Effectiveness of Solar Absorber Surfaces

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SOLAR-THERMIONIC, solar-thermoelectric, and solar-dynamic axilliary power systems for spacecraft will compete with, if not replace, solar cells for future space probes. These three systems require solar absorption on some type of surface, and this paper describes a method for comparing and evaluating such surfaces on the basis of their radiation properties.

Since the spectral distribution of solar energy is quite different from the spectral distribution of the lower-temperature energy emitted by a solar heated surface, the possibility exists of finding surfaces that have high absorptance in the solar spectrum and low emittance at their radiating temperature. The heat retained by a solar absorber radiating into free space is

$$q = \alpha_s H_s - \epsilon\sigma T^4 \quad (1)$$

where q is the solar energy retained (available for conversion to power), α_s is the solar absorptance of absorber surface, H_s is the solar incident energy, ϵ is the total hemispherical emittance of absorber surface, σ is the Steffan-Boltzmann constant, and T is the absolute surface temperature of absorber. Dividing Eq. (1) by ϵ gives

$$q/\epsilon = (\alpha_s/\epsilon)H_s - \sigma T^4 \quad (2)$$

It has been common practice to compare surfaces used in space on the basis of their ratios of solar absorptance to total hemispherical emittance (α_s/ϵ) with little concern for the absolute values of these quantities. This is valid only for the case of a surface in thermodynamic radiation equilibrium with no heat transfer other than radiation to or from the surface, as can be seen from Eq. (2); under these conditions, $q = 0$. This practice is not satisfactory when large amounts of heat are withdrawn from the surface as in the case of a solar absorber. For example, a surface with either $\alpha_s = 0.9$ and $\epsilon = 0.1$ or $\alpha_s = 0.45$ and $\epsilon = 0.05$ has $\alpha_s/\epsilon = 9.0$. Under equilibrium radiation conditions with no energy extraction ($q = 0$), both surfaces would reach the same temperature in space. However, when the purpose is to provide energy, the first surface would be the better solar absorber because it would supply twice as much available energy per unit area when operating below its radiation equilibrium temperature. Thus the absolute values of α_s and ϵ are important, but comparisons based on them are somewhat cumbersome and can be misleading, because α_s and ϵ may vary in relative importance as the conditions vary.

A more useful parameter for comparing solar absorber surfaces can be derived if we introduce the concept of an ideal selective absorber that has a spectral absorptance (α_λ) or emittance (ϵ_λ) of 1.0 at all wavelengths (λ) where the incident solar monochromatic energy level is higher than the monochromatic energy level of a blackbody at the same temperature as the surface; when the solar monochromatic energy level is lower than the blackbody monochromatic energy level, the spectral emittance is zero. If α_λ or ϵ_λ were different from this ideal case, less energy would be retained. If the absorber were a blackbody (α_λ and $\epsilon_\lambda = 1.0$ for all wavelengths), more energy would be absorbed than for an ideal absorber, but much more energy would be emitted; hence, less energy would be retained to do useful work.

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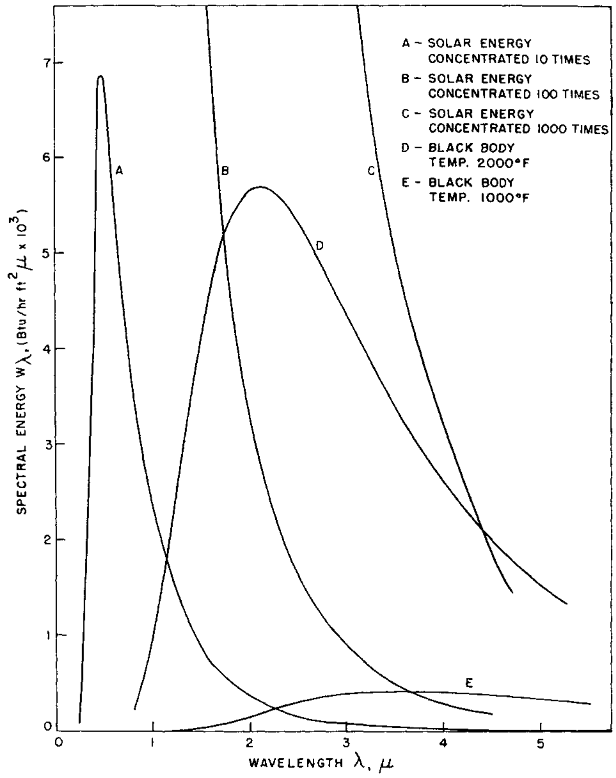

Fig. 1 Spectral energy distribution.

In Fig. 1, curve B represents the solar energy density distribution outside the earth's atmosphere concentrated 100 times, or the solar energy density distribution at a point 10 times closer to the sun than at the earth's distance. Curve D represents the spectral energy distribution for a blackbody at 2000°F. The wavelength at which curves B and D cross we will define as the cutoff wavelength, which in this case is 1.76 μ. A surface with $\alpha_\lambda = 1.0$ for all $\lambda < 1.76\ \mu$ and $\epsilon_\lambda = 0$ for all $\lambda > 1.76\ \mu$ is an ideal selective absorber under the assumed conditions. However, the surface would not be an ideal selective absorber for a different surface temperature or different solar concentration. Figure 2 shows the cutoff wavelength for the ideal selective absorber as a function of the surface temperature and solar energy concentration.

A more descriptive term than α_s/ϵ and a more useful term than the absolute value of α_s and ϵ to use when comparing solar absorbers would be an absorber effectiveness ϕ defined as the ratio of energy absorbed and retained by a particular

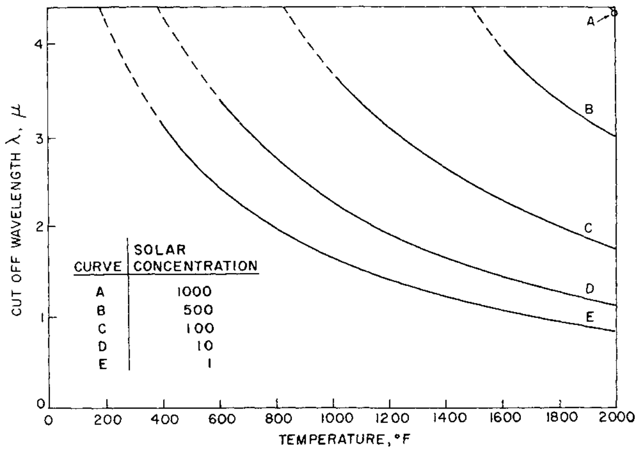

Fig. 2 Cut-off wavelength for ideal absorber.

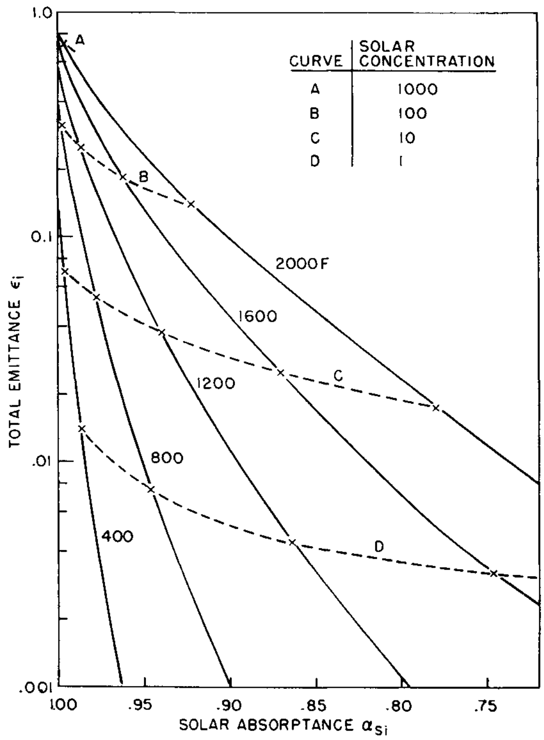

Fig. 3 Solar absorptance and total emittance of ideal absorber.

surface to that for an ideal selective absorber under the same conditions

$$\phi = \frac{q}{q_i} = \frac{\alpha_s H_s - \epsilon\sigma T^4}{\alpha_{si} H_s - \epsilon_i \sigma T^4} \qquad \alpha_{si} \neq 1 \qquad \epsilon_i \neq 0 \qquad (3)$$

where the subscript i denotes the ideal absorber. The values of α_{si} and ϵ_i depend on the cutoff wavelength (i.e. the surface temperature and solar concentration) and are plotted in Fig. 3.

Knowing the radiation properties of a material, one can plot ϕ vs T with solar energy concentration as the parameter. The solid curves in Fig. 4 show ϕ for one of the better space-stable high-temperature solar absorbers available today.[1–5] The dashed curves in Fig. 4 are for a blackbody that would be an excellent absorber for high solar energy concentrations. Also, one can see that the advantage of a low emittance value is not critical for certain conditions, because the blackbody ($\alpha_s/\epsilon = 1.0$) would give a higher ϕ than the selective surface ($\alpha_s/\epsilon = 7.0$) for a considerable range of the conditions. In general, a selective absorber has advantages over a blackbody at the lower solar concentrations and higher temperatures.

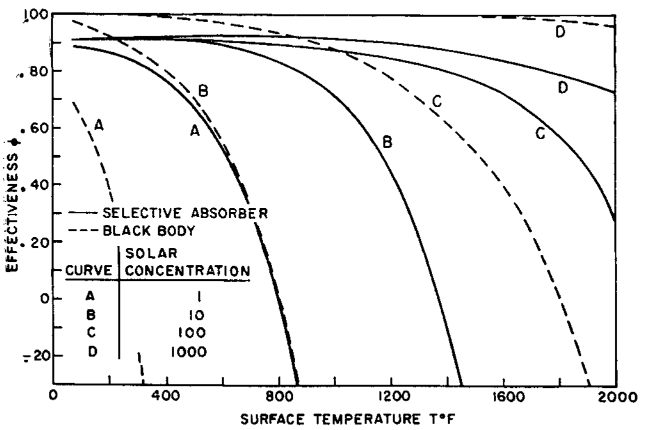

Fig. 4. Effectiveness of an available selective absorber and a blackbody.

Negative effectiveness means more energy is radiated away than absorbed; therefore the surface is no longer a solar absorber but is classified as a radiator.

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Variable-Mass Vehicle Limit-Cycle Propellant Consumption

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Nomenclature

a = Flt_0, ft-lb-sec
b = I_{x_1}, slug-ft²
c = $2Ft_0\, l_1^2/gI_{sp}$, slug-ft²
F = thrust, lb
I_t = specific impulse, sec
I_{sp} = minimum impulse increment per engine, lb-sec
I_x = vehicle moment of inertia, slug-ft²
I_{x_1} = initial moment of inertia, slug-ft²
l = moment arm of coupled motors, ft
l_1 = propellant tank distance from axis, ft
t_0 = pulse width, sec
$\bar{\dot\theta}$ = average angular rate, rad/sec
θ_r = angular limit, rad
$\dot\omega$ = propellant flow rate per rocket motor, lb/sec

THE analytic procedures used for the study of attitude control and stabilization usually assume that the mass of the orbiting vehicle remains constant during the control period. However, any vehicle that has a sustained operational life will have a bounded propellant mass fraction. Near the end of operation, the mass and principal moments of inertia will be reduced, thus altering the dynamic characteristics of the vehicle. Regardless of the type of active stabilization used, this change in vehicle dynamics will occur. In the particular system under consideration, the expulsion of propellants during operation of the reaction control system will reduce the vehicle mass. The analysis presented in this paper shows the effect of variable mass and moments of inertia and compares the results with the case of a constant mass system.

During the fine control mode of operation, it was shown by Reeves, Boardman, and Baumann[1] that the vehicle will oscil-

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