Radioisotope Thermophotovoltaic Generator Design Methods and Performance Estimates for Space Missions

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This work provides the design methodology of the radioisotope thermophotovoltaic system (RTPV) using spectral control for space missions. We focus on the feasibility of a practical system by using two-dimensional micro-patterned photonic crystal emitters, selecting the proper TPV cell and insulation material to exclude material incompatibilities, to optimize the system efficiency by impedance matching, and to design the radiator with minimum mass. In the last section, we present a design example based on the tested InGaAsSb cells. We show computationally that using the experimentally tested InGaAsSb cells, the RTPV generator is expected to reach an efficiency of 8.6% and a specific power of 10.1 W/kg with advanced radiators. Using the more efficient InGaAs cells, the system can expect to triple the figure of merits of the Radioisotope Thermoelectric Generator (RTG), promising to reach ~18% and 21 W/kg, respectively. With a high performance device, the results of this work can lead to a functional prototype for further research focusing on manufacturability and reliability.

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Nomenclature

\[ A = \text{area} \]
\[ a = \text{period of photonic crystal microstructure} \]
\[ d = \text{depth of photonic crystal microstructure} \]
\[ e = \text{elementary charge} \]
\[ E = \text{emissive power} \]
\[ F = \text{view factor} \]
\[ k = \text{thermal conductivity} \]
\[ N = \text{Number of Fourier modes in RCWA} \]
\[ I = \text{electrical current} \]
\[ n = \text{cell ideality factor} \]
\[ Q = \text{heat flow} \]
\[ r = \text{radius of photonic crystal} \]
\[ t = \text{thickness} \]
\[ t_{95} \]
\[ T = \text{absolute temperature} \]
\[ V = \text{electrical voltage} \]
\[ Z = \text{thermal impedance} \]
\[ \alpha = \text{taper angle} \]
\[ \varepsilon = \text{emissivity} \]
\[ \eta = \text{system efficiency} \]
\[ \eta_e = \text{cell quantum efficiency} \]
\[ \lambda = \text{wavelength} \]
\[ \phi = \text{diameter} \]

Subscripts

\[ \text{coat} = \text{protective coating of the photonic crystal} \]
\[ e = \text{electrical power} \]
\( j \) = cell junction
\( s \) = series resistance
\( sh \) = shunt resistance
\( t \) = thermal power

I. Introduction

In this paper, we present a design methodology of a radioisotope thermophotovoltaic (RTPV) generator using photonic crystal spectral control. The design directly leads to a functional engineering unit using the experimentally tested emitters, thermophotovoltaic (TPV) cells, and thermal insulations that have already excluded any material incompatibility. We present the construction of such a system in the following ways: the use of selective emitter spectral control to enhance the system efficiency, the practical solution of the thermal insulation, the optimization methods of the efficiency design, the challenges to reduce the radiator mass, and the design example based on the InGaAsSb cells available to us. We show computationally that an 8.6% efficiency and 10.1 W/kg can be achieved with the InGaAsSb cells. Using the status of the art InGaAs Monolithic Integrated Module (MIM) cells, an efficiency of 18% and a specific power exceeding 20 W/kg is possible. Consisting of only solid-state materials, an RTPV system has potential to triple the performances of the widely used Radioisotope Thermoelectric Generators (RTG).

Thermal-based radioisotope batteries can provide long-lasting energy to the scientific instruments and communication systems on spacecrafts when solar energy is not sufficient for their journey in interplanetary to interstellar space. The radioactive decay heat from the nuclear fuel is converted to electricity by mechanisms such as Seebeck materials [1-3], Stirling engines [4], alkali-metal thermal-to-electric converters (AMTEC) [5], and thermophotovoltaics. We chose to work on the radioisotope thermophotovoltaic system with two-dimensional photonic crystal spectral control because: 1. High efficiency (> 20%) thermophotovoltaic cells were already experimentally demonstrated [6]; 2. An RTPV system consists of only solid-state parts and doesn't have the reliability problems as in the Stirling or AMTEC systems; 3. Spectral control was successfully demonstrated in other high temperature systems to enhance the conversion efficiency, such as the combustion chambers and silicon TPVs [7, 8]. An illustrative RTPV generator using high temperature photonic crystal spectral control is shown in Fig. 1.
a) The components and configuration of a space RTPV generator. b) c) The micro-patterned photonic crystal emitter and the TPV cell. d) The photonic crystal emission spectra corresponding to GaSb and InGaAsSb cell.

**Fig. 1 RTPV system with spectral control using 2-D photonic crystals.**

In an RTPV system, the decay heat released by the plutonia fuel heats an emitter to incandescence, and the infrared photons are converted to electricity by low-bandgap TPV cells. As summarized in a recent review paper, many recent modeling and prototyping works have shown very promising results [9]. Experimentally, the prototype demonstrated by General Atomics without spectral control shows an efficiency exceeding 20% using the InGaAs MIM cells on two sides [10]. Spectral control has been widely researched to improve the system efficiency of an RTPV system, so that more convertible photons are incident on the TPV cell while the ones in the long infrared are either reflected or suppressed. Many spectral control filters/emitters have been under development for the space TPV application, including the non-planar TPV cells, tandem plasma-dielectric filters, and a tuned Frequency Selective Surface (FSS) filter array, etc. [11]. So far, researches have demonstrated one-dimensional, two-dimensional, and three-dimensional micro-structures as selective emitters [12-14]. It was predicted that an RTPV system efficiency as high as 30% was possible with nanostructured photonic devices [15]. In this work, we focused on the two-dimensional photonic crystal emitter with periodic holes because: 1. The photonic crystals were successfully fabricated [16]; 2. The emission spectra
of the emitters can be easily tailored during the micro-fabrication to be suitable for TPV cells of any bandgaps [12];

3. The integration of the photonic crystal into a working RTPV prototype was successfully demonstrated, moving it closer to a practical system [17].

II. System Components and Feasibility

A. Material Compatibility

Typically, the insulation of a radioisotope system consists of the multi-layer insulation (MLI) and/or the micro-porous insulation such as the Min-K. For the GPHS-RTG, the MLI made of molybdenum foil separated by Astroquartz cloth was used [18]. In the design of the Advanced Stirling Radioisotope Generator (ASRG), a porous material Microtherm HT was used as the insulation for the best combination of low thermal conductivity and low density [19]. In the illustrative design of the radioisotope AMTEC system, a combination of Min-K and MLI was used to shield the heat loss in different positions [20].

The efficiency of an RTPV system depends on several factors: the quality of the cell, the effectiveness of the thermal insulation, and whether spectral control is used. Most of the advanced spectral control technologies are realized by micro-fabricated structures with feature sizes similar to the emission wavelengths [21]. Their effectiveness is strongly dependent on the surface conditions. As a result, when spectral control is incorporated, the system design faces more challenges, especially with the thermal insulation as it needs to be designed very clean without any possible contaminants at high temperatures. During the testing of the prototype [17], various insulation materials were experimented to see their compatibilities with the emitter. Table 1 lists the materials tested and their applicability.

| Material                      | Thermal conductivity [W/mK] | Max Temp [°C] | Compatibility | Notes                                               |
|-------------------------------|-------------------------------|---------------|---------------|-----------------------------------------------------|
| Silica aerogel                | 0.0017                        | 600           | ×             | Sintering starts at 600°C                            |
| ZrO₂ felt                     | 0.12                          | 1200          | ×             | Outgassing, but relatively clean                     |
| ZrO₂ powder                   | 2                             | 1200          | ✓             | Sprinkled as the spacers between MLI                |
| Quartz glass                  | 3                             | 1200          | ✓             | Clean, but not suitable for flexible shapes          |
| Quartz wool                   | 0.47                          | 1200          | ✓             | Cotton like, clean but not insulating enough         |
| Min-K and similar             | 0.25                          | 1100          | ×             | Outgassing reactive gases                            |
| Stainless steel mesh          | 8                             | 1200          | ✓             | Not thermally insulating enough                      |
| High temp epoxy               | 0.01                          | 1200          | ×             | Too dirty to use                                     |

For an RTPV system with spectral control, the micro-porous insulation is in general not applicable because of outgassing. The tested materials included the products from several companies, such as Gemcolite from Unifrax and
Alfibond from Morgan Advanced Materials with and without pre-baking. The results all showed significant amount of outgassing that destroyed the micro-patterned surfaces even with protective coatings (hafnia coating) and resulted in a loss of selectivity over time. As a result, the insulation can solely be composed of MLIs made of reflective metal foils and Zirconia powder in between. The following design and analysis methods are based on these results and use only MLIs for the thermal insulation.

B. Selection of TPV Cells

The cells usable in a TPV application have bandgaps ranging from 0.3 eV - 0.8 eV. The three most commonly used TPV cells include: GaSb, InGaAs, and InGaAsSb [22, 23]. Other types of TPV cells were also explored, such as the germanium cell, and the lower bandgap InAs (0.35 eV) and InAsSbP (0.3 – 0.5 eV) cells. However, germanium cells have passivation problems because of the lack of a good oxide. The compound cells with very low bandgaps have poor electrical performances and are normally added to other cells to create a tandem structure [24].

The governing equations for the cell performance are shown in equation (1) and (2), where the photocurrent $I_{ph}$ is generated by the illuminated emitter. The $e$ is the elementary charge, $F$ is the view factor, $\frac{hc}{\lambda}$ is the energy of a single photon, $E_{ci}$ is the wavelength dependent emissive power, $\eta_E$ is the external quantum efficiency, and $\lambda$ is the wavelength. The TPV cells considered in this work are the tested GaSb cell (0.72 eV bandgap) and InGaAsSb cell (0.55 eV bandgap) [25].

We had them in our labs and were able to measure most of their characteristics in equation (2), including the quantum efficiency (QE), the dark current $I_0$, the series electrical resistance $R_{series}$, the shunt electrical resistance $R_{shunt}$, and the ideality factor $n$.

$$I = I_{ph} - I_0 \left( \exp \left( \frac{q}{nk_BT_f} (V + IR_s) \right) - 1 \right) - \frac{V + IR_s}{R_{sh}} \quad (1)$$

$$I_{ph} = qF \int_0^{\infty} \frac{\lambda}{hc} E_{ci}(\lambda) \eta_E(\lambda) \, d\lambda \quad (2)$$

The cell efficiency $\eta_{cell}$ depends on the intrinsic parameters and the optimized emitter spectrum. As the emitter temperature increases, more convertible photons are incident on the cell to contribute to more photocurrent and output power. When the temperature rises beyond the optimal point, the cell output power still increases, but the efficiency starts to decrease because the improvement in the output power cannot balance the increased radiative power from the emitter. The excess power quickly heats up the cell that makes the radiator design more challenging.

The maximum efficiencies the cells achieved in our lab are around 10% for the InGaAsSb and around 7% for the GaSb. In the TPV research, the record efficiency was achieved by the InGaAs MIM cells. The modules were firstly
developed by NASA back in 1996. With the modules fabricated on the semi-insulating InP substrate, a large area and high voltage device is possible. The cells are currently batch produced by Emcore Photovoltaics Inc., demonstrating a conversion efficiency of 20.3% with a blackbody emitter at 1,000°C [26].

C. Heat Sink

As the RTPV technology is still in the early stage of development, there hasn’t been any experimental demonstration of a comprehensive system with radiators. Most of the engineering units used a water-cooled plate to remove the excess heat coming to the TPV cell as in [10, 17]. In this section, we present the challenges facing the heat sink design, and discuss the status of the art advanced radiators possible for an RTPV system so that the technology preserves the benefit of a high specific power.

Space environment is high vacuum with very little conduction or convection, and the only way to remove heat is by radiation. In satellite and spacecraft designs, efficiently rejecting the waste heat has always been a challenge to thermal engineers. Comparing to other thermal-based radioisotope generators, such as the RTG, Stirling engine, or AMTEC, an RTPV generator has the most challenging heat sink design because the TPV cell's optimal operation temperature is near room temperature. Thus, the rejection temperatures of an RTPV system are 200 - 300°C lower than the others, requiring radiators with stronger heat rejection capabilities. The usual fin radiators for RTG and Stirling generators cannot be used for RTPV systems because the efficiency loss during the waste heat transport path. In the space RTPV generator, the TPV cell bears the largest heat loads because most of the decay heat is designed to be incident on the cell. To keep the cell at near room temperature for optimal performance, a disk radiator is chosen to attach to the cell directly.

To design the lightest radiator, we compare the mostly used materials for current space systems as shown in Table 2. The GPHS-RTG radiator consists of 8 fins, and each is 18 inches long, 3.5 inches wide, and tapers from 0.055 inch from the base to 0.015 inch at the tip. The materials used aluminum 5056 and 2219 alloys because of their high corrosion resistance and low density of 2.7 g/cm³ [19]. However, the thermal conductivities of aluminum alloys are only ~100 W/mK, making them more suitable for smaller heat loads with higher rejection temperatures. The ASRG used even lighter beryllium fin radiator with a thickness of 0.06 inch. Other lightweight metals, such as Mag-Thor, are not commonly used because of the safety concerns in the manufacturing and transportation process. Among the current radiator technology, the honeycomb panel radiator widely used in the near-orbit satellites, is also considered.
The honeycomb core maintains the structural rigidity while minimizes the amount of materials used. The efficient in-plane heat transport is realized by the embedded heat pipes filled with a phase changing working fluid. The panel’s effective density and thermal conductivity can easily be tailored by changing the honeycomb and heat pipe designs. Even though the density of the honeycomb core can be as low as 20 – 168 kg/m³ (commercially available from CEL Components Inc.), adding the face-sheets and heat pipes still gives the panel radiator a density comparable to a solid metal one. The carbon-carbon composites (C-C composites), which are matrix reinforced carbons fibers, are under development for high performance space radiators [27]. The composite material has a higher thermal conductivity above 200 W/mK and enough rigidity to be used by itself but is more massive and expensive to produce.

| Material                  | Specific areal density [kg/m²] | Applications       |
|---------------------------|--------------------------------|--------------------|
| Aluminum alloy            | 2.44 [18]                      | GPHS-RTG           |
| Beryllium                 | 2.82 [19]                      | ASRG               |
| Carbon fiber              | 3 [28]                         | SP 100             |
| Honeycomb panel           | 2.75 [29]                      | International Space Station |
| Carbon-carbon heat pipe   | 1.0-1.45 [30]                  | Under research     |
| Carbon-carbon composites  | 1.6 [31]                       | SAFE-400           |

Both the solid metal radiator and the traditional panel radiator such as the one used for the International Space Station (ISS) with a specific rejection power of 0.1 – 0.2 kW/kg are very massive for the RTPV system, so that the benefits of a high specific power is lost. An advanced carbon-carbon radiator with heat pipes, such as the one described in [30] can potentially be used for its low areal density. If more lightweight and efficient radiators, such as the Liquid Droplet Radiator (LDR) whose specific rejection power is larger than 1.4 kW/kg [32] can be realized, the RTPV system can potentially benefit from an even lighter radiator.

### III. System Modeling and Design Methodology

#### A. Modeling of Multilayer Insulation

The multilayer insulation (MLI) made of reflective metal foils separated by zirconia powder is used as the insulation. The radiating surfaces are assumed to be gray emitters obeying the Stefan-Boltzmann relationship with an emissivity $\varepsilon$. Even though most of the surfaces, especially the ones used for radiation shielding, composes of both specular and diffusive emissivity. We simplified the calculation to assume that all surfaces are diffusive. Then, we used the electrical network analogy described in [33].
For each single layer of the MLI, the governing heat transfer equation is shown in equation (3) and (4). The equation describes the heat flow from adjacent surface j to surface k. The $E_{bj}$ and $E_{bk}$ are the emissive power of respective surfaces $E = \varepsilon\sigma T^4$. The $Z_{j,k}$ represents the overall heat transfer impedance from surface j to surface k, which is composed of the radiative resistance, and the conductive resistance from the spacer material. The first two terms in equation (4) represent the radiative resistances and the last term is the conductive thermal resistance, which is dependent on the adjacent layer temperatures. When many concentric layers are used, equation (5) describes the heat transfer from the heat source across many layers of shields to the outermost chamber. The heat flux $Q_{MLI}$ is the total heat loss through the MLI.

$$Q_{MLI} = \frac{E_{bj} - E_{bk}}{Z_{j,k}}$$ (3)

$$Z_{j,k} = \frac{1}{\varepsilon_j A_j} + \frac{1}{A_k} \left( \frac{1}{\varepsilon_k} - 1 \right) + \left( \frac{T_j^4 + T_k^4}{A_{\text{spacer}} k_{\text{spacer}}} \right)$$ (4)

$$\begin{cases} Q_{MLI} Z_{5,1} = E_{b5} - E_{b1} \\ Q_{MLI} Z_{1,2} = E_{b1} - E_{b2} \\ \vdots \\ Q_{MLI} Z_{n,o} = E_{bn} - E_{bo} \end{cases}$$ (5)

We computed the thermal performance using MATLAB by solving the sequence of equations, where s and o denotes the source and the outside chamber holding the MLI. The number 1, 2 are the number of MLI layers. The accuracy of the model was verified using an experiment setup shown in Fig. 2(a). The setup includes a cartridge heater housed inside a molybdenum sheath attached to the vacuum flange with a hollow stainless support. The external surface of the sheath was painted with a high temperature emissive coating having an emissivity of ~ 0.8. 5 layers of 15 layers of copper MLIs were spirally wound around the near black surface to compare their shielding effects. As the temperature increased from room temperature to around 800°C, the power input and the temperature of the inner two layers of MLIs were measured with thermocouples.

Good agreement has been achieved between the measurement (dotted points) and simulation results (solid lines). Figure 2(b) shows that increasing the number of MLI layers from 5 to 15 can significantly increase the insulation performance. Figure 2(c) shows the temperatures probed at the 2\textsuperscript{nd} and 3\textsuperscript{rd} layers of the MLI for the 5 layer shielding and agree well with the simulation based on the electrical network analogy.
a) The setup to measure and verify the MLI performances. b) c) Comparison between the measurement and the simulation results.

**Fig. 2 MLI setup to verify the simulation model.**

The total uncertainty $U_{95}$ is defined by the ASME US national standard in 1998, and can be assessed using equation (6). The $t_{05}$ is the coverage factor and is equal to 2 while the subscript indicates a 95% confidence interval. The B denotes the bias uncertainty that is caused by the systematic error, and R denotes the precision uncertainty cause by random factors such as noises.

$$U_{95} = \pm t_{05} \sqrt{B^2 + R^2}$$  \hspace{1cm} (6)

Based on the specifications of the measurement instruments from Omega Engineering Company, the contribution of the bias uncertainty can be summarized as: 1. Thermocouple wires have a standard limit error with an uncertainty $B_1 = 2.2^\circ C$ or 0.75% of reading, whichever is greater; 2. Data acquisition OMEGAETTE® HH306 device has an uncertainty $B_2 = 0.2\%$ reading +1°C. The precision uncertainty comes from the resolution level of the data acquisition device with $R_1 = 0.1^\circ C$.

$$B = \sqrt{B_1^2 + B_2^2}$$  \hspace{1cm} (7)
\[ R = R_1 = 0.1^\circ C \]  

The uncertainty contributed by the bias and precision factors are calculated in equation (7) and (8). The uncertainty levels of \( U_{qs} \) are plotted as the error bars in Fig.2. In the uncertainty analysis, the potential error sources, including the axial temperature non-uniformity of the MLI layer, and the mounting error of the thermocouples were not included.

**B. Photonic Crystal Selective Emitter Spectra Design**

The two-dimensional photonic crystal selective emitter was used to realize spectral control. Based on the selected TPV cell, the selective emitter needs to be designed with the proper microstructures so that the maximum in-band emissivity is achieved. Due to the emitter’s high operating temperature, the photonic crystal is selected to be tantalum for its high temperature stability and better weldability comparing to tungsten. The emission spectra were simulated using the Stanford Stratified Structure Simulator (S\(^4\)) that solves the Maxwell equation in layered structures by the rigorous coupled wave analysis (RCWA) [34]. The code was extensively used to design optical devices and showed a good agreement with the experiments in the selective emitter design in [35].

In our analysis, we firstly extract the material properties, more specifically the frequency dependent permittivity based on the Lorentz-Drude model as shown in Equation (9). The \( \varepsilon_{\infty} \) is the permittivity at infinite frequency, \( \omega_{pm} \) is the plasma frequency, \( \omega_{om} \) is the natural frequency, and \( \Gamma_m \) is the damping frequency of the m-th Lorenzian oscillator. The permittivity can be related to the material’s reflectivity by Equation (10). The parameters can be extracted by fitting the real and complex part of the refractive index from the material’s reflective spectrum available from the Palik data [36]. We used the free software Reffit to extract the parameters [37].

\[
\varepsilon(\omega) = \varepsilon_{\infty} + \sum_{m=1}^{N} \frac{\omega_{pm}^2}{\omega_{pm}^2 - \omega^2 - i\Gamma_m} 
\]

\[
R(\omega) = |\frac{1 - \sqrt{\varepsilon(\omega)}}{1 + \sqrt{\varepsilon(\omega)}}|^2 
\]

When using the S\(^4\) to solve the selective emitter’s spectrum, we define the micro-structured holes on photonic crystals with parameters: period \( a \), radius \( r \), depth \( d \), and the protective coating thickness \( d_{coat} \) as shown in Fig. 3. The vacuum above and below the structure extends to infinity and has relative permittivity of 1. The protective hafnia coating has a relative permittivity of 4 at infrared frequency, and the tantalum’s permittivity used the wavelength dependent ones extracted from the Reffit software from data [36]. The light wave is normally incident with a magnitude of 1.
Fig. 3 Modeling of the photonic crystal selective emitter using S4.

The convergence of the simulation is analyzed by varying the number of Fourier components. The RCWA is a semi-analytical approach that solves the Maxwell equation along the discretize layers of the structured material. The error diminishes as the number of Fourier modes increases, but at a more and more expensive computational cost. As the exact solution is not available, we take the solution at the number of Fourier modes N = 500 to be the reference solution. We simulated the spectrum of the InGaAsSb cell (parameters listed in Table 7) and varied N from 200 to 300 with the relative error gradually decreasing with the number of modes as shown in Fig. 4. The L1 norm of the relative error is defined in Equation (11). Ω refers to the discretized the frequency range, which in this case is from 1 – 3 μm with a spacing of 0.1μm.

\[
\|u_r\| = \frac{1}{\Omega} \sum_\Omega \frac{|u^{(N)}_r - u^{ref}_r|}{\|u^{ref}\|} \tag{11}
\]

Fig. 4 Convergence analysis of the photonic crystal simulation.
C. Optimize RTPV System Efficiency

For any power delivery system, the impedance matching is an important concept. The idea can be summarized as: the maximum power is delivered to the load when the source and load impedances are matched. In the RTPV system, the maximum efficiency can also be achieved with an impedance matching method as briefly described in [38]. The generator’s complete equivalent circuit model is shown in Fig. 5.

The thermal block on the left describes the heat flow of the RTPV system with \( Q \) and \( Z \) referring to the heat flux and thermal impedances respectively. The GPHS fuel source is equivalent to a current source that outputs a fixed amount of heat flow regardless of the external configuration. Some heat is emitted from the emitter to generate electricity, and the rest is lost through ineffective surfaces and supports. The useful heat \( Q_{\text{emitter}} \) is the part that is used to generate electrical power by the TPV cell described by the electrical block on the right, where I and R referring to the electrical current and resistance, respectively.

The internal impedance is parallel to the source and is composed of the resistance through the ineffective surfaces \( Z_{\text{parasitic}} \) and the resistance from the cavity \( Z_{\text{cavity}} \). The \( Q_{\text{parasitic}} \) composes of the conductive heat loss and the radiative loss through ineffective surfaces, among which radiation loss through the MLI is dominant. The loss through the cavity is caused by the imperfect view factor, which is the proportion of radiation leaving the emitter that strikes the cell. The emitter-cell distance is adjusted to be as close as possible, and the view factor can achieve above 0.95. The external impedance denotes the resistance that the thermal circuit sees from the emitter port \( Z_{\text{emitter}} \). The thermal energy from the emitter is the useful part that contributes to the generation of the photocurrent in the TPV cell.
Fig. 5 Equivalent circuit model of an RTPV generator.

Figure 6 shows the simulation of the thermal block of an RTPV system. The blue line represents the power from the GPHS that goes toward the emitter, which is the total power subtracting the parasitic losses. The black lines represent the power emitted from the emitter with different temperatures and areas. By varying the size of the emitter, we can always find a match between the thermal power extracted from the source and the one required by the load to produce the maximum amount of electrical power.

Fig. 6 Simulation of thermal block of the RTPV system.
In our simulation, when the InGaAsSb cells are used, the maximum efficiency point is reached when the heater operates at 950°C. Similarly, for the GaSb cells, the optimal efficiency is achieved when the emitter operates at 1,150°C. Figure 7 shows the cell efficiencies and the surface plot of electrical power output as a function of the GPHS unit number and the optimized emitter area when InGaAsSb cell is in use. Intuitively, the number of GPHS sources determines the output level. When the emitter area is too large, the source temperature is too low to generate any useful photons. When the emitter is too small, there is not enough areas for useful energy generation. For any number of GPHS unit, there exists only one optimal efficiency point for the generator. The accuracy of the modeling was verified in the small prototype experiment described in [17], which composed of all the essential parts, such as the insulation, the selective emitter, the InGaAsSb cell, housed in a vacuum environment (except the radiators). The experiment was a smaller version of the RTPV generator that output 200 mW of power from 1 cm² InGaAsSb cell.

Fig. 7 RTPV system output and efficiency performances.

D. Modeling of the Heat Sink

The radiator for an RTPV system can be designed by optimizing the material's thermal conductivity $k$ and the geometry. The heat loads enter in the disk center, spread radially within the disk, and radiate to space simultaneously as shown in Fig. 8.
The disk radiator can use the model of an annular fin radiator with only radiation and conduction. The radiator performance can be approximated using the fin efficiency (defined as the actual heat flow to the maximum possible heat flow when the fin is isothermal), which is introduced because of the finite thermal conductivity of the radiator material. The hotter radiation center has higher heat rejection capability while the edges cool down and become less efficient. The one-dimensional circular fin efficiency with a rectangular profile was computed with a numerical solution that is dependent on the fin’s geometry, temperature, and thermal conductivity [39]. A disk radiator can also incorporate a trapezoidal profile to help with the weight reduction. A trapezoidal radiator often sacrifices the thermal performance because of the reduced heat conduction to the radiator edges. However, the specific radiation power could be higher, especially when a material with high \( k \) is used. For a tapered radiator, the fin efficiency is also adjusted to incorporate the taper angle \( \alpha \) [40].

Chambers and Somers in [39] described one of the solutions for the annular fin radiator with a rectangular profile. The assumptions of the solution is: the fin is a radially conductive radiator that radiates with the top surface with a gray body emissivity. The fin efficiencies were solved by a second-order nonlinear differential equations. By comparison, we built the same model in the COMSOL Finite Element Analysis (FEA) heat transfer model. The panel radiator was assumed to have a uniform thermal conductivity and density. The heat loads entered in the center of the radiator and only in-plane conductions and out-of-plane radiations were present.

### Table 3 Comparison of fin efficiencies by COMSOL and Chambers methods

| Materials                  | Stainless steel 304 | Aluminum 2219 | Copper  | Honeycomb panel |
|----------------------------|---------------------|---------------|---------|-----------------|
| k = 14.4 W/mK             | 0.3678              | 0.7820        | 0.9136  | 0.9611          |
| COMSOL FEA                |                     |               |         |                 |
| Chambers & Somers         | 0.3853              | 0.8027        | 0.9151  | 0.9515          |
The results for the fin efficiencies are well matched for a radiator with a rectangular profile (0.95 m diameter and 3.3 cm thickness) as shown in Table 3. Based on the global posterior error estimates, the L1 norm of the error in the computed temperature and the order of convergence of the FEA analysis are shown in Fig. 9.

Fig. 9 L1 norm of error in temperature with grid refinement.

We designed the radiator for the RTPV system by simulating different materials with various geometries in COMSOL. The radiator was designed with a trapezoidal profile with the heat load entering the center. The emissivity of the surfaces was assumed to be 0.92, which approximates the paint PD224 used in RTGs. The radiator was sized so that the base temperature was no higher than 310 K to allow the TPV cells to maintain their optimal performances. The thickness of the radiator was set to 1.8 cm, following the panel radiator used in the ISS [29]. We assumed that the total waste heat is radiated with a double-sided radiator. The radiator’s areal density follows the best results partially demonstrated in [30] as 1 kg/m², and the practical results of 2.75 kg/m² based on the panel of the ISS [29]. Table 4 shows the required thermal conductivity and mass with 550 W, load for different radiator sizes (trapezoidal profile with α = 6° angle and t_{super} = 1.8 cm thickness). This load corresponds to an RTPV generator output ~100 W_e using InGaAsSb cells.

| Diameter | Thermal conductivity [W/mK] | Radiator mass [kg] |
|----------|-----------------------------|--------------------|
| 0.9 m    | 900                         | 1.26 – 3.46        |
| 0.95 m   | 500                         | 1.41 – 3.88        |
| 1 m      | 350                         | 1.56 – 4.29        |
The lower ends of the radiator performances are optimistic predictions but are within reasonable range of the technologies in use today. A thermal conductivity of 350 W/mK is very reasonable with composite materials. The higher end of the required thermal conductivity is achievable with more advanced technologies. For example, the pulsed heat pipe design by Hemadri et al. [41] showed an effective conductivity as high as 900 – 2,500 W/mK. The liquid droplet or liquid sheet radiator can achieve a specific power larger than 1,000 W/kg easily [42].

E. RTPV Space Generator Design Example

Firstly launched with satellite Transit in 1961, radioisotope generators have safely powered numerous space missions without even a single accident that has caused any disastrous situation. The smallest launched generator weighed only 2 kg and output 2.7 W; while the GPHS-RTG unit used in the Ulysses, Galileo, and Cassini-Huygens weighed 57 kg and output 285 W [1, 18]. Nowadays, small size radioisotopes suitable for satellites are rarely used because the fuels are scarce and expensive. Most of the radioisotope generators are designed for planetary and extrasolar explorations. The power budgets are normally in the range of several hundred watts. The recently launched MMRTG with Curiosity Mission has a power budget of 117 W [43]. We designed the RTPV generator based on the same level of output power, so that it is not too big to handle, and has the flexibility to satisfy most mission requirements with one or several units.

Based on the InGaAsSb cells, about five GPHS units are needed to provide 1,250 W (thermal power) decay heat. The heaters are housed inside a thin-shelled tungsten canister with two rectangular stands extruded from the two smallest surfaces of the GPHS stack. The sizes of the emitter and the TPV cells need to be both 210.5 cm². The energy conversion elements can be put as a single unit, or split into two equal areas on the two smaller surfaces. We chose the latter configuration because it makes the system more symmetric and reduces the heat loads of a single radiator. Putting the MLI around non-effective surface is also easier for a symmetric configuration. The selective emitters and the TPV cells are split into two equal areas and mounted onto the stands of the canister housing. The rest of the system is insulated by MLI shielding with cutouts of the emitter stand and supports. An annular Inconel support is used to connect the heat source to the external chassis. The support can be either welded or brazed to the canister and chassis to form a metallic bond between the two parts. The generator operates in a vacuum environment, held by an aluminum chassis with two radiators attached to the TPV cells directly. The complete figure is shown in Fig. 1(a) and the design details and the estimated performance are given in Table 5. The parameters, governing equations, and constitutive relationships are presented in the Appendix.
Table 5 Space RTPV generator design details and estimated performance

| Design Parameters          |                     |
|---------------------------|---------------------|
| Heat source               |                     |
| No. GPHS units            | 5                   |
| Canister thickness        | 1 mm                |
| Emitter stand thickness   | 3 mm                |
| Conversion TPV cells      |                     |
| Emitter area (2 total)    | 210.5 cm²           |
| TPV cell type             | InGaAsSb            |
| TPV cell area (2 total)   | 210.5 cm²           |
| TPV cell mount thickness  | 0.5 mm              |
| Insulation                |                     |
| No. MLI layers            | 30                  |
| MLI foil thickness        | 0.025 mm            |
| Support and housing       |                     |
| Support thickness         | 2 mm                |
| Support perimeter         | 58 cm               |
| Chassis wall thickness    | 2.5 mm              |
| Heat sink                 |                     |
| Number of radiators       | 2                   |
| Cross section profile     | Taper               |
| Taper angle               | 6°                  |
| Radiator radius           | 1 m                 |
| Radiator thickness        | 1.8 cm              |
| Surface emissivity        | 0.92                |
| Performance Estimates     |                     |
| Output power              | 107.5 W             |
| Source temperature        | 950°C               |
| Rejection temperature     | 20°C                |
| System efficiency         | 8.6%                |
| System mass               | 10.67 kg            |
| System specific power     | 10.1 W/kg           |

The mass of the RTPV generator is analyzed and summarized in Fig. 10. The majority of the generator mass is concentrated in the heat source, which is mostly the mass of the GPHS units. The radiator takes the second largest portion of the generator mass. The insulation and energy conversion elements together take only around 10%. The specific power of the generator is approximately 10.1 W/kg. The thermal efficiency is about 85%, comparable to the 90% of status of the art RTGs [44]. The major limitation for the efficiency and specific power is the TPV cell efficiency, which is only ~10% for the InGaAsSb cell.
The system design can be easily extended to other types of the TPV cell as shown in Table 6. For the InGaAs MIM cells with a device efficiency exceeding 20%, the system efficiency is expected to be at least 18%, with a specific power ranging from 13.6 to 21.8 W/kg.

Table 6 Performance estimation of RTPV systems with common TPV cells

|                      | InGaAsSb | GaSb | InGaAs MIM |
|----------------------|----------|------|------------|
| GPHS unit number     | 5        | 8    | 3          |
| System output level  | 107.5 W_e | 110 W_e | ~135 W_e  |
| System efficiency    | 8.6%     | 5.5% | ~18%       |
| System mass (best case) | 10.7 kg | 17.2 kg | 6.2 kg    |
| System mass (worst case) | 17.5 kg | 28.5 kg | 9.9 kg    |
| System specific power | 6.1 - 10.1 W/kg | 3.9 - 6.4 W/kg | 13.6 - 21.8 W/kg |

This specific power prediction is in agreement with [45] for the current radiator technology. The low rejection temperature is a strong limitation to the system specific power. The lower bounds using the InGaAsSb cell are comparable with the current RTGs. With a similar rejection temperature, if the higher efficiency InGaAs MIM cells are used, it is possible to double or triple the status of the art specific power. With even more advanced radiators demonstrated in the laboratories, it is promising for these lightweight materials to combine with the RTPV to allow it to be three or four times more efficient and lighter for future space power solutions.
IV. Conclusion

Radioisotope generators have been proven to be very safe and reliable for the past 50 years. From the near earth satellites to the outer solar planets, the radioisotope generators have powered numerous missions which couldn't be feasible with other technologies. Radioisotope thermophotovoltaic generators are promising power solutions with high efficiency and high specific power for the next generation’s space mission. Comparing to a 6.6% conversion efficiency and 5.2 W/kg of the current Radioisotope Thermoelectric Generator (RTG), a practical RTPV generator is expected to triple the status of the art with the demonstrated devices, insulations, and heat rejection technologies.

Appendix

- **TPV cell**

\[
I = I_{ph} - I_0 \left( \exp \left( \frac{q}{n k_B T_j} (V + IR_s) \right) - 1 \right) \frac{V + IR_s}{R_{sh}}
\]  

\[
I_{ph} = qF \int_0^\infty \frac{\lambda}{hc} E_\lambda(\lambda) \eta_\lambda(\lambda) d\lambda
\]

The symbols in the equation are explained in Section II part B. The cell parameters and the corresponding selective emitter parameters are given in Table 7.

**Table 7 Parameters of TPV cell and the corresponding selective emitter designs**

| Selective emitter | Parameters | InGaAsSb cell | GaSb cell |
|-------------------|------------|---------------|-----------|
|                   | Period     | 1.37 μm       | 1.10 μm   |
|                   | Radius     | 0.61 μm       | 0.45 μm   |
|                   | Depth      | 6.74 μm       | 6.87 μm   |
|                   | Coating (HfO₂) | 20 Å         | 20 Å      |

| TPV cell | Parameters | InGaAsSb cell | GaSb cell |
|----------|------------|---------------|-----------|
|          | Rs         | 0.0299 Ω      | 0.031     |
|          | R_{sh}     | 302.599       | 700       |
|          | n          | 1.146         | 1.106     |
|          | I₀         | 0.605 μA      | 0.438 μA  |
• The heat transfer over the MLI layer (electrical network analogy method)

\[ Q_{MLI} = \frac{E_{bj} - E_{bk}}{Z_{j-k}} \]  

\[ Z_{j,k} = \frac{1}{\varepsilon_j A_j} + \frac{1}{\varepsilon_k A_k} + \frac{(T_j + T_k)(T_j^4 + T_k^4)^t}{A_{spacer}\kappa_{spacer}} \]  

\[
\begin{align*}
Q_{MLI, Z_{s,1}} &= E_{bs} - E_{b1} \\
Q_{MLI, Z_{1,2}} &= E_{b1} - E_{b2} \\
&\vdots \\
Q_{MLI, Z_{n,o}} &= E_{nb} - E_{bo}
\end{align*}
\]  

(3)

(4)

(5)

The symbols in the equation are explained in Section III part A. In design example, the spacer material is chosen to be Zirconia with a thermal conductivity of 0.1 W/mK with an area that covers roughly 10% of the metal foil. The foil is chosen to be molybdenum with an effective emissivity \( \varepsilon \approx 0.2 \).

• The heat transfer over supports, chassis, and radiators

The overall system is designed in vacuum and the heat transport mechanisms only involve conduction and radiation. With a system in thermal equilibrium, the heat transport through each component can be described in Equation (11), constituting of two parts: the conductive heat transfer and the volumetric heat source \( Q_{gen} \). The components with a heat source include the canister housing the GPHS units, the TPV cell with irradiation from the emitter, and the chassis with irradiation heat from the MLI heat leakage. The components with radiative heat loss obey the Stefan-Boltzmann relationship in Equation (12), where \( A \) is the area, \( F \) is the view factor that is slightly less than 1 for the emitter-cell radiation calculated based on [46], and \( \varepsilon \) is the emissivity. The selective emitter emits to the TPV cell at room temperature, and the chassis and the radiator emit to the outer space with \( T_{amb} \approx 4 \) K. The effective emissivity of the photonic crystal emitter \( \varepsilon_{eff} \) is calculated based on Equation (13), by averaging the wavelength dependent emissive power over a blackbody.

The boundary conditions are set by Equation (14) and (15). The emitter operates at the optimal temperature discussed in Section III part C, and the cell temperature is maintained near room temperature based on Section III part D. The design geometries are given in Table 5 and the detailed materials’ parameters are listed in Table 8.

\[ 0 = \nabla \cdot (k_i \nabla T) + Q_{gen} \]  

(11)

\[ Q_{rad} = -Q_{gen} = AF \varepsilon_{eff} \sigma (T^4 - T_{amb}^4) \]  

(12)

\[ \varepsilon_{eff} = \frac{\int_0^{\infty} e^{\frac{-zhc}{kT}} \frac{hc}{kT} dz}{\int_0^{\infty} e^{\frac{-zhc}{kT}} \frac{hc}{kT} dz} \]  

(13)
\[ T_{\text{emitter}} = T_{\text{optimal}} = 950^\circ C \]  
\[ T_{\text{cell}} \approx 310 \text{ K} \]  

Table 8 Material parameters of the system simulation

| Components | Parameters | Material | \( k \) [W/mK] | \( Q_{\text{gen}} \) [W] | Density [g/cm\(^3\)] |
|------------|------------|----------|----------------|-----------------|-------------------|
| Emitter    | Tantalum   | 56       | 0              | 16.65           |
|            |            | (1000 K) |                 |                 |
| Chassis    | Aluminum   | 115      | \( Q_{\text{MLI}} \) | 2.7             |
| Canister   | Tungsten   | 118      | \( Q_{\text{source}} \) | 19.25           |
|            |            | (1000 K) |                 |                 |
| TPV cell   | InGaAsSb   | 9        | \( Q_{\text{emitter}} \) | 5.61            |
| Support    | Inconel    | 13.188   | 0              | 8.44            |
| Cell mount | Copper     | 400      | 0              | 8.96            |

Funding Sources

This work was partially supported by the Army Research Office through the Institute for Soldier Nanotechnologies under Contract No. W911NF-07-D0004, the MAST contract 892730 and by the S3TEC DE-SC0001299. The work was partially supported by the National Key Research and Development Program of China under Grant 2016YFA0302300 and Grant 2016YFA0200400, and the National Natural Science Foundation of China under Grant 61306105.

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