/N -44
//4/22
p- 12

High Efficiency Thermal to Electric Energy Conversion Using Selective Emitters and Spectrally Tuned Solar Cells

Donald L. Chubb and Dennis J. Flood
Lewis Research Center
Cleveland, Ohio

and

Roland A. Lowe
Cleveland State University
Cleveland, Ohio

NASA

(NASA-TM-105755)   HIGH EFFICIENCY
THERMAL TO ELECTRIC ENERGY
CONVERSION USING SELECTIVE EMITTERS
AND SPECTRALLY TUNED SOLAR CELLS
(NASA)   12 p

N92-30426

Unclas

G3/44   0114122

HIGH EFFICIENCY THERMAL TO ELECTRIC ENERGY CONVERSION USING SELECTIVE

EMITTERS AND SPECTRALLY TUNED SOLAR CELLS

Donald L. Chubb and Dennis J. Flood
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

and

Roland A. Lowe
Cleveland State University
Cleveland, Ohio 44109

SUMMARY

Thermophotovoltaic (TPV) systems are attractive possibilities for direct thermal-to-electric energy conversion, but have typically required the use of blackbody radiators operating at high temperatures. Recent advances in both the understanding and performance of solid rare-Earth oxide selective emitters make possible the use of TPV at temperatures as low as 1500 K. Depending on the nature of parasitic losses, overall thermal-to-electric conversion efficiencies greater than 20 percent are feasible.

INTRODUCTION

Efficient direct conversion of thermal energy to electrical energy at moderate operating temperature (1000 to 1500 K) would make a nuclear space power system more tractable. Thermophotovoltaic (TPV) energy conversion is an attractive concept for attaining efficient direct conversion at moderate temperatures. In TPV conversion, thermal energy is first converted to radiant energy, which is then converted to electrical energy by a photovoltaic (PV) cell. There are two types of TPV systems, illustrated in figure 1. One system uses a blackbody like thermal emitter (fig. 1(a)). The other system uses a selective emitter that emits in a narrow energy band just above the PV cell bandgap energy, E_g, where the PV cell is most efficient (fig. 1(b)). Since the thermal emitter emits large amounts of radiation at energies that cannot be efficiently converted by the PV cell, a bandpass filter is placed between the emitter and the PV cell. The ideal filter allows all photons with energy near the PV bandgap energy, E_g, to pass from the emitter to the PV cell and reflects all photons with energy greater or less than E_g back to the emitter. In other words, the filter makes the thermal emitter perform like a selective emitter.

In the filter TPV system, most of the emitted radiation is circulated back and forth between the emitter and filter. Therefore, even a small filter absorptivity, α_f, will result in a major loss. Also, if the thermal emitter does not perform lie a blackbody (emissivity $= \varepsilon_E =$ absorptivity $= \alpha_E = 1$) the efficiency will be reduced. As a result of these losses, it has been shown (ref. 1) that only for very optimistic filter ($\alpha_f < 0.01$) and thermal emitter ($\varepsilon_E = \alpha_E > 0.9$) will the filter TPV system be more efficient than the selective emitter system to be described in this report.

There are two major obstacles to the development of an efficient, moderate-temperature selective-emitter TPV system. First, an efficient selective emitter must be developed. Second, a PV cell having a bandgap energy very close to the emission band energy of the selective emitter must also be developed. The remainder of this paper is concerned with these two problems.

SELECTIVE EMITTERS

The early work of White and Schwartz (ref. 2) recognized the benefits of selective emitters for efficient TPV energy conversion. However, finding an efficient selective emitter has been a difficult task. The most promising solid selective emitters have been the rare-Earth elements (ref. 3). For doubly and triply charged ions of these elements in the crystals, the orbits of the valence 4f electrons, which account for emission and absorption, lie inside the 5s and 5p electron orbits. As a result, the rare-Earth ions in the solid state have radiative characteristics much like they would have if they were isolated. They emit in narrow bands rather than in a continuum as do most solids. The 5s and 5p electrons "shield" the 4f valence electrons from the surrounding ions in the crystal.

Early spectral emittance work (ref. 3) on rare-Earth oxides suitable for TPV showed strong emission bands. However, the emittance for photon energies below the bandgap for PV materials was also significant. As a result, the efficiency of these emitters was low. In the last few years, however, Nelson and Parent (refs. 4 and 5) have reported a large improvement in rare-Earth oxide emitters. Their emitters are constructed of fine (5 to 10 μm) rare-Earth oxide fibers similar to the construction of the Welsbach mantle used in gas lanterns. The very small characteristic dimension of the emitter results in low emittance for the low energy part of the spectrum, thus giving a much higher efficiency than previous emitters.

Rare-Earth Oxide Solid Selective Emitters

The mantle type emitters of Nelson and Parent (refs. 4 and 5) show a single strong emission band centered around some photon energy, E_b. For photon energies below and above this emission band the emissivity is greatly reduced. Therefore, Chubb (ref. 1) used the following model to describe the rare-Earth oxide emitters. There is a single emission band of width ΔE_b, with emissivity, ϵ_b. Outside the emission band the emissivity is ϵ_l for $E \leq E_b - \Delta E_b/2$ and ϵ_u for $E \geq E_b + \Delta E_b/2$. The emitter radiative efficiency is defined as follows:

$$\eta_E = \frac{P_E}{P_{RAD}} \tag{1}$$

where P_E is the emitted radiative power per unit area from the emission band at E_b and P_{RAD} is the total emitted radiative power per unit area. Obviously, this efficiency does not include thermal conductive or convective heat loss (P_L in fig. 1). A PV material with $E_g \approx E_b$ is capable of efficient conversion of this useful energy, P_E. Chubb (ref. 1) has derived the following expression for η_E.

$$\eta_E = \left\{ 1 + \frac{\epsilon_l}{\epsilon_b} G\left[\frac{E_b}{kT_E}, \frac{\Delta E_b}{E_b}\right] + \frac{\epsilon_u}{\epsilon_b} H\left[\frac{E_b}{kT_E}, \frac{\Delta E_b}{E_b}\right] \right\}^{-1} \tag{2}$$

The functions G and H are defined in reference 1 and the wavelength and photon energy are related by $\lambda = hc/E$. As can be seen from equation (2), there are four parameters that determine the efficiency. Figure 2 shows η_E as a function of E_b/kT_E for several values of $\epsilon_l/\epsilon_b = \epsilon_u/\epsilon_b$ and with $\Delta E_b/E_b = 0.1$ representative of the rare-Earth oxides (refs. 4 and 5). There are two important observations from figure 2. First of all, if the emissivity ratios are low enough ($\epsilon_l/\epsilon_b = \epsilon_u/\epsilon_b < 0.05$), then $\eta_E \geq 0.7$ is possible. Secondly, the maximum efficiency occurs at $E_b/kT_E = 4$. Therefore, if $T_E \leq 1500$ K then $E_b \leq 0.52$ eV

2

($\lambda \geq 2.4$ μm) in order to obtain maximum efficiency. As a result, an efficient TPV system for this condition ($T_E \leq 1500$ K) will require a PV material with a low bandgap energy E_g. If $\epsilon_u = \epsilon_1$, then the value of E_b/kT_E for maximum η_E will be shifted. From the results of Chubb (ref. 1) for $\epsilon_1 > \epsilon_u$ then $E_b/kT_E < 4$, which means higher T_E for a given E_b. If $\epsilon_u > \epsilon_1$, then $E_b/kT_E > 4$, which means lower T_E for a given E_b.

Three rare-Earth oxides have low emission band energy: neodymia Nd_2O_3, holmia, Ho_2O_3 and erbia, EB_2O_3. Characteristics of these three are listed in table I. Only Nd_2O_3 has the potential for reaching its maximum efficiency if T_E is limited to 1500 K. However, Ho_2O_3 at $T_E = 1500$ K rather than 1800 K (temperature for maximum η_E) results in a negligible reduction in η_E (fig. 2).

The mantle-type emitters of Nelson and Parent (refs. 4 and 5) have been used in combustion driven systems. However, other geometries that are more rugged and easily coupled to any thermal source have the potential for higher efficiency. Two of these concepts being investigated at the Lewis Research Center are the thin film selective emitter and the small-particle selective emitter (fig. 3). Both of these concepts can utilize a smaller characteristic dimension than the mantle-type emitter, which uses 5 to 10 μm diameter fibers. As already pointed out, Nelson and Parent (refs. 4 and 5) have demonstrated the importance of the small characteristic dimension for obtaining high efficiency.

So far, most of the work has been concentrated on the thin film selective emitter. An analysis using a modification of the three-band model described earlier which includes scattering has been completed. Although detailed results of that analysis will be presented elsewhere, the important results will now be discussed. The important variables affecting the performance are the substrate emittance, $\epsilon_{\nu s}$, the film optical depth,

$$K_\nu = \left(a_\nu + \sigma_\nu\right)d \tag{3}$$

where a_ν is the absorption coefficient, σ_ν is the scattering coefficient, d is the film thickness and Ω_ν the scattering albedo,

$$\Omega_\nu = \frac{\sigma_\nu}{a_\nu + \sigma_\nu} \tag{4}$$

As already mentioned the spectrum is modeled by three bands of constant properties; in the emission band ($E_b - \Delta E_b/2 \leq h\nu \leq E_b + \Delta E_b/2$), $K_\nu = K_b$, $\Omega_\nu = \Omega_b$ and $\epsilon_{\nu s} = \epsilon_{bs}$; below the emission band ($h\nu \leq E_b - \Delta E_b/2$), $K_\nu = K_1$, $\Omega_\nu = \Omega_1$ and $\epsilon_{\nu s} = \epsilon_{1s}$; above the emission band ($h\nu \geq E_b + \Delta E_b/2$) $K_\nu = K_u$ $\Omega_\nu = \Omega_u$ and $\epsilon_{\nu s} = \epsilon_{us}$. For given values of K, Ω, and ϵ_s the emittance for each band can be calculated and used in equation (2) to calculate η_E. Similar to the results of figure 2, where ϵ_1, ϵ_b, and ϵ_u are assumed to be constants, the maximum value of η_E occurs at $E_b/kT_E = 4$ when $\epsilon_u = \epsilon_1$.

The importance of the optical depth and substrate emittance is illustrated in figure 4. The emitter efficiency, η_E, is shown as a function of the optical depth for the emission band, K_b, for several values of the substrate emittance at the optimum value of $E_b/kT_E = 4$. It is also assumed that $\Delta E_b/E_b = 0.1$, $\epsilon_{1s} = \epsilon_{bs} = \epsilon_{us}$ and that $K_1 = K_u = 0.05 K_b$. From Nelson and Parent's results, it is expected that $0.01 K_b \leq K_1 \leq 0.1 K_b$ and $0.01 K_b \leq 0.1 K_u \leq 0.1 K_b$ for the rare-Earth oxides. Also, $\Delta E_b/E_b = 0.1$ is representative of the rare-Earth oxides. In figure 4(a) no scattering is present, and in figure 4(b) equal scattering and absorption coefficients are assumed ($\Omega = 0.5$).

3

The first item to notice is that scattering has negligible effect on the maximum efficiency. However, with scattering present, the optical depths required to reach the maximum efficiency are more than 50 percent larger than with no scattering. The importance of maintaining low substrate emittance is evident from the results shown in figure 4. It appears that $\varepsilon_s > 0.1$ results in efficiencies that are too low to be of interest. Also, except for $\varepsilon_{bs} = \varepsilon_{1s} = \varepsilon_{us} = 0$, there is an optimum K_b for maximum η_E, and η_E rises very sharply from $\eta_E = 0$ to the maximum value. The efficiency decreases more slowly for $K > K_{opt}$. For $K_1 = K_u > 0.05 \, K_b$, the curves will be shifted to lower efficiency. Similarly, for $K_1 = K_u < 0.05 \, K_b$ the efficiency will be higher than in figure 4.

Besides efficiency, the power emitted in the emission band is another important performance parameter for a thin-film selective emitter. Large emitted power/area translates into a low-mass space power system. Using the emitted power/area, P_E, define the dimensionless power-density as follows:

$$p_E \equiv \frac{P_E}{\sigma T_E^4} = \varepsilon_b \frac{\int_{E_b-(\Delta E_b)/2}^{E_b+(\Delta E_b)/2} e_E dE}{\int_0^\infty e_E dE} \tag{5}$$

where σ is the Stefan-Boltzmann constant $(\sigma = 5.67 \times 10^{-8} \, w/m^2 k^4)$ and e_E is the blackbody emissive power.

$$e_E = \frac{2\pi E^3}{h^2 c^2} \left\{ \exp\left[\frac{E}{kT_E}\right] - 1 \right\}^{-1} \tag{6}$$

In equation (6) h is the Planck constant, k is the Boltzmann constant and c is the speed of light in vacuum. Using equation (6) in equation (5) yields the following:

$$p_E = \frac{15}{\pi^4} \varepsilon_b \int_{s[1-(t/2)]}^{s[1+(t/2)]} \frac{x^3}{e^x - 1} dx \tag{7}$$

where,

$$s = \frac{E_b}{kT_E} \quad \text{and} \quad t = \frac{\Delta E_b}{E_b} \tag{8}$$

The behavior of p_E as a function of the optical depth, K_b, is entirely different than that of the efficiency. Figure 4 shows there is an optimum optical depth to attain maximum efficiency. However, as equation (7) shows, p_E depends on optical depth only through ε_b. Since ε_b increases monotonically with K_b, the power density, p_E, will also be a montonically increasing function of K_b. Also, the substrate emittance, ε_s, will affect p_E only for small optical depths. Most important, however, is the scattering effect on p_E. As discussed earlier, scattering has negligible effect on the optimum efficiency. However, scattering causes a reduction in p_E since ε_b decreases with increasing scattering. These points are illustrated in figure 5, where p_E is shown as a function of K_b for the same conditions as figure 4.

4

From figure 4 we see that the optimum optical depths are less than one for $\epsilon_s < 0.05$. However, in order to obtain larger power density, it may be desirable to use a larger optical depth. As figure 4(a) for the no scattering case shows, for $K_b \approx 1$ the efficiency is only slightly reduced from the maximum values. Similarly, for $\Omega = 0.5$ figure 4(b) shows that $K_b \approx 2.0$ causes only a small decrease in η_E. Therefore, to estimate the power density that can be expected from a rare-Earth oxide selective emitter, assume that $K_b \approx 1.0$ for $\Omega = 0$ and that $K_b \approx 2.0$ for $\Omega = 0.5$. At $K_b = 1$ and $\Omega = 0$, figure 5(a) shows that $p_E \approx 0.058$. For Nd_2O_3 at $T_E = 1500$ K ($E_b/kT_E = 4$), $p_E = 0.058$ yields $P_E = 1.7$ w/cm^2. This compares with the solar flux at Earth orbit of 0.135 w/cm^2. For $K_b = 2$ and $\Omega = 0.5$, figure 5(b) gives $p_E \approx 0.055$. In this case Nd_2O_3 at $T_E = 1500$ K will produce $p_E = 1.6$ w/cm^2. Thus, although scattering reduces p_E, the larger optical depth that can be used without greatly reducing η_E means that the emitted power, P_E, will be nearly the same both with and without scattering.

The important theoretical results for the solid-state rare-Earth oxide selective-emitters can be summarized as follows. For maximum efficiency the emitter temperature must satisfy $E_b/kT_E \approx 4$. If T_E is limited to 1500 K, then only Ho_2O_3 and Nd_2O_3 have the potential for operation near maximum efficiency. For the thin-film selective emitter, the substrate emissivity, ϵ_s, is a critical parameter for determining efficiency. If $\epsilon_s < 0.02$ then efficiencies greater than 0.5 are possible. Also, maximum η_E occurs at a single optical depth, $K_b = (a_b + \sigma_b)d_{opt}$. Finally, although scattering causes a reduction in the emitted power, P_E, if scattering is present, larger optical depths can be used without greatly reducing the efficiency. As a result, P_E is expected to be nearly the same both with and without scattering.

SOLAR CELL TECHNOLOGY

Solar Cell Performance

Figure 6 is a plot of theoretical solar cell efficiency in the air mass zero (AM0, or outer space) spectrum as a function of energy bandgap (ref. 6), with the bandgaps of several common solar cell materials noted. The plot was derived for a simple, single-junction solar cell with idealized characteristics, but realistic parameters; even so, it provides an estimate of the expected "practical" efficiency, rather than a theoretical thermodynamic limit efficiency, which would typically be much higher. The primary reason for the maximum in the curve is the fact that photons with energies less than the bandgap of the material pass through the solar cell without creating any electron-hole pairs, while those photons with significantly greater energies than the bandgap excite the valence band electrons into the higher energy states of the conduction band; since there are empty states near the bottom of the conduction band, the carriers give up their excess energy as heat to the crystalline lattice and fall to the lowest energy levels available. Hence, there is a bandgap for a given spectrum of incident light which is optimum for that spectrum. As seen in the figure, the optimum bandgap for the AM0 spectrum is approximately 1.56 eV.

On the other hand, those photons with energies near, but still greater than the bandgap energy of the solar cell excite the valence band electrons directly into the lowest unfilled states in the conduction band; there is little or no energy lost as heat. For this reason, the efficiency of a solar cell under monochromatic illumination can be expected to be greatest for light with photon energies very near the cell bandgap. A useful measure of the performance of a solar cell made from a given material is the spectral response. The spectral response is simply the ratio of the short circuit current density of the cell at a given wavelength to the incident power density at that same wavelength, and is usually given in mamps/mwatt. Spectral response depends a great deal on the design of the cell, and is affected not only by the presence of defects in the bulk semiconductor material forming the active regions of the cell, but also by the nature of the surfaces and interfaces of the structure. The spectral response can be maximized for a given wavelength of incident light by a suitable cell design.

Spectrally Tuned Solar Cells

In principle, it is possible to select a semiconductor bandgap that will maximize cell efficiency for a particular wavelength of light. In practice it is difficult for the very short (i.e., less than 400 nm), and the very long (greater than about 2.5 μm) wavelengths. In those cases, factors related to cell design, the quality of the bulk material, and cell interfaces and surfaces begin to become major problems. Figure 7 shows the calculated variation of efficiency with bandgap using monochromatic light; the wavelength of the incident light corresponds to the energy bandgap in each case (ref. 7). For this figure the cell temperature was assumed to be 25 °C. Under such conditions, solar cell efficiency will not have an optimum bandgap, as was the case in the AM0 spectrum. Instead it will asymptotically approach a limiting value of efficiency as shown in the figure. Gallium arsenide cells, for example, are predicted to have an efficiency exceeding 60 percent. Data are available at present only on GaAs cells designed for maximum efficiency in the AM0 spectrum. Even so, efficiencies exceeding 50 percent in these nonoptimized structures have been shown (ibid). Monochromatic illumination efficiencies of the GaSb cell, with a bandgap of 0.62 eV have not yet been measured. Based on its performance as the bottom cell of a two-junction multiple bandgap solar cell, which has been shown to be as much as 8 percent in the full AM0 spectrum (ref. 8), the monochromatic cell efficiency can be expected to be in the vicinity of 30 percent in a real device.

SELECTIVE EMITTER THERMAL-TO-ELECTRIC CONVERSION EFFICIENCY

It can be seen from figure 7 that the efficiency of spectrally-tuned solar cells falls dramatically for the lower bandgap materials, particularly for bandgaps below about 0.8 eV. Nonetheless, efficiencies approaching 30 percent could be expected for bandgaps as low as 0.50 eV. According to table I, a cell with this bandgap would be suitable for use with a neodymium-oxide emitter, which, at an operating temperature of 1500 K, has a strong emission band centered about a photon energy of 0.52 eV. From figure 2, the emitter radiative efficiency can be as high as 80 percent, depending on the emissivity ratio achieved. Values of 0.1 or less are reasonable to expect. The total radiative power to electrical power conversion efficiency could therefore be as much as 24 percent, so that even if only 50 percent of the emitter's initial thermal energy input ends up as radiated power, the total thermal-to-electric conversion efficiency can be as much as 12 percent. If the emissivity ratio goes up to 0.1, the total conversion efficiency in this extreme case would still be nearly 7 percent.

The overall efficiency can be increased substantially if a higher temperature heat source is available. The holmium-oxide emitter requires an operating temperature of 1800 K to achieve its peak radiative efficiency, and radiates in a narrow band centered on photon energy of 0.62 eV. In this case, the total thermal-to-electric conversion efficiency could be as high as 16 percent, and as low as 9 percent, again, assuming that at least 50 percent of the initial thermal input power ends up as radiative power. Nelson and Parent have determined from their experiments that up to a 10 percent thermal-to-electric power conversion efficiency could be achieved using their ytterbium-oxide emitters in a gas flame (ref. 9). Although the materials and configurations discussed in this analysis have not yet been tested for their thermal-to-radiative power conversion efficiency, the prior results are at least encouraging. It should be noted that a TPV system requires a cooling loop for the PV cells. In this regard, the TPV is no different than a thermoelectric or dynamic conversion system.

A key point is that the conversion system, beginning with the thermal input to the emitter, is an entirely static process. In principle, such a system could be designed to replace the thermoelectric conversion subsystem in the SP-100 space nuclear reactor. Without taking into account the parasitic losses that can always be expected, the total thermal-to-electric conversion efficiency of the reactor system could

as high as 12 percent for an output temperature of 1500 K. This enhancement of performance is a strong justification for further work on this promising concept.

REFERENCES

1. Chubb, D.L., "Reappraisal of Solid Selective Emitters," Conference Record of 21st Photovoltaic Specialists Conference, 1990.

2. White, D.C. and Schwartz, R.J., "PIN Structures for Controlled Spectrum Photovoltaic Converters," "AGARD Colloguium," Cannes, France 1964, New York, Gordon Breach Science, pp. 897-922, 1967.

3. Guazzoni, G.E., "High Temperature Spectral Emittance of Oxides of Erbium, Samarium, Neodymium and Ytterbium," Appl. Spectr. 26, 60 (1972).

4. Nelson, R.E., International Power Sources Symposium, 32nd Proceedings, Pennington, NJ, Electromechanical Society, 1986.

5. Parent, C.R. and Nelson, R.E., "Thermophotovoltaic Energy Conversion with a Novel Rare Earth Oxide Emitter," Proceedings of the 21st IECEC, 1986.

6. "Solar Cells - Outlook for Improved Efficiency," Report by the Ad Hoc Panel on Solar Cell Efficiency, National Research Council, National Academy of Sciences, Washington, DC, 1972.

7. Olsen, L.C., Dunham, G., Huber, D.A., Addis, W., Anheier, N., and Coomes, E.P., "GaAs Solar Cells for Laser Power Beaming," Proceedings of the 11th Space Photovoltaic Research and Technology Conference, Lewis Research Center, Cleveland, OH, pp. 26-1, 1991.

8. Avery, J.E., Fraas, L.M., Sundaram, V.S., Mansoori, N., Yerkes, J.W., Brinker, D.J., Curtis, H.B., and O'Neill, M.J., "Lightweight Concentrator Module With 30% AM0 Efficient GaAs/GaSb Tandem Cells," Conference Record of the 21st IEEE Photovoltaic Specialists Conference, 1990.

9. Parent, C.R., Nelson, R.E., and Olow, J.F.S., "Exploratory Research on Natural Gas-Fired Thermophotovoltaic Systems," Gas Research Institute Final Report #5086-260-1277, April 1988.

TABLE I.—EMISSION BAND DATA FOR RARE-EARTH OXIDES

Emitter material	Emission band transition	Photon energy at center of emission band, E_b, eV	Photon wavelength at center of emission band, μm	Dimensionless bandwidth from refs. 5 and 6, $\Delta E_b / E_b$	Emitter temperature for maximum efficiency $T_E/_{opt} = 1/4 \; eE_b/k$, K
Erbia Er_2O_3	$^4I_{13/2} - {}^4I_{15/2}$	0.827	1.5	0.05	2400
Holmia Ho_2O_3	$^5I_7 - {}^5I_8$	0.62	2.0	0.10	1800
Neodymia Nd_2O_3	$^4I_{13/2} - {}^4I_{9/2}$	0.52	2.4	0.10	1500

(a) Filter - thermal emitter TPV system.

α_E = emitter absorptivity
α_f = filter absorptivity
τ_f = filter transmittance
r_f = filter reflectivity

$\alpha_f + \tau_f + r_f = 1$

$\eta_f = \tau_f / (1 - \alpha_E \, r_f)$

(b) Selective emitter TPV system.
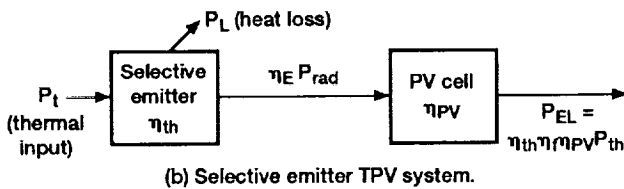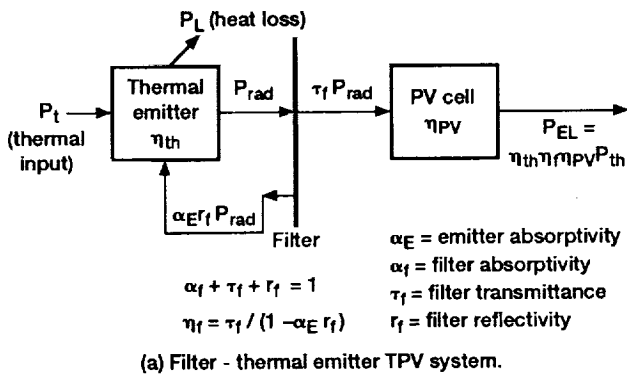
Figure 1.—Schematic of TPV systems.
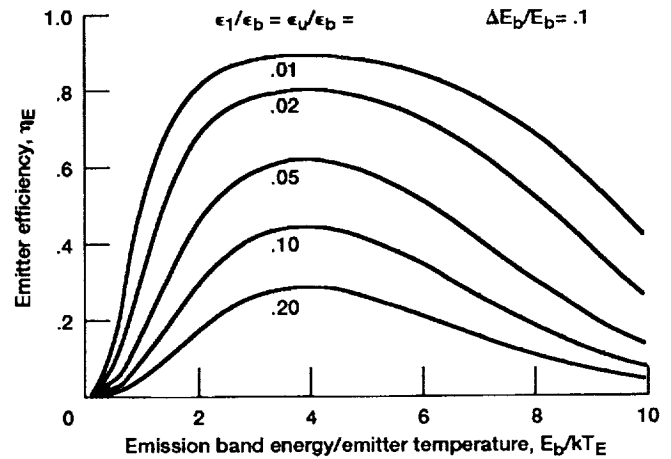
Figure 2.—Selective emitter efficiency.

(a) Thin film selective emitter.

(b) Small particle selective emitter.
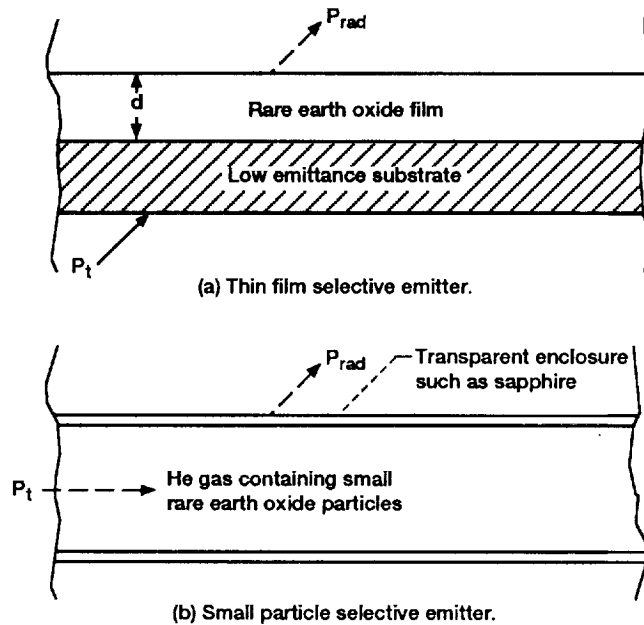
Figure 3.—Schematic of possible rare earth oxide selective emitters.

(a) Scattering Albedo, $\Omega_b = \Omega_1 = \Omega_u = 0$.

(b) Scattering Albedo, $\Omega_b = \Omega_1 = \Omega_u = .5$.
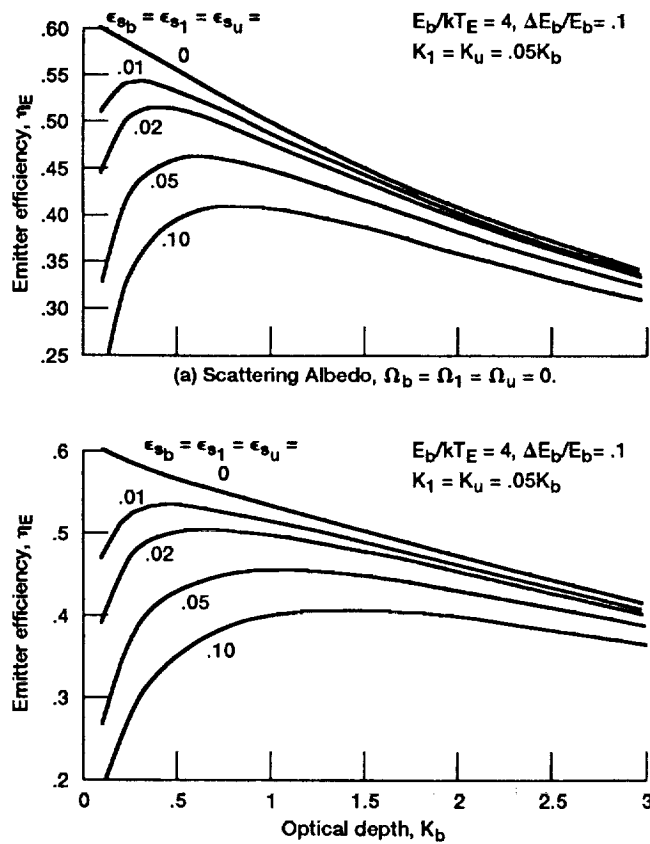
Figure 4.—Thin film emitter efficiency.

(a) Scattering Albedo, $\Omega_b = \Omega_1 = \Omega_u = 0$.

(b) Scattering Albedo, $\Omega_b = \Omega_1 = \Omega_u = .5$.
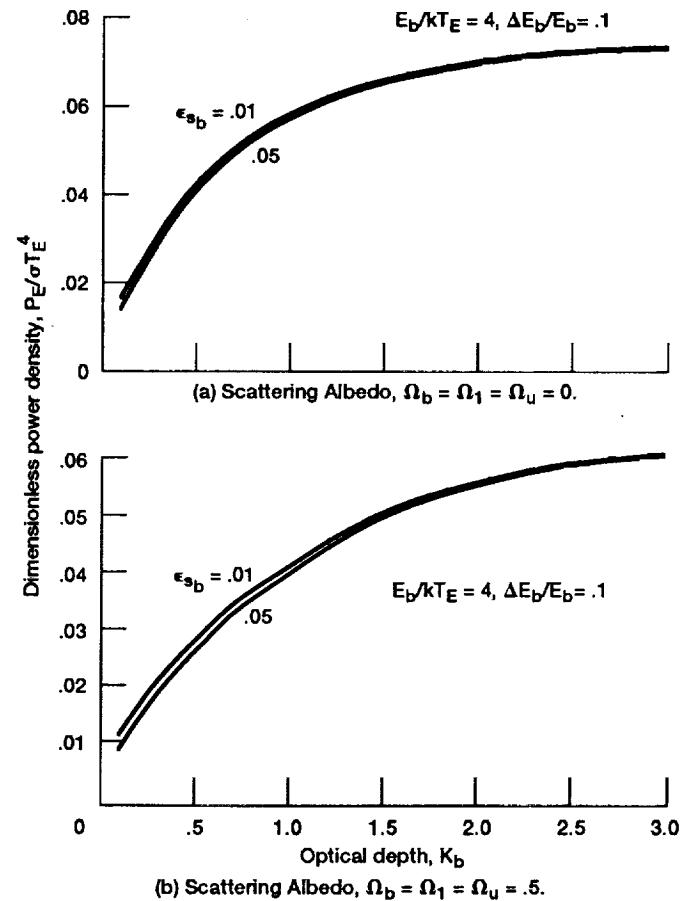
Figure 5.—Thin film emitter dimensionless power density.

9
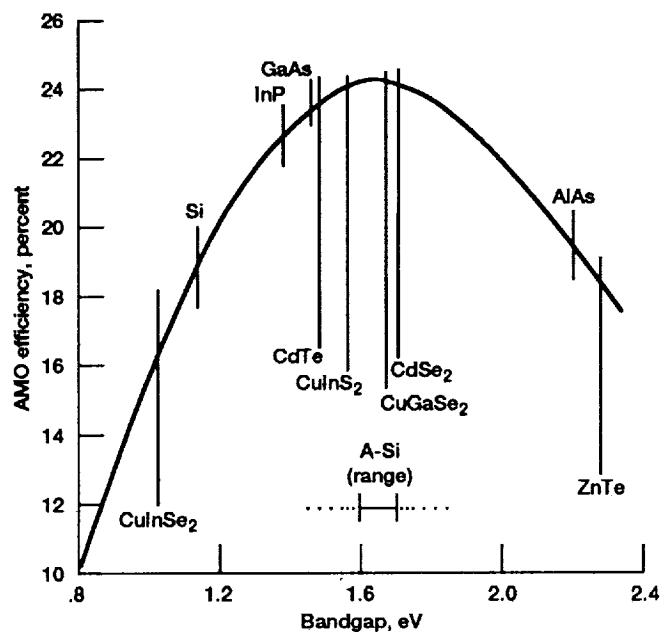
Figure 6.—Achievable efficiency for a single junction solar cell as a function of the bandgap of the material.
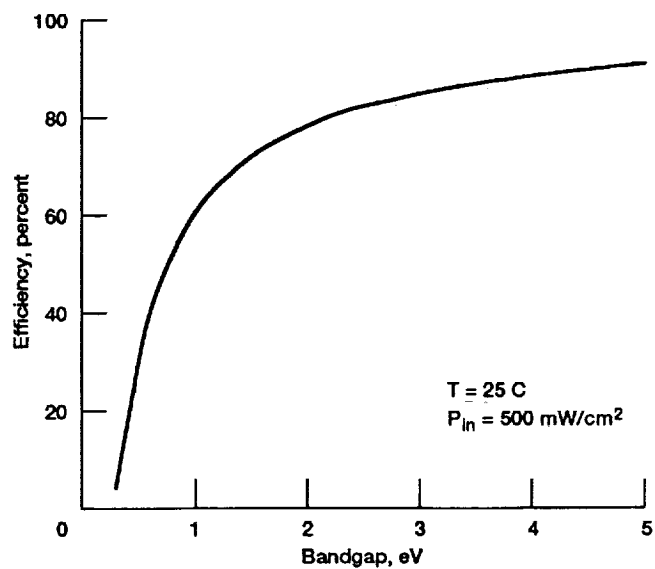
Figure 7.—Calculated efficiency for monocromatic cells coupled to laser light tuned to the cell material bandgap, and assuming an input power of 500 mW/cm².

REPORT DOCUMENTATION PAGE

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	August 1992	Technical Memorandum

4. TITLE AND SUBTITLE

High Efficiency Thermal to Electric Energy Conversion Using Selective Emitters and Spectrally Tuned Solar Cells

5. FUNDING NUMBERS

WU–506–41–11

6. AUTHOR(S)

Donald L. Chubb, Dennis J. Flood, and Roland A. Lowe

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

8. PERFORMING ORGANIZATION REPORT NUMBER

E–7166

9. SPONSORING/MONITORING AGENCY NAMES(S) AND ADDRESS(ES)

National Aeronautics and Space Administration
Washington, D.C. 20546–0001

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

NASA TM–105755

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Unclassified - Unlimited
Subject Categories 44 and 20

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Thermophotovoltaic (TPV) systems are attractive possibilities for direct thermal-to-electric energy conversion, but have typically required the use of black body radiators operating at high temperatures. Recent advances in both the understanding and performance of solid rare-earth oxide selective emitters make possible the use of TPV at temperatures as low as 1500 K. Depending on the nature of parasitic losses, overall thermal-to-electric conversion efficiencies greater than 20 percent are feasible.

14. SUBJECT TERMS

Selective emitter; Thermophotovoltaic (TPV) conversion; Thin film; Low bandgap photovoltaics

15. NUMBER OF PAGES
12

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	