N91-19210

Radioisotope Thermal Photovoltaic Application of the GaSb Solar Cell

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Introduction

Thermophotovoltaic (TPV) systems have been studied by numerous investigators in the past, due to the possibility of high efficiencies on the order of 30% [refs. 2,3]. In a TPV system solar cells are exposed to the radiant spectrum of an incandescent emitter rather than the solar spectrum. The emitter temperature is chosen so that the peak of its blackbody emission spectrum is close to the optimum wavelength for conversion by the cells, generally near the band edge. Thus, the energy return per absorbed photon may be a factor of two or more greater than it would be for the same cell exposed to the solar spectrum.

The TPV system of ref. 2 consisted of a optical concentrator which focused sunlight on the absorber/emitter, the absorber/emitter which was essentially a blackbody radiator heated by the sun, a reflective cavity used to recycle the unused portion of the radiated blackbody spectrum and silicon solar cells. Due to the nature of the band-gap of silicon, the absorber/emitter had to be maintained at a temperature of 2000 K to 2300 K for high efficiency. The cavity was designed to return energy of a longer wavelength than the band-gap (>1.1 μm for silicon) back to the absorber/emitter to help maintain its equilibrium temperature. The cell, in effect, acted as an optical notch filter absorbing energy from the emitted blackbody spectrum only in that wavelength region where photovoltaic conversion is most efficient. The efficiency of the cell to that portion of the spectrum of wavelength shorter than 1.1 μ then becomes the upper limit of the STPV converter and theory shows that such efficiency can exceed 50 percent [ref. 3]. The study of this system included prototype fabrication and testing. A demonstrated overall efficiency of 13% was achieved using off-the-shelf silicon cells which confirmed the viability of the TPV concept.

Several persistent design challenges arise in attempting to make TPV systems practical. One of these is the necessity of recovering the long wavelength, sub-bandgap energy, usually by cell back-surface reflection. Another arises from temperature limitations on the radiant emitter. Temperatures in excess of 1500 C are needed for efficient operation with silicon cells, which may lead to cavity contamination or be hard to attain with practical heating systems, including solar. Significant progress has been made in some areas, particularly on IR transparent silicon cell technology. However, advances in competing conversion approaches such as tandem cells have reduced the relative advantages of solar-heated TPV.

If one looks beyond solar heated systems the potential for TPV power is still strong. Many applications now being served by radioisotope thermoelectric generators (RTGs) could be better served with solar cells in place of the thermoelectric elements. These include space power applications in which solar panels are unattractive, including missions to the outer planets, Mars rovers, high radiation orbits, and missions in which array pointing torques may disrupt other spacecraft activities. This paper will explore the possibilities for radioisotope TPV, or RTPV power.

One development which may help to make RTPV power the system of choice for such missions has come directly out of the tandem cell effort. This is the GaSb cell as developed at Boeing for use in its GaAs/GaSb tandem cell [ref. 1]. Recent measurements carried out at Sandia laboratories have established AM1.5 efficiency of 37% for stacked cells under concentration. The GaSb cell itself converts only 8% under an AM0 spectrum, but its voltage, fill factor, and quantum efficiency are such that it is an excellent converter of energy near its 1.7 μm band edge. The efficiency of GaSb cells to wavelengths of 1.5 to 1.6 μm is now approximately 35%. By contrast, RTG systems have only recently exceeded efficiencies of 7% and do not appear likely to go much higher. The next section will discuss the expected efficiency for a RTPV conversion cavity which could be constructed with minimal adaptations to the existing GaSb cell.

Performance Analysis

GaSb Cell Requirements

The sub-bandgap reflectance of a GaSb cell is determined by free-carrier absorption in the bulk as well as by the reflectivity of the rear contact metal [ref. 4]. The substrates now being used are doped to 2.5 x 10^{17}. This is a relatively low doping, but not so low as to make carrier absorption negligible. A cell with lower doping could probably be made successfully. However, the existing substrate material was assumed in making performance estimates. The measured transmission of a wafer 0.28 mm thick is shown in figure 1. The overall transmittance is limited by the air interfaces at front and back and the high index of refraction of the GaSb. However, the curve indicates near theoretical transmittance near the bandgap with free carrier absorption increasing as the wavelength increases. The data are consistent with an absorption coefficient of 5 cm^{-1} at 8 μm and a cubic dependence on wavelength. This is very similar to values determined elsewhere for GaAs. A sub-bandgap reflectivity of 0.95 should be achievable with a suitable metal contact on rear-polished wafers. The net cell reflectance expected is shown in figure 2, with a 1100 C blackbody also shown for reference.

Another important feature of the GaSb cell for this application is its spectral response. Figure 3 shows the normalized spectral response of this cell as compared with the normalized blackbody spectrum at 1100 C. As the operating temperature increases the effeciency of the system increases as well. However, there always exists the tradeoff between optimum theoretical performance and the reality of having to maintain an emitter at high temperatures.

Configuration

In the first configuration discussed, the PuO_2 General Purpose Heat Source (GPHS) is used as a source of power. The heat source is encased in graphite and iridium, intended to withstand large impact forces without rupture even in the event of catastrophic mission failure or reentry. The 250 W GPHS modules were developed under a multiyear program managed by the Department of Energy. The configuration is based largely on the design of an RTG generator developed for Mars Rover [ref. 7]. The dimensions of a 250 W unit are 3.66 x 3.83 x 2.09 inches, and weigh 1.45 kg. A proposed configuration using sixteen units in a 2 x 2 x 4 stack is shown in figure 4.

The emitter temperature depends on a number of factors, including power output of the isotope, surface to volume ratio of the module stack, and power recycling via solar cells and other surfaces. For a system with electrical output of 573 watts it was found that the cells should cover approximately 30% of the emitter surface to maintain the emitter temperature in the 2 x 2 x 4 configuration. Other surfaces are covered with a multilayer reflective insulation such as Mo/quartz, with a net heat reflectance of 0.98.

There are other isotopes that have suitable characteristics for this application. A listing of these nuclides with some of their properties is shown in table 1. The two candidates that are the most suitable are Curium-244 (Cm-244) and Strontium-90 (Sr-90). And while Actinium-227 and Uranium 232 may be more desirable in their characteristics, the availability of these isotopes appear to be severely limited.

When applying any of the these isotopes to the model, we will attempt to design for a slightly higher emitter temperature. This is because as emitter temperature is increased the efficiency of the system is increased as well. It is found that by increasing the temperature by 9% (from 1100 C to 1200 C) the efficiency is increased by 18%. A schematic of the system utilizing a Sr-90 disk source is shown in figure 5. The dimensions of this system is based on a 500 watts electrical output. As with the GPHS configuration, this features 30% cell coverage with the remaining area a multilayer reflective insulation to provide 98% reflectance of non-absorbed energy back to the emitter. The heat source is 26 cm in diameter and 2.5 cm thick. Terrestial cladding for Sr-90 has been a super alloy of nickel, Hastelloy [ref. 5]. However, for space qualification, materials that will be able to sustain catastrophic failure are required.

Another configuration of interest would be utilized by microspacecraft. These craft would weigh less than 5 kg, meeting mission goals through multiple, frequent launches as opposed to the current approach of highly reliable, component redundant, single spacecraft. The power needs of the microspacecraft would be met by a small RTPV system employing a higher specific power isotope. This conformation is similar in nature to the GPHS form but on a smaller scale. The total electrical power requirement over 5 years would be about 5 watts [ref. 6]. The heat source would be a cylindrical pellet 1.5 cm in diameter and 1.0 cm thick of Cm-244.

On the negative side of the last two approachs, the use of a new isotopic heat source would require space qualification. This means a substantial expenditure of time, effort and money. And while some of the ground work has already been covered, a program much like that which went into the GPHS qualification would be expected.

Performance Predictions

A computer model of the GaSb TPV conversion cavity was created to test various assumptions regarding cell requirements, efficiency vs. emitter temperature, and system power to weight ratios. The calculation divides the radiant energy spectrum into bins by wavenumber, in intervals of 100 cm^{-1} (approximately 0.03 μm near the band edge). Quantities which are spectrally dependent include cell absorption coefficient based on a free carrier absorption model, emissivity of the radiant emitter, and cell response. For all calculations reported here the emissivity was chosen as 0.85. Selective emitters could also be useful but were not considered here. For the cell, V_{oc} = 0.465 V (as measured at 300 K and 44 suns), fill factor = 0.77, and quantum efficiency = 0.90.

Efficiency as a function of emitter temperature is shown in figure 6 for the system as described above. At any temperature above 850 C the RTPV appears to outperform an RTG system in efficiency; if the overall system has comparable weight, the RTPV should therefore have a substantially higher power density. Discussions with DOE personnel indicate that the GPHS modules should be able to operate as hot as 1100 C without damage to the iridium case. At this temperature the efficiency calculated is 14.4% and the electrical output is 573 watts for sixteen heat sources in a 2 x 2 x 4 stack. The total GPHS weight is 23.2 kg. Calculations were also made for a 1 x 15 stack. This required a lower cell coverage factor to maintain the emitter temperature, about 18%. The resulting efficiency drops to 12.4%, and the output power to 458 watts.

The close relation of the system efficiency with emitter temperature relates to the overlap between the blackbody spectrum and the spectral response of the the cell (See also figure 3). If a heat source other than the GPHS is warrented and higher operating temperatures are possible, significant gains could be achieved. Table 2 outlines the performance of a Sr-90 source and a Cm-244 source and allows a comparison between these systems and the GPHS system. Important points are the specific power of each system and the requirements for a 500 watt output system. The high specific power of Cm-244 gives the capability for much smaller overall systems.

System weights can be estimated by simple analogy with the Mars Rover RTG study carried out by Fairchild [ref. 7]. In that study a 1 x 18 stack gave an electrical output of 280 W BOM. The system weight was 58.67 kg and the specific power was 4.77 watts/kg. The weight is a factor of 2.25 higher than the GPHS weight alone. A similar configuration was assumed for this study except that thermoelectric elements are replaced by cells (lighter weight) and the thermal control system must be made considerably heavier. Otherwise, weights for the canister, insulation, housing, and structural supports should be nearly identical.

In the Mars Rover design the cooling fins operate at about 550 K and the thermal control system contributes 4.7% of the system mass. Modeling of the temperature behavior of the GaSb RTPV predicts that the output will drop by 0.53% per degree near 300 K. The thermal control fins to maintain an RTPV at 300 to 350 K are likely to be larger, perhaps by as much as a factor of five. Including this penalty in our RTPV weight estimate results in a system mass of 61.9 kg and a power to weight ratio of 9.25 watts/kgfor the 2 x 2 x 4 stack configuration. A 1 x 15 stack leads to a weight estimate of 58.0 kg and specific power of 7.90 watts/kg. Either of these power densities is significantly higher than the 4.74 watts/kg now obtainable with thermoelectric generators.

After applying the 500 watt Sr-90 configuration to our model efficiencies and total system power and weights were predicted. The Sr-90 heat source is modeled as a disk of material with a total isotope mass of 6.37 kg. A total power output was modeled at 487 watts at a 17% efficiency and 12.7 watts/kg. However, this system carries with it a heavy radiation dose which is discussed below.

The total mass of the Cm-244 micro-satellite RTPV system is predicted at 100 grams with a electrical output of 6 watts. The small size of the system necessitates the use of more cells per unit area due to the size restriction of the cells themselves; consequently, cell coverage is modeled at 80%. The down side of this is that it will reduce the amount of energy returned to the emitter thus requiring more isotope to maintain the desired temperature. However, by increasing the cell area, the efficiency of the system is boosted to almost 20% at 1200 C.

Source Radiation

Radiation doses are of concern both for material handling by personnel and for long-term degradation of the cells. Personnel protection from gamma doses will involve the same precautions which have been established for RTG missions using the GPHS sources. In addition, both of the alternate isotope candidates have radiation concerns. The Sr-90 material has a high associated gamma dose due to bremsstralung radiation of the emitted β particles. And while this is not expected to be a problem with the cells, there is a real concern associated wth material handling by personnel. The gamma dose is ~1000 R/hr. at 1 meter from the source. This value depends strongly on the Z-number of the isotope cladding material.

Solar cells, however, are known to degrade in neutron environments due to reduced minority carrier lifetimes. Plutonium fuel releases approximately 6000 n/gm-sec at an energy of 1.6 MeV. An RTPV with a 468 watt output requires sixteen modules with 9.54 kg of plutonium oxide, so over a ten year period 1.8 x 10^{16} neutrons would be released. The cells in the system modeled cover 485 cm^2, which is 30% of the total solid angle of emission. The neutron fluence over ten years is then 1.1 x 10^{13} n/cm^2. In addition, the Cm-244, while having a low gamma component, has high neutron emission. The neutron emission, due to its spontaneous fission decay, is approximately 2.73 x 10^5 n/gm-sec. This is about 45 times more neutrons than the PuO_2 emits. The total ten year neutron fluence from 500 watt system with a Cm-244 source is 5.16 x 10^{13}. Data are not available for neutrons in GaSb, but GaAs test results have shown a power loss of about 15% after exposure to 1 x 10^{13} n/cm^2 at 1 MeV. Both GaSb and GaAs are direct bandgap materials with short absorption lengths, hence, their response to neutrons should be similar. Therefore, it appears that neutron degradation will be a concern but a manageable one.

The computer modeling discussed here is only the first step in the development of a RTPV power system and we look forward to the many technical challanges that must be hurdled prior to the first working protype.

Conclusions

An examination of an RTPV conceptual design has shown a high potential for power densities well above those achievable with RTG systems. An efficiency of 14.4% and system specific power of 9.25 watts/kg were predicted for a system with sixteen GPHS sources operating at 1100 C. The model also showed a 500 watt system power by the strontium-90 isotope at 1200 C at an efficiency of 17.0% and a system specific power of 11.8 watts/kg. The key to this level of performance is a high-quality photovoltaic cell with narrow bandgap and a reflective rear contact. Recent work at Boeing on GaSb cells and transparent back GaAs cells indicates that such a cell is well within reach.

References

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Table 1: Listing of suitable radioisotopes for the RTPV application.

Isotope	Half-life (yr)	Compound	Melting Temp. (K)	Watts/gm
Strontium-90	28	SrO	2700	0.453
Curium-244	18	Cm2O3	2400	2.35
Uranium-232	72	UO2	3100	4.22
Actinium-227	22	Ac2O3	---	12.7

Table 2: A comparison of RTPV operating characteristics with different radionuclide source material.

Isotope and/or Configuration	Operating Temperature (C)	Efficiency	Output Power (watts)	Mass (kg)	Watts/kg
GPHS (1x15)	1100	12.4	458	58	7.90
GPHS (2x2x4)	1100	14.4	573	61.9	9.25
Sr-90	1200	17.0	487	41.2	11.8
Sr-90	1200	17.0	49	3.85	12.7
Cm-244	1200	17.0	413	7.56	54.6
Cm-244	1200	19.9	6	0.10	60.0
RTG	1000	7.42	278	58.6	4.74

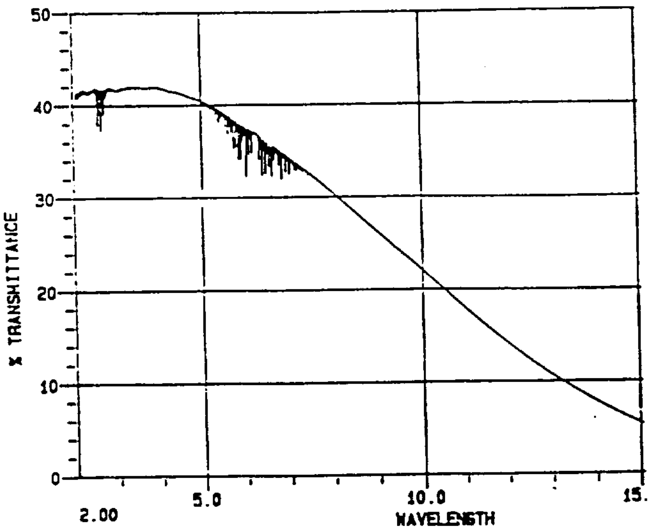

Figure 1: Transmission through a GaSb wafer doped to 2.5 x $10^{17}/cm^3$.

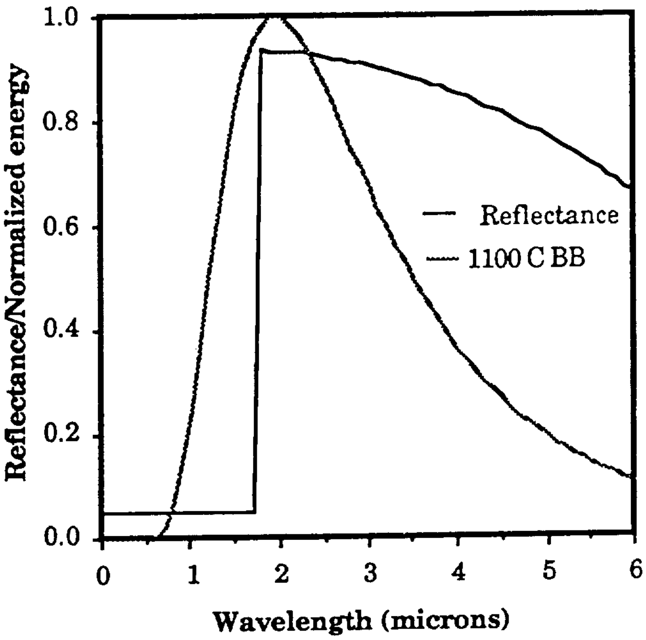

Figure 2: Predicted reflectance of GaSb cell with reflective rear contact. The emission spectrum of a 1100 C blackbody is included for reference.

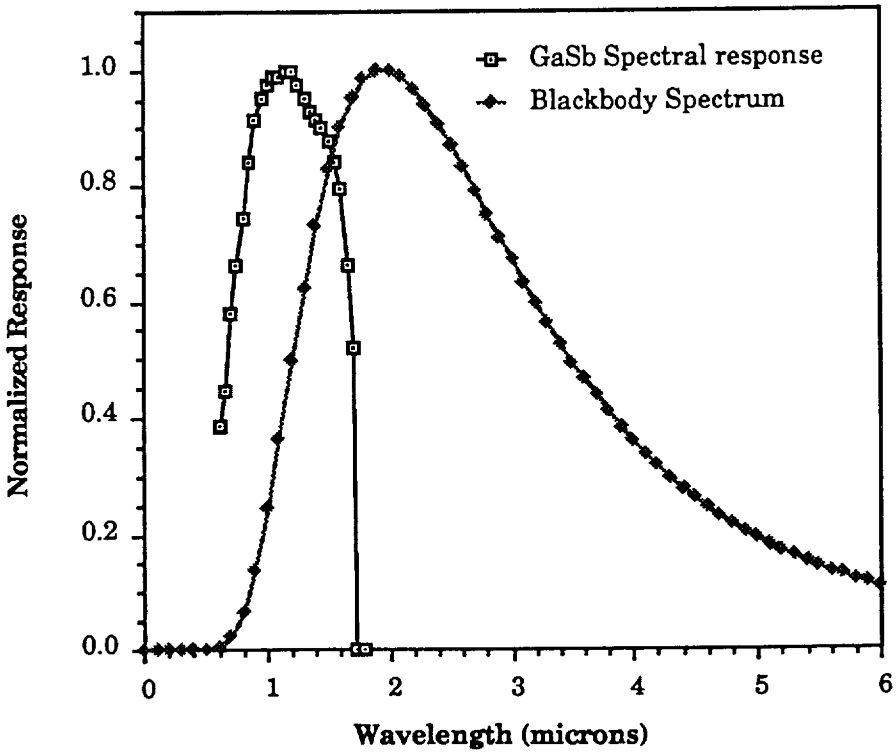

Figure 3 Normalized spectral response of the Boeing GaSb cell and a normalized 1100 C blackbody spectrum.

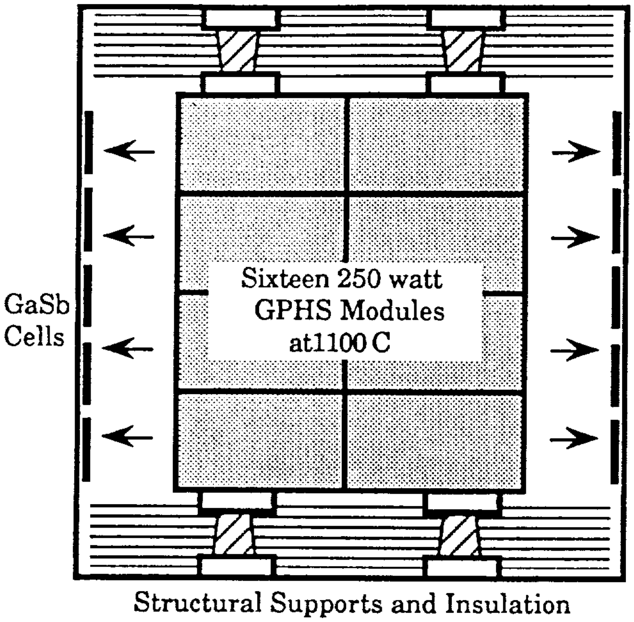

Figure 4. Configuration of an RTPV generator, based on use of GPHS source modules.

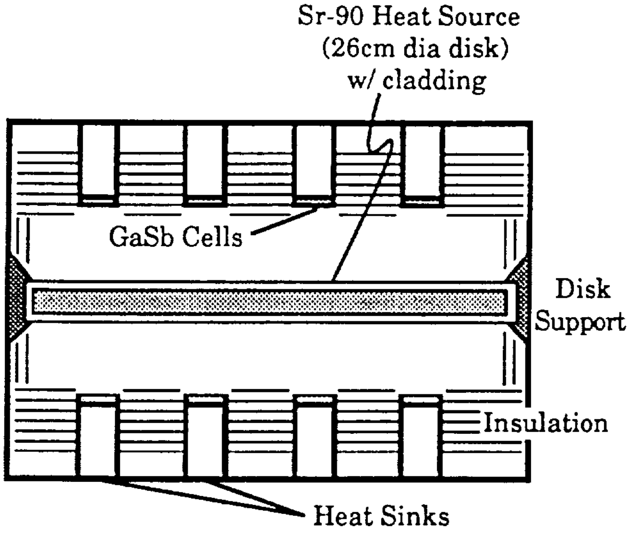

Figure 5: Schematic of a cylindrical 500 watt Sr-90 RTPV system.

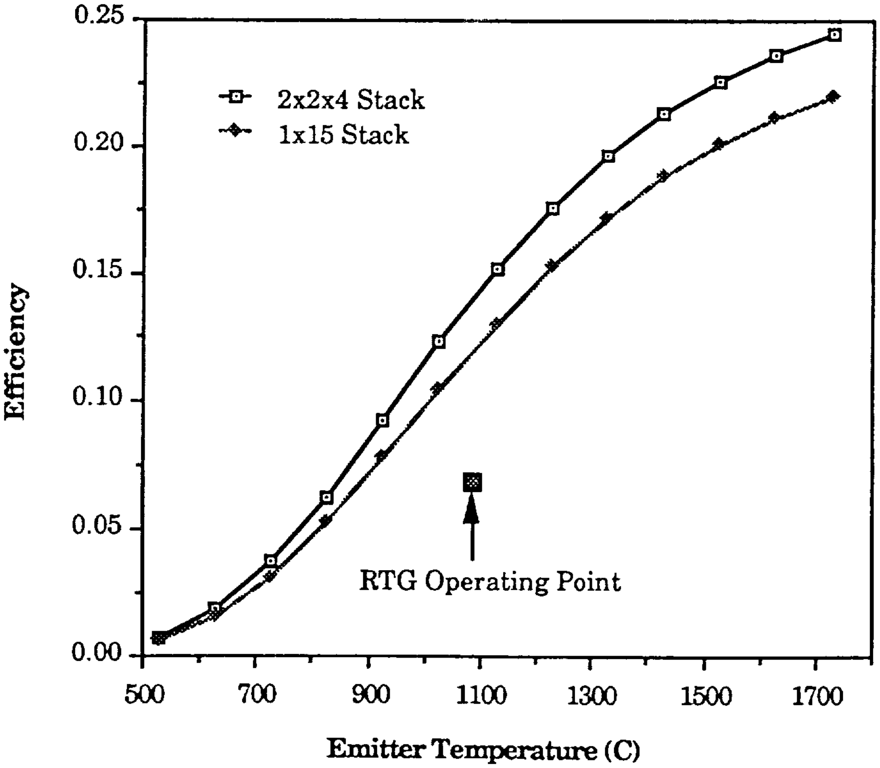

Figure 6: Efficiency of system which utilizes the GPHS verses temperature.