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PRELIMINARY DESIGN OF A 10-kW THERMOPHOTOVOLTAIC SYSTEM FOR SPACE APPLICATIONS

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SUMMARY

A very high degree of reflection of sub-bandgap energy photons from the cell back to the emitter was found to be crucial in achieving high efficiencies for a TPV system. Results show that small increases in reflectance above 0.85 lead to progressively larger increases in cell efficiency. In general, for a required power output, the radiator area, emitter temperature, emitter material and cell temperature may be chosen to satisfy various external constraints. The results can then be used to determine the optimum cell material and its operating temperature.

INTRODUCTION

Thermophotovoltaics (TPV) offers an interesting alternative to solar photovoltaics for large scale power generation in space. Amongst the possible advantages of a TPV system, compared to a flat panel or medium concentration (10 to 100 suns) solar array are; (1) its compact size, using a nuclear power source; (2) increased photovoltaic cell efficiency due to both operation under high concentration and a more closely matched incident energy spectrum than that of the sun and (3) the possible shielding of the photovoltaic (PV) cells from space radiation.

Interest in TPV has existed since the early 1960's (refs. 1 to 3). Recently, however, there has been a significant interest in the design of high power (>10 kW) TPV systems for space use (refs. 4 to 6). These recent publications have dealt with efficiency calculations and various aspects of TPV system design. In this paper we give the results of detailed calculations on the design of a 10 kW TPV system based on a computer code that we developed (ref. 7). Calculations were made to determine the choice of cell material and cell operating temperature given the constraints of cell area, size of waste heat radiator and emitter temperature. The PV cell materials considered were Si, Ge and GaAs.

TPV CONCEPT AND SPECTRAL EFFICIENCY

The TPV concept increases the efficiency of a photovoltaic energy conversion system in the following ways. First, the incident energy spectrum is matched to the PV cell's bandgap in such a way that most of the incoming photons have an energy at or just above that of the material's bandgap. This spectrum corresponds to a blackbody radiating at temperatures much lower than that of the sun (6000 K). TPV also operates under a closed system. Therefore, any low energy photons not absorbed by the PV cell can be reflected and thus returned to the TPV emitter as useful energy.

Figure 1 shows, for the specific case of a 2500 K blackbody emitter and a Si PV cell with a 95 percent reflectance of sub-bandgap energy photons, the fractions of the total spectral power which constitute; (1) the useful spectral power as defined below; (2) the power wasted in unreflected sub-bandgap energy photons; (3) the power wasted in the PV cell due to above-bandgap energy photons each creating only one electron-hole pair; and (4) the sub-bandgap photon power reflected by the PV cells and reabsorbed by the emitter.

An initial analysis was performed through spectral efficiency comparisons. The spectral efficiency (SE) is defined as the ratio of useful spectral power to the sum of the two wasted powers and the useful spectral power (i.e., the net power supplied by the emitter). The useful spectral power is defined as the product of the bandgap E_g and the number of photons per cm^2 per sec in the incident spectrum with energy greater than or equal to E_g.

Spectral efficiencies were calculated as a function of sub-bandgap energy photon reflectance for various emitter temperatures (incident blackbody spectra) for the bandgaps of Ge, Si, and GaAs. Figure 2 shows the results for Si. Note that SE increases and the maximum in SE shifts to lower emitter temperatures with increasing reflectance of low energy photons.

Figure 3 is a plot of the maximum in SE versus sub-bandgap energy photon reflectance for Ge, Si, and GaAs. It should be noted that for a given reflectance of sub-bandgap photons the maximum in SE is independent of the bandgap of the PV cell. However, this maximum will occur at increasing emitter temperatures as the bandgap increases. Figure 3 clearly shows the need for sub-bandgap photon reflectances greater than 0.85 to obtain maximum spectral efficiencies of 0.6 or above. In all subsequent calculations a sub-bandgap energy photon reflectance of 0.95 is used. This value appears feasible for Si (ref. 8).

TPV CELL EFFICIENCY

In order to choose the optimum cell material for a TPV system from among Ge, Si, and GaAs, we calculated the efficiencies of TPV cells made of these materials as functions of emitter and cell temperatures. The cell efficiency is defined as

$$\eta = \frac{V_{oc} J_{sc} FF}{P_{AB}}$$

where V_{OC}, J_{SC}, and FF are the open circuit voltage, short circuit current density and fill factor respectively and P_{AB} is the net power density absorbed by the cell and the back surface reflector.

The cell geometry chosen was a PIN structure for Ge and Si, and a p/n cell with an AlGaAs window for GaAs. For the Ge and Si PIN cells, V_{OC} and J_{SC} were calculated from the PIN photodiode model used by Swanson (ref. 9).

For GaAs, V_{OC} and J_{SC} were obtained from a model developed at Cleveland State University for GaAs-based concentrator solar cells (ref. 10). The fill factor was calculated from a semiempirical equation developed by Martin Green (ref. 11) with realistic values of series resistance chosen.

Of the several possible emitter materials, tungsten was selected for this study because of its suitability and long operating life. In order to calculate P_{AB}, the wavelength dependent emissivity of tungsten and reflections at the emitter and the front and back surfaces of the cell were taken into account (ref. 7).

Figures 4 to 6 show the variation of cell efficiency as a function of emitter temperature for different cell temperatures. As one would expect, these figures show that the degradation of cell efficiency with increasing cell temperature is more pronounced for the lower bandgap materials. Also, at low emitter temperatures, the lower bandgap materials have a better cell efficiency due to the better match with the incident spectrum. These curves are now used to calculate the cell and waste heat radiator areas needed for a 10 kW TPV system.

TPV CELL DESIGN FOR A 10 kW SPACE POWER SYSTEM

Choice of the TPV cell material and its operating temperature are governed not only by the cell efficiency but also by the cell and waste heat radiator areas required. Figures 7 to 9 show calculations of required cell area for a 10-kW TPV system as functions of cell and emitter temperatures for Ge, Si and GaAs cells. A one-to-one ratio of emitter-to-cell area is assumed in these figures. It is apparent from these curves that lower emitter temperatures (and therefore lower power densities) and higher cell temperatures (lower cell efficiencies) require larger cell areas for a given output power.

Figures 10 to 12 show, for Ge, Si and GaAs respectively, the required radiator area as a function of emitter and cell temperatures and ambient temperature in Low Earth Orbit (LEO) and Geosynchronous Earth Orbit (GEO) for a 10 kW power output system. These calculations assume a conventional (passive) heat radiator that rejects heat according to Planck's equation.

$$P_{RAD} = 0.85 \times 5.67\ E\text{-}8 \times \left(T_1^4 - T_2^4\right)$$

where

P_{RAD} heat power rejection density of the radiator, W/m^2

0.85 the emissivity of the radiator surface

5.67 E-8 Stefan-Boltzmann constant, $W/m^2\text{-}K^4$

T_1 surface temperature of the radiator, K

T_2 sink temperature, K

T_1 is assumed to be 25 K below the cell temperature. T_2 is 250 K for LEO and 0 K for GEO.

These figures show certain expected tendencies. The radiator area required for LEO is always greater than for GEO. The differences between the radiator size for LEO and GEO decreases as the cell operating temperature increases. At cell temperatures of 500 K and above, the radiator size required for either LEO or GEO is approximately the same.

Consider the germanium cell in figure 10 at emitter temperatures below 1900 K. An increase in cell temperature from 300 to 400 K decreases radiator size due to the greater heat rejection capability of a radiator with a higher surface temperature. Note however that as cell temperature rises above 400 K, radiator size increases. The radiator heat rejection capability increases due to a higher cell temperature, but the increased cell temperature decreases the cell efficiency and increases the amount of heat needed to be rejected. This latter tendency overrides the first at cell temperatures above 400 K for Ge, and radiator size increases. Therefore, there is no advantage in operating Ge cells above 400 K in this emitter temperature range.

Our results show that each cell has a certain operating temperature above which any increase in cell temperature will not only reduce efficiency but also increase radiator area. Therefore, there is no advantage in operating the cell above this temperature. At this point, these values can be considered the maximum cell operating temperatures for the corresponding emitter temperature range.

Table 1 presents representative data to illustrate how a choice of cell material and cell temperature might be made for a given set of constraints on cell and radiator areas and emitter temperatures. Three emitter temperatures are chosen for this comparison: 1500, 2000, and 2500 K. Each material is considered only up to its maximum cell operating temperature.

Note again that low efficiencies require large radiator sizes. Therefore, radiator size constraints will limit the lowest emitter temperature that can be considered for a given cell material and cell temperature.

The choice of a cell material, emitter temperature and cell temperature are often mission dependent. A certain selection may give a high system efficiency. Another may give the smallest radiator area. But a third choice may be the optimum selection based on a compromise between the two. It is therefore impossible to choose the combination of variables unless the mission requirements and constraints are known. For example, if the emitter temperature is constrained to be 1500 K then the best compromise between minimum cell and radiator areas appears to be for Ge cells operated at 400 K. On the other hand if the emitter temperature can be 2000 K, the best choice could be either Ge or Si cells operating at 400 K. At a still higher temperature of 2500 K, Si at 400 or 500 K appears to be a good choice.

CONCLUDING REMARKS

In this paper we have attempted to show how a choice of TPV cell material and its operating temperature can be made under constraints of emitter temperature, cell area and waste heat radiator area for a given 10-kW TPV space power system in LEO and GEO. We have shown that there is a trade-off between the cell temperature and the waste heat radiator area. For operation in both LEO and GEO the waste heat radiator area decreases with increasing cell temperature up to a certain maximum cell temperature above which further increases in cell temperature increase the radiator area. At the same time, lower power densities at low emitter temperatures lead to extremely large cell areas that increase with increasing cell temperature.

It was further shown that a high degree of sub-bandgap photon reflection is essential to achieve these high efficiencies and that a reflectance of 0.95, feasible for Si, or higher is desired.

In conclusion, Si cells operating in the range of 400 to 500 K with a tungsten emitter in the temperature range of 1400 to 2000 K would lead to a good TPV converter. However, materials' stability at these high temperatures present a major technological barrier for the system.

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TABLE I. - CELL EFFICIENCY, CELL AREA AND RADIATOR AREA FOR A 10-kW OUTPUT POWER SYSTEM USING A TUNGSTEN EMITTER AND ASSUMING 95 PERCENT REFLECTION OF SUBBANDGAP ENERGY PHOTONS

Emitter temperature, K	Material	Cell temperature, K	System efficiency, percent	Cell area, m^2	GEO radiator area, m^2	LEO radiator area, m^2
1500	Ge	300	27.9	1.75	93.6	295.3
	Ge	400	14.4	3.36	62.3	77.6
	Si	300	14.8	13.6	209.5	660.8
	Si	400	9.17	21.9	103.9	129.5
	GaAs	300	5.90	46.1	579.1	1827.0
	GaAs	400	5.28	51.5	188.3	234.7
	GaAs	500	3.69	73.5	106.3	115.1
2000	Ge	300	31.4	.25	79.3	250.2
	Ge	400	18.8	.417	45.3	56.5
	Ge	500	7.85	.997	-----	51.9
	Si	300	29.7	.857	85.9	271.2
	Si	400	20.3	1.25	41.1	51.2
	Si	500	11.2	2.27	32.3	35.0
	GaAs	300	20.7	1.96	138.6	437.4
	GaAs	400	18.5	2.20	46.1	57.4
	GaAs	500	14.2	2.88	24.7	26.8
	GaAs	600	10.1	4.03	16.9	17.5
2500	Ge	300	31.6	.071	78.7	248.3
	Ge	400	20.3	.111	41.3	51.5
	Ge	500	9.90	.226	37.1	40.2
	Si	300	35.8	.151	65.0	205.0
	Si	400	25.8	.210	30.2	37.6
	Si	500	15.8	.342	21.7	23.5
	GaAs	300	28.6	.291	90.3	285.0
	GaAs	400	24.9	.355	31.7	39.5
	GaAs	500	19.2	.434	17.1	18.6
	GaAs	600	14.4	.579	11.3	11.7

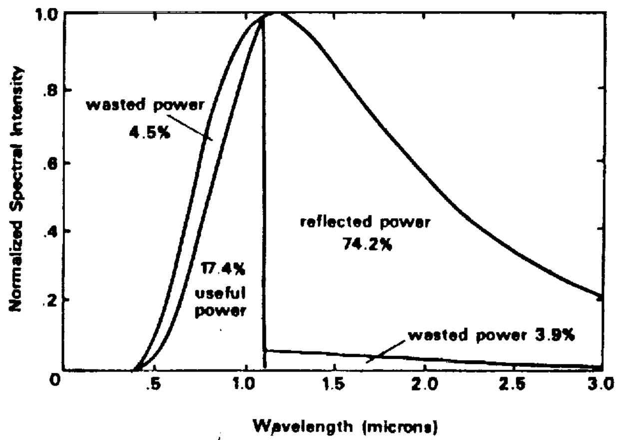

Figure 1. - Spectral usage of a silicon cell under TPV operation for an emitter temperature of 2500 K with 95-percent reflection of all subbandgap photons.

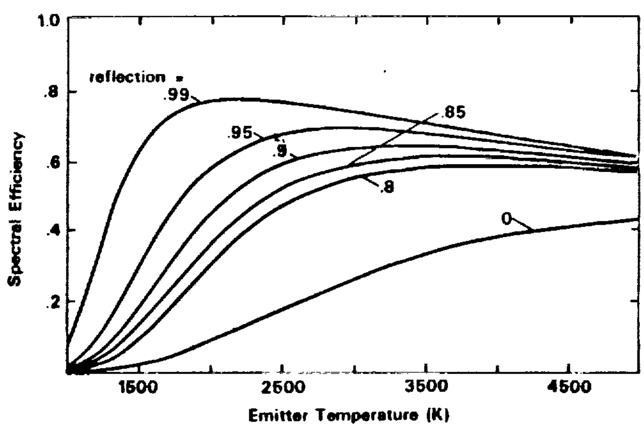

Figure 2. - Spectral efficiency of Si for different values of subbandgap photon reflection.

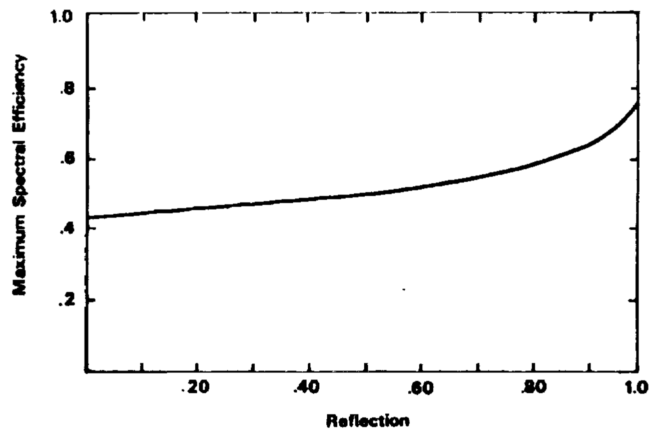

Figure 3. - Maximum spectral efficiency as a function of subband-gap photon reflection.

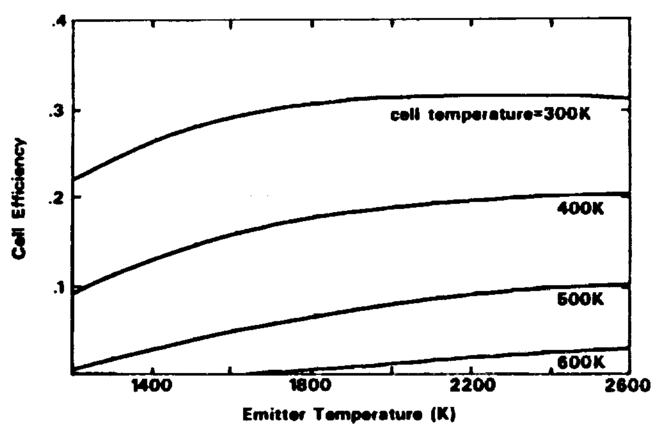

Figure 4. - Germanium cell efficiency with 95-percent back surface reflection and tungsten emitter.

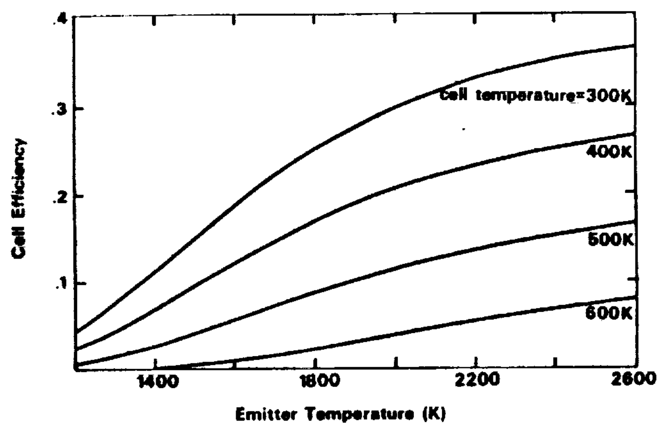

Figure 5. - Silicon cell efficiency with 95-percent back surface reflection and tungsten emitter.

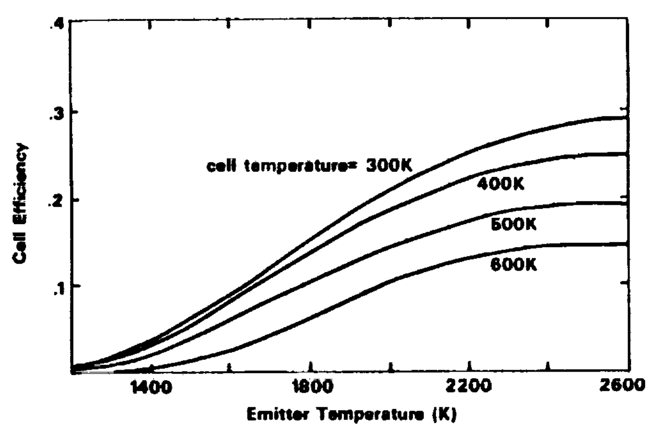

Figure 6. - Gallium arsenide cell efficiency with 95-percent back surface reflection and tungsten emitter.

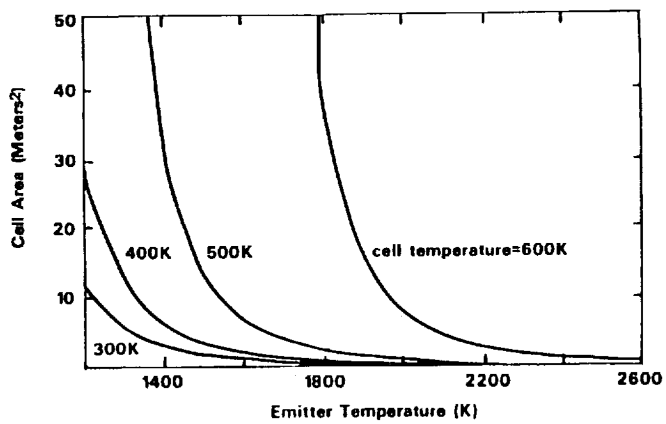

Figure 7. - Cell area required for a 10 kW output power using germanium cells.

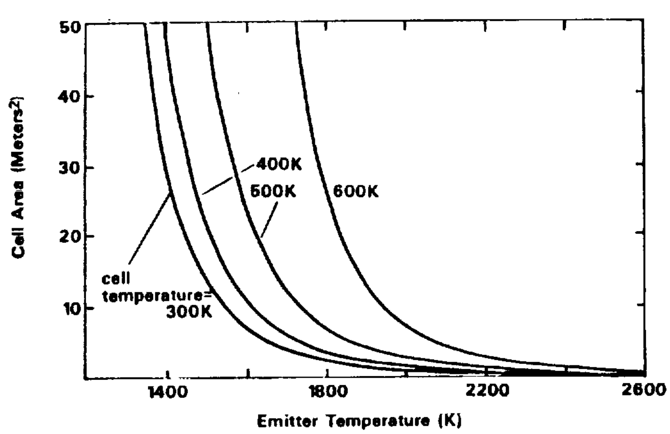

Figure 8. - Cell area required for a 10 kW output power using silicon cells.

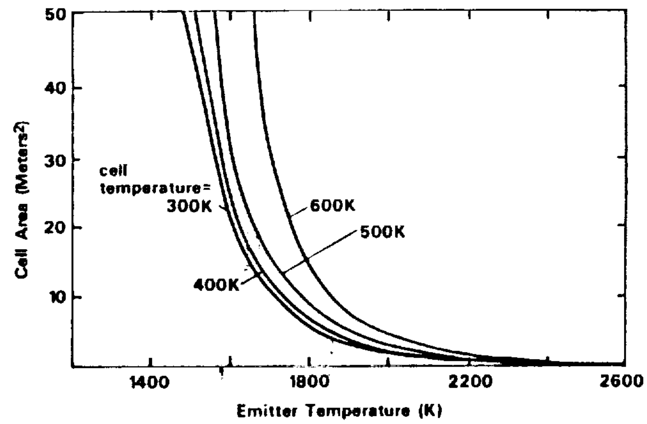

Figure 9. - Cell area required for a 10 kW output power using gallium arsenide cells.

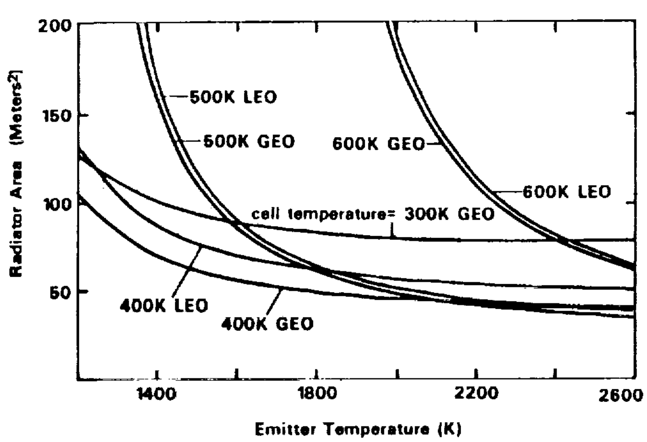

Figure 10. - Radiator area required for a 10 kW output power using germanium cells.

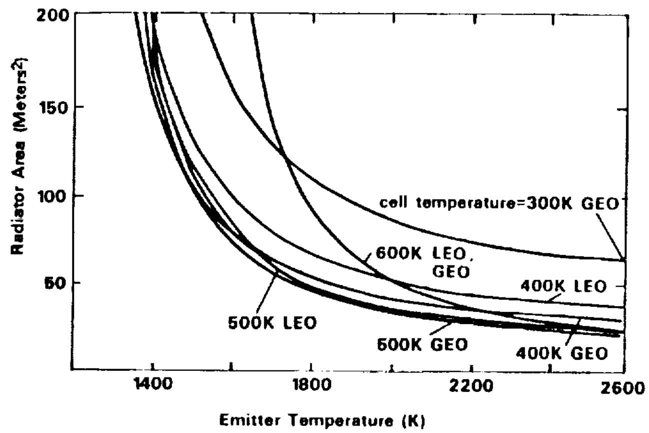

Figure 11. - Radiator area required for a 10 kW output power using silicon cells.

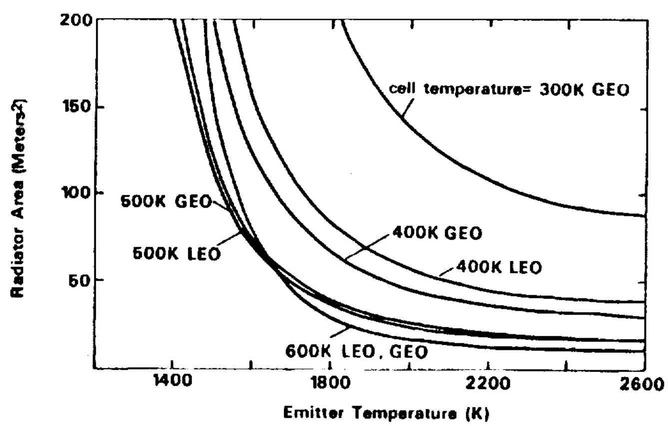

Figure 12. - Radiator area required for a 10 kW output power using gallium arsenide cells.

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15. Supplementary Notes

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