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by Curt H. Liebert and Robert R. Hibbard

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SUMMARY

An analysis was made and equations and charts were developed that make it easy to calculate the temperatures of opaque, thin, flat plates in a Sun-planet system. The analysis is general and includes the effects of sunlight, albedo, and Earth radiation at any altitude and for any orientation; it requires that the absorptance and emittance of the plate surfaces be known.

This analysis was applied to three thin-film cadmium sulfide solar cells, and it uses experimentally determined optical properties to calculate equilibrium temperatures in various Earth orbits. The calculations consider the effect of painting the inactive side with a black paint or a white, zinc oxide (ZnO) paint and the effect of lowering the solar absorptance of the active side at wavelengths not used in photovoltaic energy conversion.

The results show that the temperature of present day cells with the inactive side not painted may vary from 346° K in sunlight to 92° K in the Earth's shadow. It was observed that the temperatures in sunlight may be lowered by painting the inactive side with a ZnO paint. In some cases, a black paint is as effective in lowering the temperature as a ZnO paint. Further temperature reductions may be achieved by lowering the solar absorptance of the active side at wavelengths not used in photovoltaic energy conversion.

INTRODUCTION

Thin-film solar cells are relatively new and may be used in the future to generate electric power in space (ref. 1). The temperatures that these cells reach in space influence both their performance and life; their performance because efficiency varies with temperature and their life because they may degrade when thermally cycled through wide temperature ranges (ref. 2). It is desirable, therefore, to be able to calculate the operating temperatures of thin-film cells in the various space environments to which they may be exposed.

Temperatures are related to the energy flux that is absorbed from various radiating sources and to that which is radiated away. The sources are the Sun, the planet albedo (sunlight reflected from the Earth and clouds), and direct planet radiation. The energy flux absorbed varies with the distances from the Sun and the planet, the orientation of the solar cell relative to the Sun and the planet, and the optical properties of the cells. The energy flux that is radiated away will depend on the temperature of the cell and its optical properties. In addition, the temperature will also depend on the amount of solar energy that will be converted by the cell to electric power. The analysis presented herein was performed by equating these energy losses and gains. Equations and charts were devised that facilitate the calculation of the cell temperature.

The normal absorptance to solar flux and total hemispherical emittance of three cadmium sulfide solar cells of different construction was experimentally determined. These data were used with the present analysis to calculate the temperatures that the three cells would achieve in various Earth orbits.

SYMBOLS

A	area, m^2
a	albedo flux evaluated at the surface of planet, W/m^2
D	distance from plate to Sun in astronomical units (1 AU = 1.5×10^8 km)
E	planet heat flux evaluated at surface of planet, W/m^2
H	distance between flat plate or solar cell and center of sphere (planet) divided by radius of sphere (which, for Earth, equals 6376 km (3963 miles)), km; miles
Q	rate of heat flow, W
Q/A	heat flux, W/m^2
S	solar flux evaluated at distance of plate or cell from Sun, W/m^2
T	temperature of solar cell in planet orbit, $^{\circ}K$
Y	geometry factor
α	absorptance
β	angle between normal to plate and line from plate to center of Earth, deg

ϵ emittance

η efficiency of solar cell in converting incident sunlight to electricity

θ angle of incidence of solar flux, deg

σ Stefan-Boltzmann constant, 5.67×10^{-8} $(W/(m^2)(^oK^4))$

Subscripts:

a albedo

ab absorbed

e planet radiation

l lost

nλ normal, spectral

s solar radiation

1, I side 1

2, II side 2

HEAT-BALANCE EQUATIONS

Analysis

A surface in a Sun-planet system absorbs some energy directly from the Sun and also from sunlight reflected from the planet and its clouds (albedo). The surface also absorbs some of the energy emitted directly from the planet. The fraction of energy from a source absorbed by a surface is called the total absorptance and depends on the nature and temperature of the absorbing surface and the wavelength distribution of the incident radiation. The values of total absorptance and incident radiation can be different for each source. The surface will also radiate to its surroundings at a rate that varies with its temperature and emittance. Terms defining these quantities are now developed.

The solar flux absorbed per unit area of side 1 (active or sunlit surface) of a flat plate is $\alpha_{1,s}S \cos\theta$, where θ is the angle of incidence of solar flux. The solar flux S is evaluated at the distance of the plate from the Sun, and $\alpha_{1,s}$ is the absorptance to incident solar radiation. The albedo flux absorbed per unit area of side 1 of the plate is $\alpha_{1,a}aY_I$, where a is the albedo radiation, $\alpha_{1,a}$ is the ratio of absorbed to incident albedo radiation, and Y_I is a geometry factor obtained from reference 3. This geometry factor is a function of the distance between the plate and the center of the planet and the orientation of the plate. In the same manner, the albedo flux absorbed per unit area of side 2 is $\alpha_{2,a}aY_{II}$. Similarly, the planet radiation absorbed per unit area of both sides of the flat plate is $\alpha_{1,e}EY_{I}$ and $\alpha_{2,e}EY_{II}$. The total energy absorbed per unit area is the sum of the radiations absorbed from the Sun, albedo, and planet:

$$\left(\frac{Q}{A}\right)_{ab} = \alpha_{1,s}S\cos\theta + \alpha_{1,a}aY_{I} + \alpha_{2,a}aY_{II} + \alpha_{1,e}EY_{I} + \alpha_{2,e}EY_{II} \tag{1}$$

In theory, it is possible that sunlight may be incident on side 2. In practice, it is unlikely that solar cells will be operated so close to the Sun or at such an angle from the perpendicular to the Sun so that the backside will be irradiated. Therefore, this term $(\alpha_{2,s}S\cos\theta)$ was omitted from equation (1) and only the term $\alpha_{1,s}S\cos\theta$ included.

The rate of emission per unit area of side 1 is $\epsilon_1\sigma T_1^4$, where ϵ_1 is the total hemispherical emittance and σT_1^4 is the emissive power of a blackbody. Similarly, the rate of emission of side 2 is $\epsilon_2\sigma T_2^4$. If a flat plate is a solar cell, some of the incident solar energy is converted to electric power. This is accounted for by the terms $\eta S\cos\theta$, where η is the conversion efficiency of the cell (plate). The total flux lost $(Q/A)_l$ is the sum of the heat flux emitted from both sides of the plate plus that removed by the conversion of sunlight to electric power. This sum is expressed as

$$\left(\frac{Q}{A}\right)_{l} = \epsilon_1\sigma T_1^4 + \epsilon_2\sigma T_2^4 + \eta S\cos\theta \tag{2}$$

Equating the energy absorbed to the energy lost on a very thin plate gives

$$T = \left[\frac{(\alpha_{1,s} - \eta)S\cos\theta + (\alpha_{1,a}a + \alpha_{1,e}E)Y_{I} + (\alpha_{2,a}a + \alpha_{2,e}E)Y_{II}}{(\epsilon_1 + \epsilon_2)\sigma}\right]^{0.25} \tag{3}$$

when $T_1 = T_2 = T$.

Values of Fluxes and Geometry Factors for Sun-Earth System

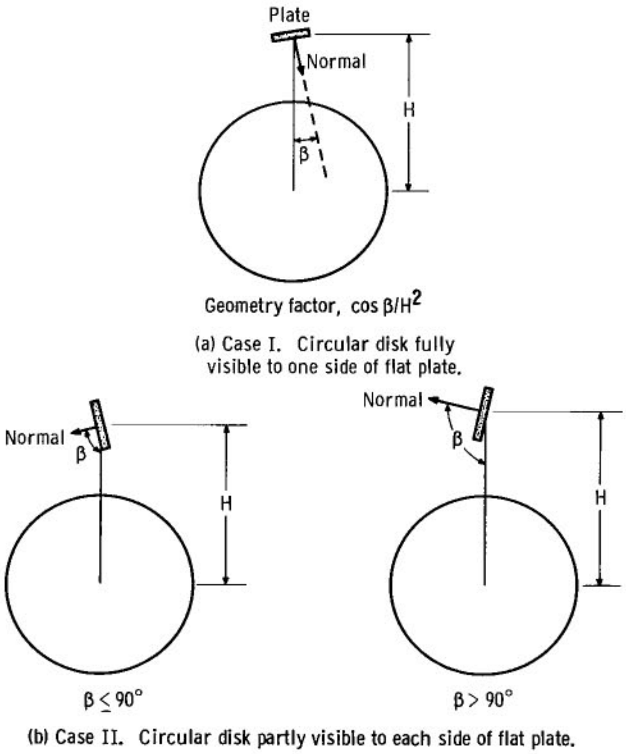
Equation (3) is completely general and can be applied to a flat plate at any point in a Sun-planet system when the temperature does not vary with time. The equation can be used for a plate near the Earth by substituting appropriate values for S, a, E, Y_I, and Y_{II}. These quantities are considered in that order.

Solar flux. - The plate solar flux was taken as the solar constant of the Earth. During the past 30 years, estimates of the solar constant have ranged from 1320 to 1430 watts per square meter (ref. 4). The value of S used herein was 1350 watts per square meter. For other distances from the Sun, S can be approximated by the relation

$$S = \frac{1350 \text{ W/m}^2}{D^2}$$

where D is the distance from the plate to the Sun in astronomical units.

Albedo. - The albedo a consists of the solar reflection from land, sea, ice, and clouds. Therefore, to an Earth-orbiting system, the albedo varies with the time, season, and position over the Earth. Observations from the first Orbiting Solar Observatory (OSO-I) showed the fraction of incident solar flux reflected from the Earth to vary between 10 and 38 percent with an average of 23 percent from 17 determinations (ref. 5). These determinations were obtained during the months of March, April, and May and over a narrow span of latitude centered over the tropics. For a solar constant of 1350 watts per square meter, the average albedo then becomes $1350 \times 0.23 = 310$ watts per square meter.



(b) Case II. Circular disk partly visible to each side of flat plate.

Figure 1. - Geometries for case I and case II defined in reference 3.

Earth radiation. - The Earth radiation E was also determined by OSO-I and ranged from 0.42 to 0.51 langley per minute (294 to 357 W/m^2) (ref. 5). The average of seven values was 330 watts per square meter.

Geometry factors. - Cunningham derived a relatively simple expression for the geometry factors where the plate is oriented so that the sphere, as seen from the plate, appears as a circular disk (ref. 3). This geometry factor includes the distance between the plate and the center of the sphere H, and the angle β, between the normal to a given side of the plate and a line from the plate to the center of the sphere as variables (see fig. 1, case I). A much more sophisticated analysis was required in reference 3 for the case where the side of the plate receives radiation from only a portion of the circular disk. The geometry for this situation is shown in figure 1 for case II. Again, the geometry factors are a function of β and H.

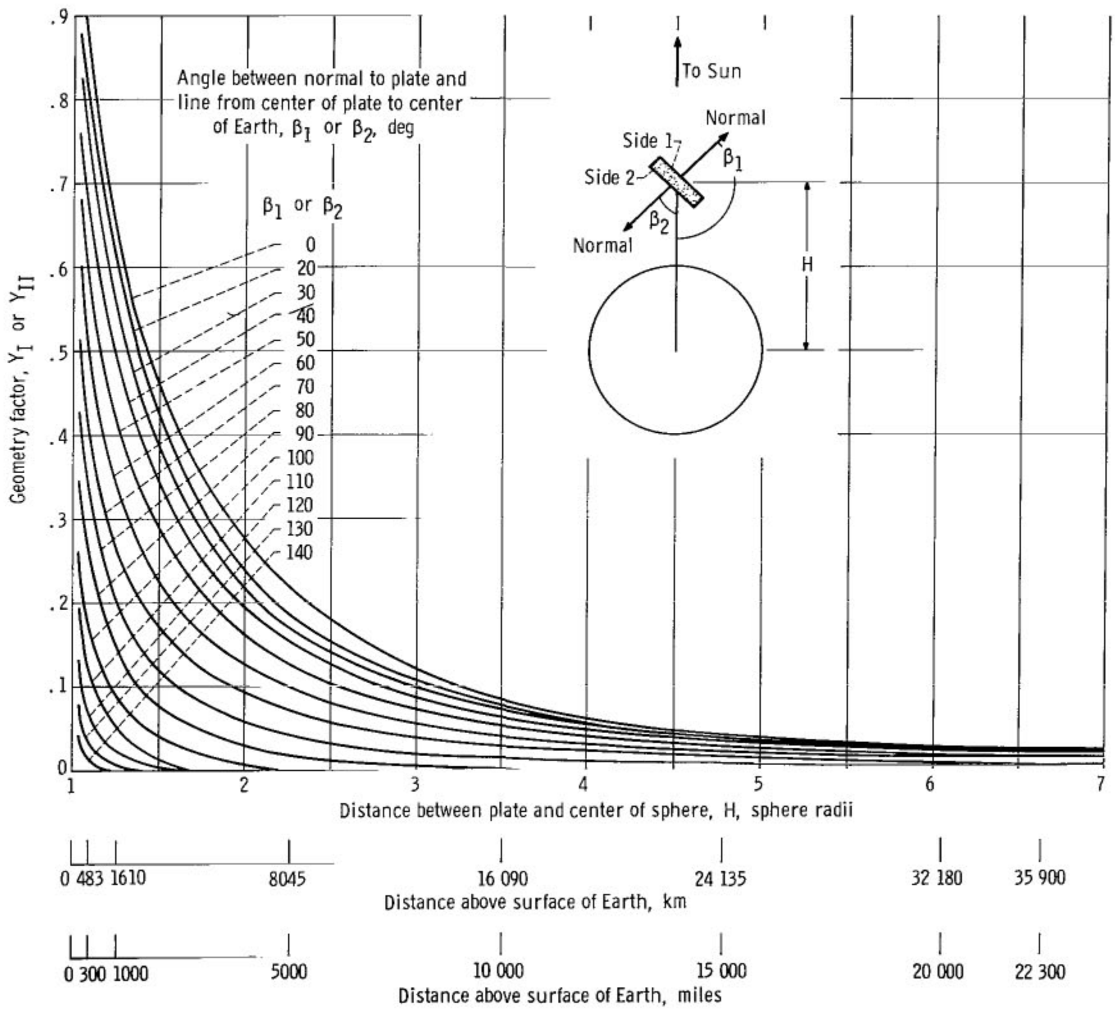


Figure 2. - Geometry factors as function of distance between plate and center of sphere. (Correspondence between scales is based on Earth radius, 6376 km or 3963 miles, where 1 mile = 1.609 km.)

The geometry factors derived in reference 3 for the two cases were combined, extended, and are presented as a single plot in figure 2. This figure may be used to estimate the geometry factors of a flat plate at any position relative to the Earth. The factors Y_I and Y_{II} are shown as a function of altitude with the angles β_1 and β_2 as the parameters and are defined in the sketch of figure 2. The angle β_1 and the distance H are used to determine Y_I, and β_2 and H are used to find Y_{II}. The angles β_1 and β_2 are supplementary, that is, $\beta_1 = 180^\circ - \beta_2$.

The curves in figure 2 show that only one geometry factor often need be considered. For example, if $\beta_2 = 0^\circ$, then $\beta_1 = 180^\circ$ and $Y_I = 0$ for any altitude H. Another example is with $H = 2.0$ and $\beta_2 = 30^\circ$, then $\beta_1 = 150^\circ$, and $Y_I = 0$. For both these examples, the term containing Y_I can be dropped from equation (3).

When $\beta_1 = 90^\circ = \beta_2$, then $Y_I = Y_{II}$ or the same geometry factor applies to both surfaces, which is another way of saying that equal amounts of earthlight can be incident on both surfaces.

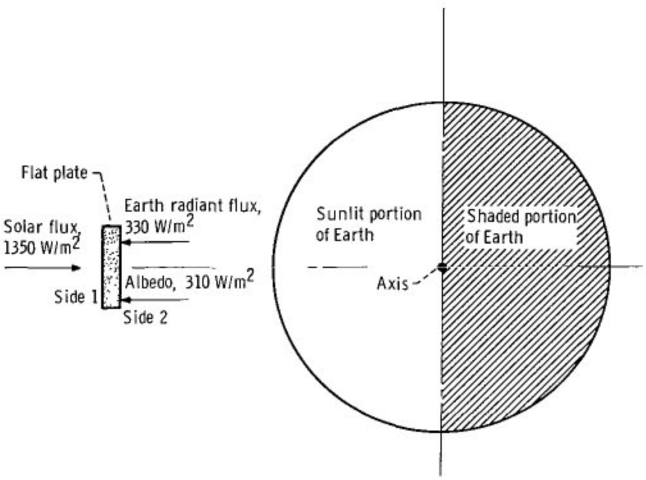
Equilibrium temperature equations. - For Earth-orbiting satellites, the solar constant of 1350 watts per square meter can be used, and, if the average values for albedo and Earth radiation are also used, equation (3) becomes

$$T = \left[\frac{1350(\alpha_{1,s} - \eta)\cos\theta + (310\alpha_{1,a} + 330\alpha_{1,e})Y_I + (310\alpha_{2,a} + 330\alpha_{2,e})Y_{II}}{(\epsilon_1 + \epsilon_2) \times 5.67\times10^{-8}}\right]^{0.25} \tag{4}$$

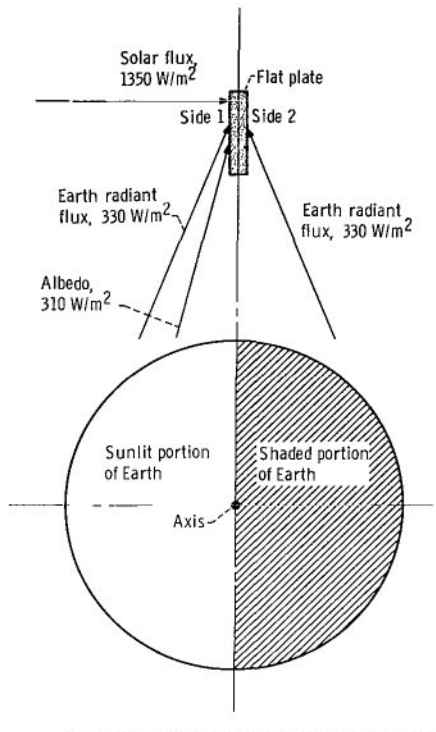
A simplification of equation (4) is to assume, for solar cells, that the active surface (side 1) is normal to the sunlight at all times. The angle θ is then 0 and $\cos\theta = 1.0$ in the first term of equation (4). While temperatures can be calculated easily for other θ, this simplification is used in all the temperature calculations presented hereinafter for real cells. It is also assumed that $\eta = 0$, that is, that the cells are operating against an open circuit. The effect of efficiency on cell temperature is considered in the section Calculated Temperatures.

Three cases of Sun-Earth flat-plate orientation were examined and are shown in figure 3.

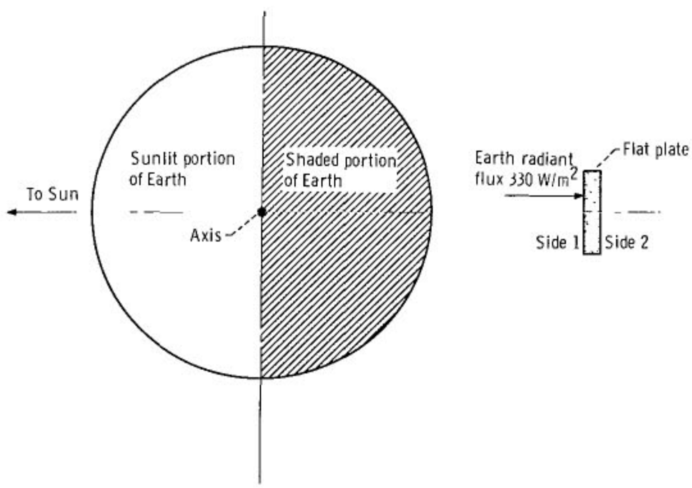
Case A (fig. 3(a)) is for the Earth-noon position. For this case, $\beta_1 = 180^\circ$ and $\beta_2 = 0^\circ$, and thus $Y_I = 0$. Substituting $Y_I = 0$, $\eta = 0$, and $\cos\theta = 1$ into equation (4) gives



(a) Position of flat plate in Sun-Earth system for case A.



(b) Position of flat plate in Sun-Earth system for case B.



(c) Position of flat plate in Sun-Earth system for case C.

Figure 3. - Sun-Earth flat-plate orientations in vicinity of equator.

$$T = \left[\frac{1350\alpha_{1,s} + (310\alpha_{2,a} + 330\alpha_{2,e})Y_{II}}{(\epsilon_1 + \epsilon_2) \times 5.67\times10^{-8}}\right]^{0.25} \tag{5a}$$

Case B (fig. 3(b)) is for the cell at the Earth-twilight position where $\beta_1 = \beta_2 = 90^{\circ}$. Both sides of the cell now have an equal view of the Earth ($Y_I = Y_{II}$), but the back views no albedo ($\alpha_{2,a} = 0$) while the sunlit side views both Earth radiation and albedo. Substituting $\alpha_{2,a} = 0$, $\eta = 0$, and $\cos\theta = 1$ into equation (4) gives

$$T = \left[\frac{1350\alpha_{1,s} + (310\alpha_{1,a} + 330\alpha_{1,e})Y_I + 330\alpha_{2,e}Y_{II}}{(\epsilon_1 + \epsilon_2) \times 5.67\times10^{-8}}\right]^{0.25} \tag{5b}$$

Case C (fig. 3(c)) is for the Earth-midnight position where only Earth radiation is incident on surface 1 ($\beta_1 = 0^{\circ}$), and where no radiation is incident on surface 2. The temperature then is given by

$$T = \left[\frac{330\alpha_{1,e}Y_I}{(\epsilon_1+\epsilon_2) \times 5.67\times10^{-8}}\right]^{0.25} \tag{5c}$$

Equations (5) are used in the subsequent calculations of solar cell operating temperatures.

RESULTS AND DISCUSSION

Optical Properties of Cadmium Sulfide Cells

Equations (5) require, in addition to Y_I and Y_{II} which are functions of altitude and orientation, the various optical properties $\alpha_{1,s}$, $\alpha_{1,a}$, $\alpha_{1,e}$, ϵ_1, $\alpha_{2,a}$, $\alpha_{2,e}$, and ϵ_2. In this section these properties are described for cadmium sulfide thin-film solar cells of varying construction (see table I). All the optical property data to be discussed are summarized in table II.

The total normal absorptances of both cell surfaces to simulated sunlight, $\alpha_{1,s}$ and $\alpha_{2,s}$, and their total hemispherical emittances near 300° K, ϵ_1 and ϵ_2, were measured by Mr. Henry B. Curtis of the Lewis Research Center in the apparatus described

TABLE I. - CONSTRUCTION OF CADMIUM SULFIDE

THIN-FILM SOLAR CELLS

Cell	Components	Approximate thickness, mm
1	H-film	0.050
	Nylon	.012
	Gold grid	.005
	Cuprous sulfide	<<.001
	Cadmium sulfide	.025
	Molybdenum substrate	.050
2	H-film	0.008
	Mylar	.050
	Nylon	.012
	Gold grid	.005
	Cuprous silfide	<<.001
	Cadmium sulfide	.025
	Molybdenum substrate	.050
3	Mylar	0.025
	Epoxy cement	-------
	Silver-plated copper grid	.005
	Cuprous silfide	<<.001
	Cadmium sulfide	.025
	Zinc	<<.001
	Substrate of silver-filled, Pyre-ML coated on H-film	.050

in references 6 and 7. The results are believed to be correct within ±5 percent and are indicated in table II by the notation (experimental).

Experimental values of the normal spectral absorptance (equal to the normal spectral emittance) of the active side of the three cells were determined in part by Miss Evelyn Anagnostou of the Lewis Research Center and are presented in figure 4. These values were used to calculate $\alpha_{1,s}$ for the three cells. The calculated $\alpha_{1,s}$ compared within 4 percent of that directly obtained by Curtis and recorded in table II. The data of table II were used herein.

The absorptances to the albedo, $\alpha_{1,a}$ and $\alpha_{2,a}$, could not be measured directly. However, it is generally assumed that the spectral distribution of this reflected sunlight is identical to that of direct sunlight, and therefore $\alpha_{1,a} = \alpha_{1,s}$ and $\alpha_{2,a} = \alpha_{2,s}$. Also, the absorptance of a surface to earth thermal emission (a blackbody source near 300° K) should be substantially the same as the measured emittance near 300° K so that $\alpha_{1,e} = \epsilon_1$ and $\alpha_{2,e} = \epsilon_2$. (These assumptions as to the spectral qualities of the albedo and earthlight were also used in ref. 5 to deduce the values for albedo and earthlight

TABLE II. - OPTICAL PROPERTIES OF CADMIUM SULFIDE

THIN-FILM SOLAR CELLS

(a) Side 1

Cell	Total normal absorptance			Total hemispherical emittance, ϵ_1 (experimental)
	Solar, $\alpha_{1,s}$ (experimental)	Albedo, $\alpha_{1,a}$ (assumed)	Earth, $\alpha_{1,e}$ (assumed)	
1	0.86	0.86	0.90	0.90
2	.72	.72	.93	.93
3	.74	.74	.89	.89

(b) Side 2

Cell	Paint on side 2	Total normal absorptance			Total hemispherical emittance, ϵ_2 (experimental)
		Solar, $\alpha_{2,s}$ (experimental)	Albedo $\alpha_{2,a}$ (assumed)	Earth, $\alpha_{2,e}$ (assumed)	
1	Black	0.96	0.96	0.96	0.96
	Zinc oxide	.25	.25	.93	.93
2	Black	0.96	0.96	0.96	0.96
	Zinc oxide	.25	.25	.93	.93
3	None	0.51	0.51	0.79	0.79
	Black	.96	.96	.96	.96
	Zinc oxide	.25	.25	.93	.93

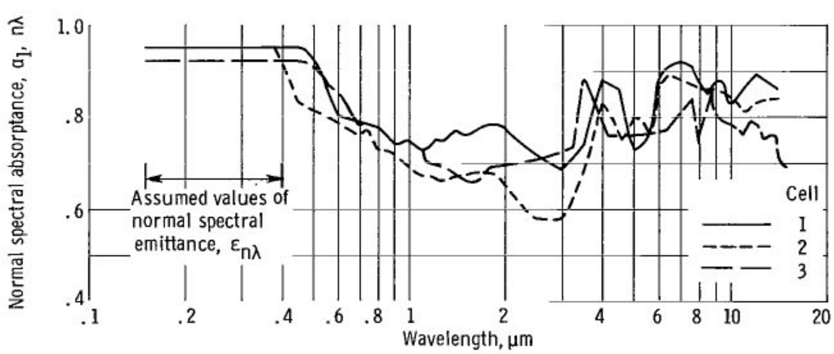


Figure 4. - Room temperature spectral absorptance of cadmium sulfide solar cells.

from emissivity sensors on OSO-I.) The absorptances to albedo and earth emission are indicated in table II with the notation (assumed). Errors introduced by these assumptions are certainly less than the errors that arise from assuming that the albedo and Earth emission are constant (average) quantities at all seasons and over all parts of the Earth.

Of the three cadmium sulfide solar cells studied (table I), two had molybdenum foil substrates (side 2) that were painted with either a black paint or a white, zinc oxide paint. The third cell had a silver-filled plastic substrate and its optical properties were measured in the unpainted condition and with black and white paints. The total normal solar absorptance $\alpha_{2,s}$ and the total hemispherical emittance near 300° K ϵ_2 were experimentally determined for the black paint on side 2 of all the cells, and both were 0.96. Therefore, $\alpha_{2,a}$ and $\alpha_{2,e} = 0.96$ for the cells coated with black paint. The optical properties of the ZnO paint used on side 2 of all the cells were taken from reference 7, which shows that α_s values of ZnO-pigmented paints incorporating different binders and having varying thicknesses can range from 0.13 to 0.37 and can have values of ϵ that vary from 0.83 to 0.96 at temperatures near 300° K. The values used herein are $\alpha_{2,s} = \alpha_{2,a} = 0.25$ and $\alpha_{2,e} = \epsilon_2 = 0.93$ and were taken as being representative. The experimental values of $\alpha_{2,s}$ and ϵ_2 for the bare, silver-filled plastic substrate only were determined as 0.51 and 0.79, respectively. Therefore, $\alpha_{2,a}$ of the cell 3 substrate was taken to be 0.51 and $\alpha_{2,e}$ as 0.79. All these optical properties of side 2 are given in table II.

Calculated Temperatures

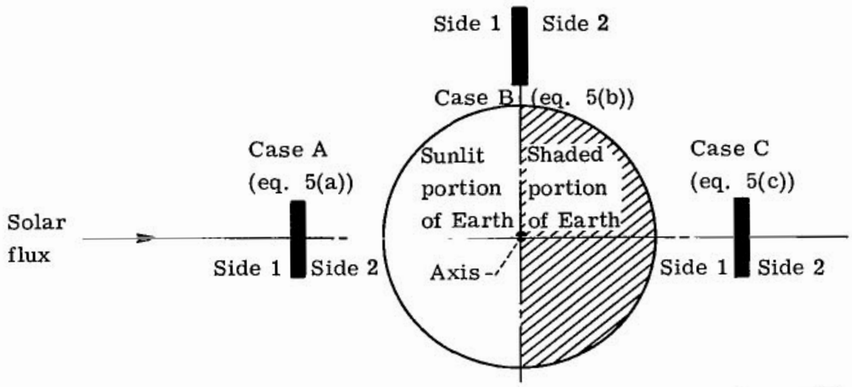
Table III presents the temperatures of the three cells calculated from equations (5) at altitudes of 483 and 35 900 kilometers (300 and 22 300 miles) and for the several coatings on side 2.

The temperatures of cell 1 for cases A and B are larger than those of the other two cells. These greater temperatures are the result of the larger absorption to sunlight $\alpha_{1,s}$ of the active side of cell 1 compared with the other cells and of the insensitivity of ϵ_1 to the construction of the three cells (see table II).

Table III shows that the temperature of cell 3 for a case A 483-kilometer orbit is 346° K if the inactive side is unpainted. This temperature may be lowered if the unpainted side is covered with a ZnO paint. However, a black paint will not lower the cell temperature, as was demonstrated by cells 1 and 2, the temperatures of which were lowered when ZnO paint was used.

Contrary to the results for the case A 483-kilometer orbit, the temperature of cell 3 for a case B 483-kilometer orbit or a case A and B 35 900-kilometer orbit will be

TABLE III. - CALCULATED TEMPERATURES



Case	Altitude		Cell						
	km	mi	1		2		3		
			Paint on side 2						
			Black	Zinc oxide	Black	Zinc oxide	None	Black	Zinc oxide
			Temperature, ^{o}K						
A	483	300	356	346	344	333	346	348	337
	35 900	22 300	325	326	310	310	321	313	314
B	483	300	339	341	325	326	336	329	330
	35 900	22 300	324	324	309	309	320	312	314
C	483	300	222	223	223	224	227	222	222
	35 900	22 300	90	90	90	90	92	90	90

lowered if either a black or ZnO paint is incorporated. The temperatures of all cells are about the same when either a black or ZnO paint is used.

For minimum temperatures and maximum photovoltaic efficiencies, a solar cell should have the following spectral absorptance-reflectance qualities. (All cells considered herein have zero transmittance.) The cell junction should have high absorptance (low reflectance) to that portion of sunlight that can be converted to electric power. The cell should have high reflectance (low absorptance) to the rest of the sunlight, and it should have high emittance (high absorptance and low reflectance) at the long wavelengths important at lower temperatures.

The cadmium sulfide cell can convert to electricity only that portion of sunlight that is between about 0.4 and 1.1 microns. This is 65 percent of the Sun's energy. There is about 12 percent unusable at wavelengths less than 0.4 micron and 23 percent unusable at wavelengths greater than 1.1 microns. Ninety-eight percent of the Sun's energy is at wavelengths less than 3.0 microns. And, for an emitter at 300^{o} K, about 98 percent of the energy is radiated at wavelengths larger than 5.2 microns. Therefore, an ideal CdS cell should have high absorptance between 0.4 and 1.1 microns, low absorptance at wavelengths less than 0.4 micron, low absorptance between 1.1 and 3.0 microns, and high emittance (high absorptance) at wavelengths greater than 5.2 microns.

Figure 4 shows the spectral normal absorptance of the front or active surface of the three thin-film cells as determined between 0.4 and 15 microns. It can be seen that there is an undesirably high absorptance at wavelengths less than 0.4 micron, a somewhat lower than ideal absorptance ($\alpha_{1,n\lambda} = 1.0$) between 0.4 and 1.1 microns, and an undesirably high absorptance between 1.1 and 3 microns. At wavelengths greater than 5.2 microns, the spectral emittance (identical with spectral absorptance) is about 0.8, where values as close as possible to 1.0 would be better.

Since the cadmium sulfide cells are composites of several materials, as shown in table I, it is difficult to determine clearly the contribution of each material to the spectral qualities of the finished cell. However, the outermost layer, either Mylar or H film, has a low reflectance of about 0.1 at all wavelengths shown in figure 4, and therefore, absorbs and transmits about 90 percent of the radiation. At wavelengths less than 0.4 micron, both plastics are strongly absorbing. Thus, the high cell absorptances at wavelengths less than 0.4 micron (fig. 4) are a result of the high plastic absorptance. At wavelengths from 0.4 to 3 microns, the plastics exhibit a high transmittance; therefore, the large values of $\alpha_{1,n\lambda}$ obtained for the cell at wavelengths from 0.4 to 3 microns are probably a result of the emission of the other cell components through the plastic. Both plastics have generally high absorptance at wavelengths greater than about 10 microns, so that they contribute to the desired high emittance in this long wavelength region (fig. 4). Between 3 and 10 microns, the plastics show several broad regions of strong and lesser absorption. This variation in absorption is characteristic of organic materials and probably accounts for the irregularities in $\alpha_{n\lambda}$ shown in figure 4 for the three cells.

The greatest improvement possible for these thin-film cells would be to reduce drastically their normal spectral absorptance at wavelengths of less than 0.4 micron and in the wavelength region from 1.1 to 3 microns. For example, if, for the ZnO-coated cell 3, $\alpha_{1,n\lambda}$ were 0.1 at 0.15 to 0.4 micron, and 0.1 at 1.1 to 3 microns, $\alpha_{1,s}$ would be reduced from 0.74 to 0.53, and the temperature of this cell in a case A 483-kilometer orbit would be reduced from 337° to 317° K. It is not known whether a significant change could be made in the optical properties over these wavelength regions without impairing the electrical output of the cell.

The temperature of a cell of construction identical to that of the unpainted cell 3 was measured in a solar simulator and was 323° K. The calculated temperature for the bare cell 3 in this environment is 320° K. This good agreement of experiment and theory lends credence to these calculations.

The calculations performed for lower altitudes could not be verified experimentally.

As an alternative, limited calculations were performed herein to determine the uncertainty of this analysis. The largest and smallest values of Earth emission and albedo determined from OSO-I and variations in the optical properties of ±5 percent were used to calculate maximum and minimum values of temperature from equations (5). Within the uncertainty of these data, the temperature may be calculated within ±5 percent.

These temperatures are valid only if the cell is in the vicinity of the positions described by the various cases at times long enough for equilibrium to be approached closely. An approximate calculation based on the heat storage capacity of the cell was made which indicated that the temperature of cell 3, coated with ZnO, would vary from 220° to 335° K in about $1\frac{1}{2}$ minutes. A cell in orbit at 483 kilometers above the Earth's surface has a half-period of 48 minutes. Thus, it is reasonable to assume that the cells in their various orbits will achieve the temperatures given in table III.

These calculations assume that no energy was converted into electric power. However, many cells are about 5 percent efficient (ref. 1). Calculations indicate that a 5-percent efficient cell will be from 3° to 6° K lower than those listed in table III.

CONCLUDING REMARKS

Equations and charts were developed to predict the temperature of a thin flat plate upon which sunlight, albedo, and planet radiant flux is incident. Values of the parameters of the equations developed from the theory were determined experimentally or obtained from the literature and were used to calculate the temperature of several types of thin-film cadmium sulfide cells in an Earth orbit. It was concluded that

1. The temperature of present day cells with the inactive side not painted varies from 346° K in sunlight to 92° K in the shadow of the Earth.

2. The temperature of these cells in sunlight may be lowered by 5° to 9° K by painting the inactive side with a zinc oxide paint. A black paint is usually as effective in lowering the temperature as is a zinc oxide paint.

3. Significant temperature reductions (approx. 20° K for a zinc oxide-coated cell) may be achieved by lowering the solar absorptance of the active side to 0.1 in wavelength regions not used in photovoltaic energy conversion.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 16, 1967,
120-27-01-20-22.

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