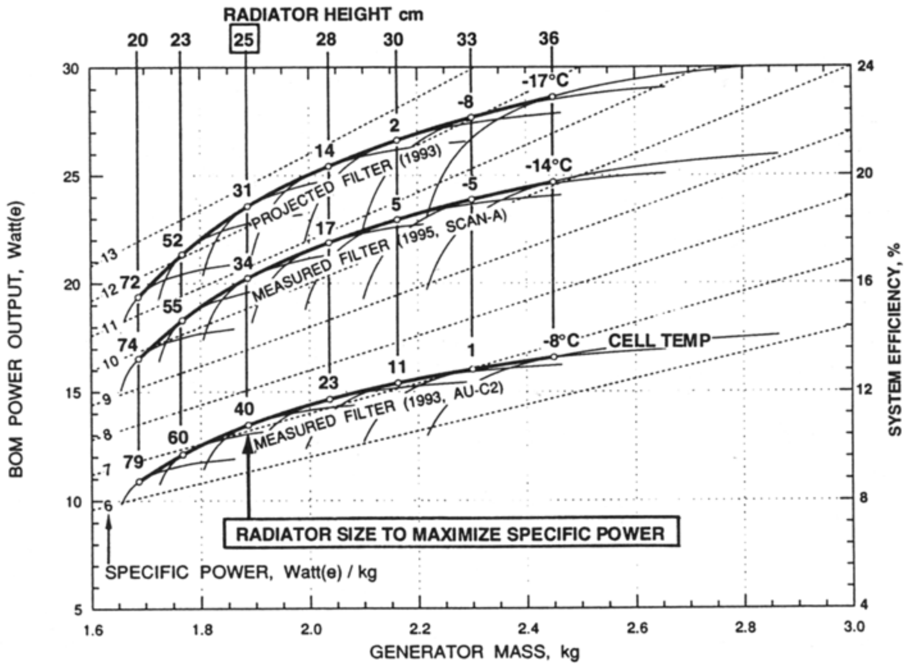


FIGURE 13. Effect of Filter on System Performance for Various Radiator Sizes.

Comparison of the three envelopes shows that EDTEK's improved filter (SCAN-A) has already succeeded in closing ~75% of the performance gap between their 1993 measured and projected filters.

As seen in Figure 13, for all three performance models the system's specific power is maximized with a 25 cm radiator height. But note that this optimum is quite broad. As illustrated in Table 1, major deviations from the optimum design result in only modest reductions in specific power. Thus, the designer has wide latitude in trading off power and efficiency versus mass and size to meet specific mission goals.

Table 1. Effect of Off-Optimum Design on RTPV Performance.

Goal	Low Mass	Max Sp Power	High Power
Radiator Height, cm	20	25	36
Cell Temperature, °C	72	31	-17
Power (BOM), Watt	19	24	29
Efficiency (BOM), %	15.5	18.9	22.9
System Mass, kg	1.7	1.9	2.5
Specific Power, W/kg	11.5	12.5	11.7

ADDENDUM

After completing the 20-watt RTPV generator study requested by the NASA Administrator, OSC decided to supplement it with a similar study of an even smaller generator, based on a 62.5-watt (1-fuel-capsule) derivative of the previously flown (4-capsule) General Purpose Heat Source (GPHS) module. As before, the small heat source employs a fuel pellet, clad, impact shell, and thermal insulation identical to the GPHS, and uses the same aeroshell material and wall thickness to minimize the need for new development.

As shown in Figures 14 and 15, the 62.5-watt heat source is inserted into a TPV converter that is smaller but otherwise identical to the previious designs, using 6.2 x 6.8 mm PV cells. The converter contains 128 filtered PV cells, connected in a 64 x 2 series-parallel network to yield a 28-volt output.

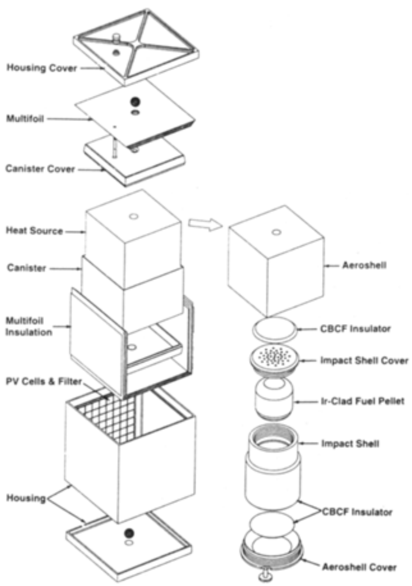


FIGURE 14. Exploded View of 62.5-Watt Heat Source and Thermophotovoltaic Converter

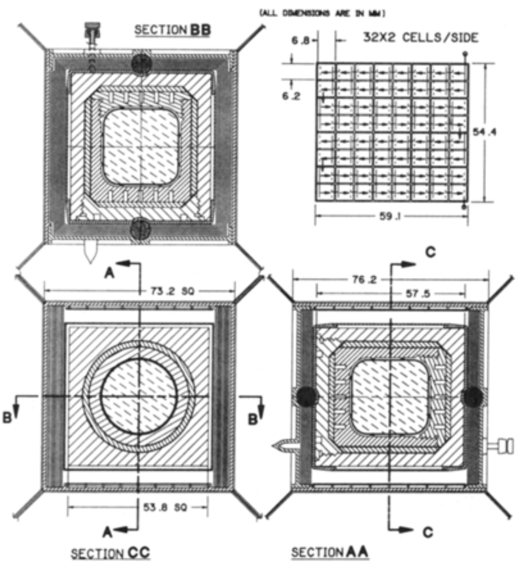


FIGURE 15. Sectioned View of 62.5-Watt Heat Source and Thermophotovoltaic Converter

As shown, the converter is roughly a 76 mm (3") cube. The combined mass of the heat source and converter is 0.94 kg.

The generator employing the 62.5-watt heat source uses the same radiator configuration as the previous design, and its size represents a trade-off between maximizing the power output and system efficiency versus minimizing the generator size and mass. As shown in Figure 16, for the illustrated radiator size the generator is a 18 cm (7") cube weighing 1.18 kg.

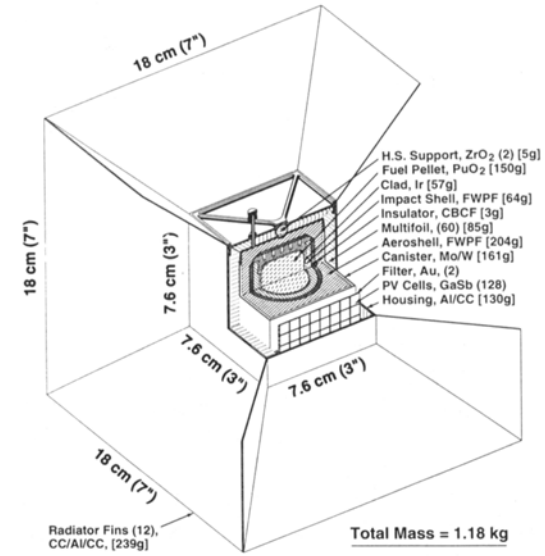


FIGURE 16. Cutaway View and Mass Breakdown of RTPV Generator with 62.5-Watt Heat Source

The analytical results for the smaller generator, for both the measured and projected filter and cell performance models, are displayed in Figure 17. As can be seen, the specific power of the generator maximizes with a 18 cm (7") radiator, at a system mass of 1.18 kg. For the best filter (SCAN-A) demonstrated to date and the measured cell performance, the generator yields a BOM power output of 8.8 watts(e), a system efficiency of 14%, and a 7.4 w/kg specific power. For the projected filter and cell performance, the generator's BOM power rises to 11 watts(e), the system efficiency to 18%, and the specific power to 9.4 w/kg. If desired, its BOM power and efficiency could be raised to 12.5 watts and 20% by employing a 23 cm radiator, which would raise the generator mass to 1.36 kg, but yield almost the same specific power (9.3 w/kg). Conversely, an 8.4-watt output could be achieved with a 13 cm cubical generator weighing 1.04 kg.

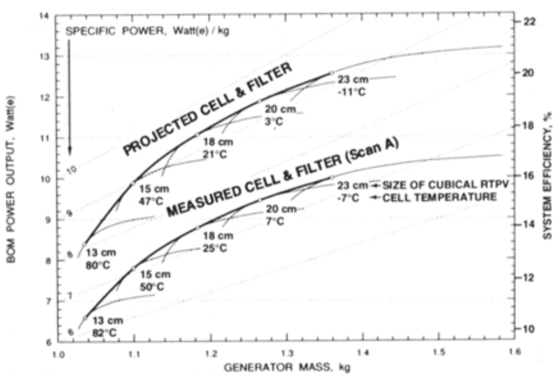


FIGURE 17. Effect of Filter and Cell Models on Performance of RTPV with 62.5-Watt Heat Source

Finally, Figure 18 compares the generator performance maps for RTPVs employing 125- and 62.5-watt heat sources based on projected filter and cell performance models. As can be seen, the smaller generator has about half the size and power output as the larger unit. The efficiencies of the two generators are about the same, but the specific power of the smaller unit is significantly lower.

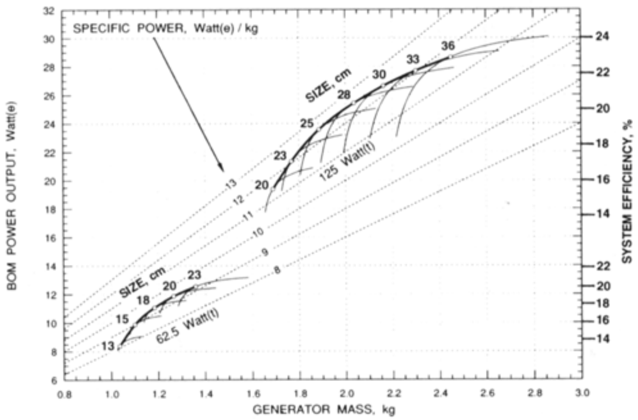


FIGURE 18. Effect of Generator Size on RTPV System Performance. Based on Projected Filter and Cell Characteristics

Because of its compact size and low mass and fuel inventory, either generator may be of considerable interest for powering the highly miniaturized spacecraft planned for NASA's New Millennium program. To illustrate this, Figure 19 depicts a possible arrangement for integrating two 10-watt RTPVs with JPL's preliminary design for a New Millennium spacecraft for missions to the outer solar system. This arrangement has not yet been analyzed, but it seems clear that even better performance could be achieved by utilizing the spacecraft's 46 cm diameter graphitic high-gain antenna as the RTPV's radiator

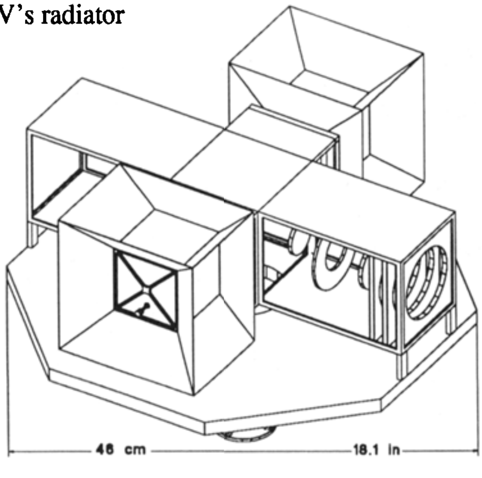


FIGURE 19. Illustrative Arrangement for Mounting Two 10-Watt RTPVs on JPL's Design for New Millennium Miniaturized Spacecraft for Outer Solar System Missions

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