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NASA CONTRACTOR REPORT

NASA CR-91

NASA CR-91

N64 27758

(ACCESSION NUMBER) (THRU)

25

(PAGES) (CODE)

1

(NASA CR OR TMX OR AD NUMBER) (CATEGORY)

SPACECRAFT TEMPERATURE CONTROL BY THERMOSTATIC FINS-ANALYSIS

by J. A. Wiebelt and J. F. Parmer

Prepared under Grant No. NsG-454 *by*
OKLAHOMA STATE UNIVERSITY
Stillwater, Okla.

for

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • AUGUST 1964

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SPACECRAFT TEMPERATURE CONTROL

BY THERMOSTATIC FINS-ANALYSIS

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SUMMARY

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A spacecraft temperature control system is proposed which consists of thermostatic fins, mounted in pairs. The operation of these fins in conjunction with a white base material is analyzed to determine the surface average temperature with various energy fluxes leaving the surface.

As a result of the analysis work in this report, it is proposed that a spacecraft surface system may be designed for given conditions such that the surface temperatures will remain within acceptable limits for electronic apparatus. Although the problem when manned space probes are considered is not examined in detail, the system should be capable of maintaining inhabitable, although not comfortable, environmental temperatures for these missions.

author

INTRODUCTION

Objective. The object of this investigation was to determine analytically the characteristics of a particular spacecraft system. This system (described in the approach following) basically was to be a system which could vary the ratio α_s/ε as a function of the surface temperature.

General Approach. In the space environment a spacecraft system gains or loses energy entirely by radiant exchange with the environment. As pointed out Edwards (ref. 1) the parameter which is most important for a system which must radiate energy away is the ratio $q''/\sigma T_s^4$, where q'' is the energy radiated away from the surface per unit area, Btu/hr-ft^2; σT_s^4 is the Plankian radiation from a black surface which has a temperature, T_s.

This ratio is given the symbol e_r', i.e.,

$$e_r' = q''/\sigma T_s^4 \tag{1}$$

As can be seen from the definition, when e_r' has a positive value, energy is radiated away from the spacecraft, or the spacecraft is experiencing a net energy loss to space from that portion of the surface for which e_r' (a point function) is positive. When e_r' is negative the surface element under consideration has a net energy gain from the space environment.

Since all spacecraft will be dissipating heat from internal parts (electronic equipment, men, etc.) the usual requirement for e_r' will be a positive value. However, if the spacecraft is shaded from solar input, the value of e_r' must not change radically. In order for a surface to meet these criteria, the surface must change the average value of e_r' within specified limits. The value of e_r' is a function of three variables for the surface element; ε, the emittance at the temperature of the surface, α_s, the solar absorptance and T_s, the surface temperature. The value of e_r' as determined in (ref. 1) is:

$$e_r' = \varepsilon - \alpha_s \frac{G_s}{\sigma T_s^4} \tag{2}$$

where G_s is the solar irradiation.

The fourth variable in the equation, G_s, is dependent upon the surface element orientation or shading by other elements. With the complex trajectories used today and the complex geometry of spacecraft, G_s is a very difficult quantity to predict (note this must include reflections from other portions of the spacecraft). For this reason, reliable simple control of e_r' must depend on varying ε and α_s for the surface.

Control of ε and α_s for individual points on the surface would require a

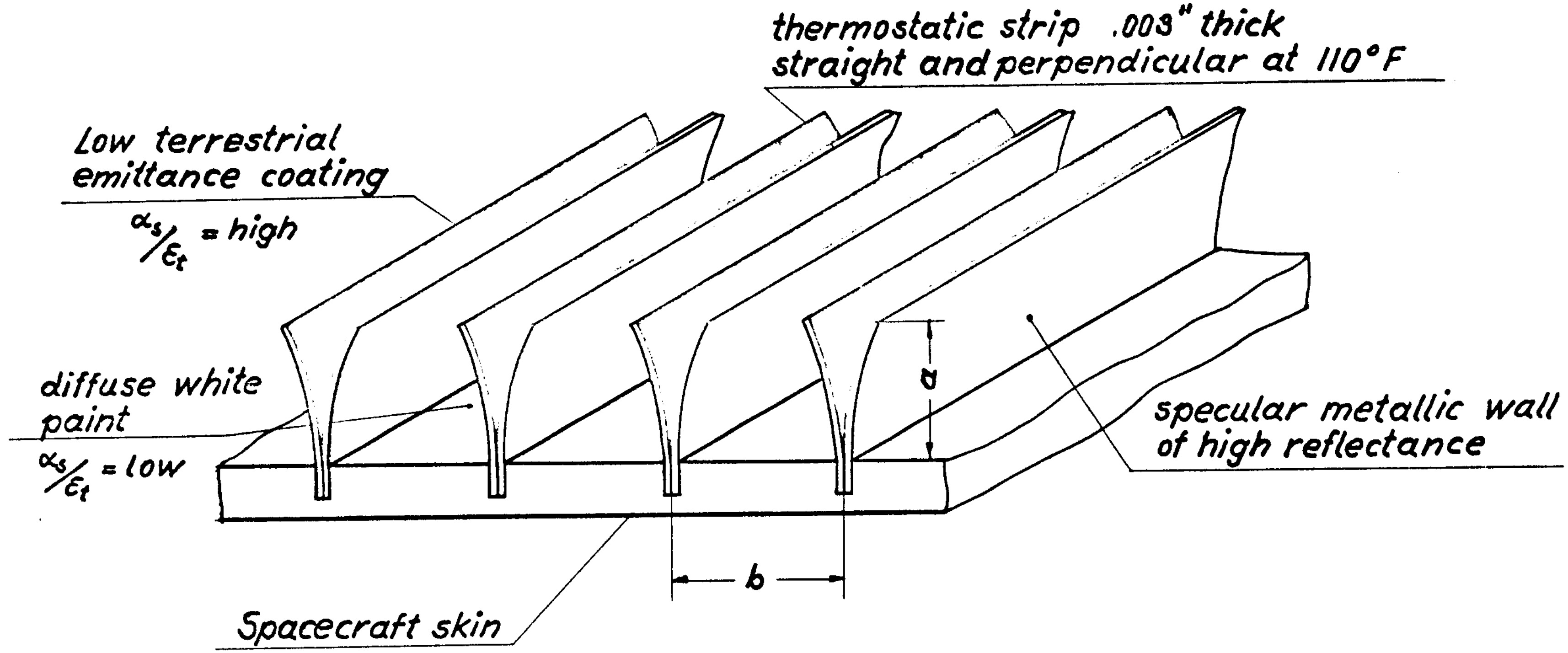

Figure 1. NASA Spacecraft Thermostat Surface.

local surface with variable characteristics. Such a surface would have the characteristic of a paint or coating which changed "color" with temperature change. The control of e_r' averaged over the entire surface would effectively accomplish the same result if sufficient internal mass is present to distribute the resulting temperature variations. For this reason a surface element having an average e_r' equal to the required e_r' was considered to be the proper design criteria.

Specific Approach. The average value of e_r' will depend on the average value of ϵ and α_s for the surface. For a surface area A let A_1 be a portion of the area associated with ϵ_1 and α_{s1} and A_2 be the portion of the surface area associated with ϵ_2 and α_{s2}. If the areas A_1 and A_2 can be controlled by means of a thermostatic material, the average values of ϵ and α_s can be controlled. The method used to control areas herein is shown in Figure 1. The base material is a good white paint ($\alpha_s = .1$, $\epsilon = .8$) as obtained from (ref. 2). Pairs of fins with spacing "b" and height "a" as shown are mounted on the base material. These fins are made of 0.003 inches thick thermostatic material. As the temperature decreases, the fins are mounted such that they warp inwards or tend to shade the base material. This is accomplished by mounting each pair of fins with the low expansion sides adjacent. When the temperature increases, the fins tend to assume the vertical position since the high expansion side faces the base material between the fins. In order to get the largest area change, a very active thermostatic fin material was chosen. This material is "Truflex P-675R". As described by the manufacturer the deflection of the top of the fins (see Figure 2) is given by

$$d = \frac{(113 \times 10^{-7})\ (T_2 - T_1)\ a^2}{t} \tag{3}$$

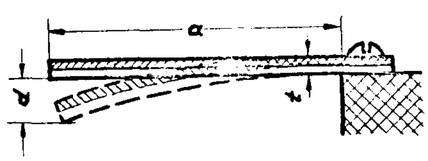

Figure 2.

in which d is the deflection in inches,
$T_2 - T_1$ is the temperature change in degrees F,
t is the thickness in inches.

As can be seen from equation (3), large deflections for a given temperature difference require small thicknesses, t, or large lengths, a. For this analysis, the thinnest material available (t = 0.003 inches) was chosen. Since the amount

ρ_b = Reflectance of the white base section.
x = Length of base section which is irradiated by the incoming radiation after being reflected by the walls n times.
y = Length of base section which is irradiated by the incoming radiation after being reflected by the walls n + 1 times.
G_s or G_s = Intensity of incoming heat radiation flux Btu/hr-ft^2 or Btu/hr-ft^2
S = Solar constant 442 Btu/hr-ft^2.
a = Height of wall.
b = Width of the base.
ϕ = Angle of inclination of incoming radiation or solar angle.
J = Radiosity of surface base section x or y.
I = Irradiation of surface base section x or y.
F_{XT} = Total fraction of energy which leaves surface area x and reaches opening 4.
A_x = Area of base section o to x.
ρ_e/ρ_b = Effective reflectance ratio.

The method used herein assumes that the groove is being irradiated by a source which is far enough from the surface so that the incoming rays are parallel. Therefore, a certain fraction of the incoming radiation will be absorbed by interreflections between the specular walls, the number of interreflections being controlled by the radiations' angle of inclination (ϕ). The irradiation of the base surface can be broken up into two parts. Figure 3 illustrates the multiple reflections which irradiate the base surface. When the angle ϕ is between arctan(mb/a) and arctan(nb/a), where (m,n) = (0,1), (1,2), ..., (m, m+1),..... the irradiation of A_x and A_y is:

$$I_x = S\rho_w^m \cos\phi \qquad I_y = S\rho_w^n \cos\phi \ . \tag{4}$$

For example, the irradiation of the surface from 0 to x_o (Figure 3a) consists of both reflected and direct irradiation, the surface from o to y only of reflected radiation. However, for purposes of calculation, the base section is divided into two areas; the area from 0 to X (A_x) is assigned an irradiation of S cosϕ. The radiosity of A_x is therefore,

$$J_x = \rho_b S \cos\phi \tag{5}$$

and the radiosity of Ay is, similarly,

$$J_y = \rho_w \rho_b S \cos\phi \ . \tag{6}$$

of control required may vary from case to case "a" values of 0.25 inch, 0.75 inch, and 2.0 inches were used. Inasmuch as the deflection "d" increases as the square of the "a" dimension, the control or ability to maintain a controlled temperature increases as "a" increases.

Examination of equation (3) shows that the deflection depends on the temperature change of the thermostatic fins, i.e., $T_2 - T_1$. The fin material can be formed into any desired shape by stressing beyond the elastic limit. After stress relief by heating, the fin material will assume a required shape at some given temperature, T_1. An arbitrary choice of shape and temperature was used in this analysis. Fins were assumed to be vertical when the average temperature was 110°F. This value can be changed to meet any desired fin surface characteristic. With the assumed surface temperature of 110°F, analysis indicated that 37.5 Btu/hr-ft2 could be radiated away from the surface when the surface faced the sun. In order to obtain this value of energy loss, the fin surfaces must be specular in their reflection.

The basic action of the finned surface may be described by assuming the fins are not in the vertical position. When the fins are warped open, two areas may be described:

A_1 - the area between fins (nearly equal to the dimension "b" in Figure 1 if the temperature is near 110°F.)

A_2 - the area between adjacent fin elements (equals 2d, darkened area in Figure 1).

These two areas have apparent emittance and reflectance values which differ considerably. Area A_1 will have an apparent solar absorptance α_{s1}, which is very much lower than α_{s2}. This is because the slit formed by a fin has a small angle and therefore will be nearly black. Similarly, the emittance of the two areas will be different, although the emittance variation is not as large as the solar absorptance variation. Both of the above statements depend on the slit having a small angle. As the fins cool to a temperature significantly different than 110°F the slit angle becomes larger. Considering large slit angles as a case to be examined later, the case of small slit angles was examined.

ANALYSIS

<u>Calculation of Effective Reflectance to Solar Radiation of a Groove with Specular Sides and a Diffuse Bottom.</u>

Assumptions
1) Specular Vertical Walls
2) Diffuse Horizontal Base
3) Infinitely Long Grooves

Definitions

ρ_e = Effective reflectance, the fraction of the total incoming radiation which leaves the groove.

$\rho_{e\lambda}$ = Monochromatic effective reflectance.

ρ_w = Reflectance of the specular wall.

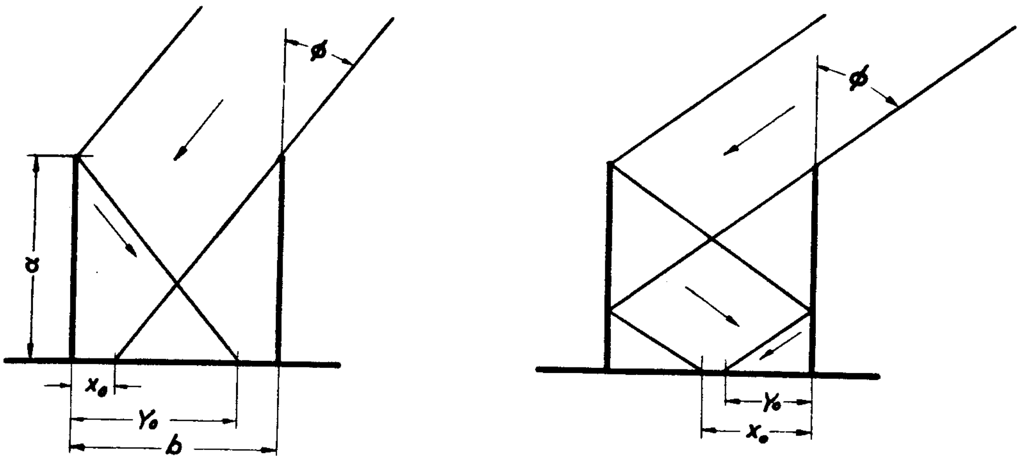

Figure 3. Illumination of base surface.

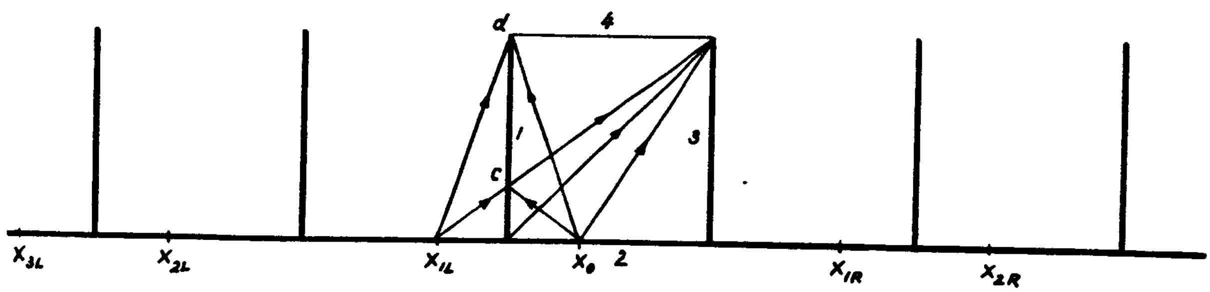

Figure 4. Illustration of illuminstion of opening 4 by virtual images.

In general

$$J_x = I_x \rho_b \quad \text{and} \quad J_y = I_y \rho_b \; . \tag{7}$$

Note that since A_x and A_y overlap in reality A_x will have a true radiosity of $J_{XT} = J_x + J_y$, but since the calculation of effective reflectance will be based on the fractions of energy which leave A_x and A_y and eventually escape through the opening, the following relation is true

$$F_{yt} A_x J_x + F_{yt} J_y A_y = F_{xt} (J_x + J_y) A_x + F_{(y-x)T} A_{(y-x)} J_y \cdots\cdots \tag{8}$$

In which F_{xT}, F_{yT}, and $F_{(y-x)T}$ are the total fractions of energy, which, after being reflected from areas, Ax, Ay, or A_{y-x}, reach the groove opening. These "view" factors include the energy which travels directly to the opening from the base as well as the energy which first undergoes one or more reflections from the walls before reaching the opening.

The effective reflectance is defined as the total outgoing energy divided by the total incoming energy.

$$\rho_e = \frac{A_x F_{xT} J_x + A_y F_{yT} J_y}{b \; S \; \cos\emptyset} \tag{9}$$

Calculation of F_{xT} and F_{yT}. Figure 4 illustrates how the opening of the groove sees surface A_{xo}. Part of the energy reflected from A_{xo} travels directly to the opening. This fraction is designated F_{xo-4}. Surface A_{xo} has a virtual image A_{x1L} in the left specular surface and therefore the energy which is reflected from A_{xo} and strikes the left wall between c and d is reflected once from the wall and the opening 4 "sees" this energy as if the energy had come from the surface A_{x1L}. This particular fraction of energy is designated F_{x1L-4} and is numerically equal to the view factor from the virtual image A_{x1L} to the opening -4. Similarly, energy which leaves A_{xo} to the left and undergoes 2 reflections would appear to be coming from A_{x2R} (A_{x2R} being the virtual image of A_{x1L} in the right wall) this fraction is designated F_{x2R-4}. The total energy which finally reaches the opening from A_{xo} is:

$$A_x J_x \; F_{xo-4} + \sum_{n=1}^{\infty} \rho_w^n \left(F_{xnL-4} + F_{xnR-4}\right) \tag{10}$$

$$= A_x \; J_x \; F_{xT}$$

The total energy which reaches the opening from both A_x and Ay is therefore,

$$A_x \; J_x \; F_{xT} + A_y \; J_y \; F_{yo-4} + \sum_{n=1}^{\infty} \rho_w^{\;n} \left(F_{nyL-4} + F_{ynr-4}\right) = A_x J_x F_{xT} + A_y J_y F_{yT} \tag{11}$$

Since the surfaces involved are infinitely long, McAdam's method of crossed strings is used to evaluate the various view factors involved. This method yields:

$$F_{xn-4} = \frac{\sqrt{(nb+x)^2 + a^2} + \sqrt{(n-1)^2 b^2 + a^2} - \sqrt{n^2 b^2 + a^2} - \sqrt{((n-1)\ b + x)^2 + a^2}}{2x}$$

$n = 1,3,5......$ (12)

$$F_{xm-4} = \frac{\sqrt{(m+1)^2 b^2 + a^2} + \sqrt{(mb-x)^2 + a^2} - \sqrt{m^2 b^2 + a^2} - \sqrt{(mb + b - x)^2 + a^2}}{2x},$$

$m = 2,4,6.....$ (13)

$$F_{xnr-4} = \frac{\sqrt{(n+1)^2\ b^2 + a^2} + \sqrt{(nb-x)^2 + a^2} - \sqrt{(nb+b-x)^2 + a^2} - \sqrt{(nb) + a^2}}{2x}$$

$n = 1,3,5......$ (14)

$$F_{xmr-4} = \frac{\sqrt{(mb+x)^2 + a^2} + \sqrt{(m-1)^2 b^2 + a^2} - \sqrt{(mb)^2 + a^2} - \sqrt{((m-1)\ b+x)^2 + a^2}}{2x}$$

$m = 2,4,6.....$ (15)

$$F_{x-4} = \frac{\sqrt{b^2 + a^2} + \sqrt{x^2 + a^2} - a - \sqrt{a^2 + (b-x)^2}}{2x} \quad ..... \qquad (16)$$

for F factors from surface y substitute the subscript "y" for "x" in the above equations.

Now by using equations (4) and (7) in (9) and then dividing by ρ_b one obtains the effective reflectance ratio

$$\rho_e/\rho_b = \frac{\rho_w^{\ m} A_x F_{xT} + \rho_w^{\ n} A_y F_{yT}}{b} \qquad (17)$$

in which the values of F_{xT} and F_{yT} are calculated for a given a/b ratio and angle of inclination $\emptyset$ by use of equations (12) thru (16).

The effective reflectance ratios for a/b = .667, 1, and 2 were calculated and the results are shown in Figures 5,6, and 7. These graphs enable one to calculate a monochromatic effective reflectance curve for a particular groove if the monochromatic reflectance data for the wall and base material are known. This is accomplished by first looking up the ρ_e/ρ_b value which corresponds to the wall reflectance at a particular wavelength and angle and then multiplying this value of ρ_e/ρ_b by the reflectance of the base material at the same wavelength. By doing this for as many different wavelengths as needed to have a smooth curve, one obtains the monochromatic effective reflectance characteristics of the surface. The

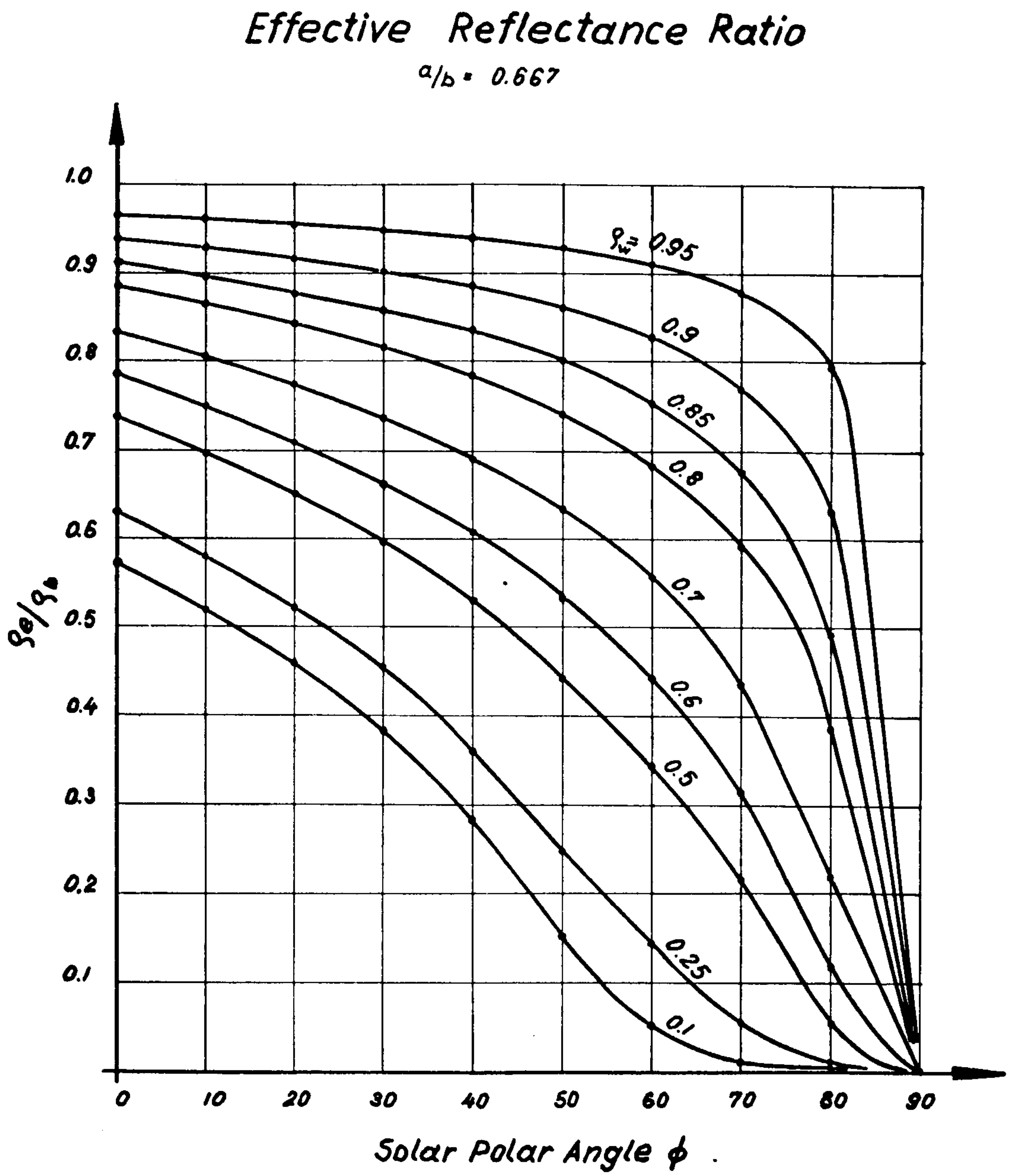
Effective Reflectance Ratio
a/b = 0.667
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
ρe/ρb
ρw = 0.95
0.9
0.85
0.8
0.7
0.6
0.5
0.25
0.1
0
10
20
30
40
50
60
70
80
90
Solar Polar Angle φ

Figure 5.

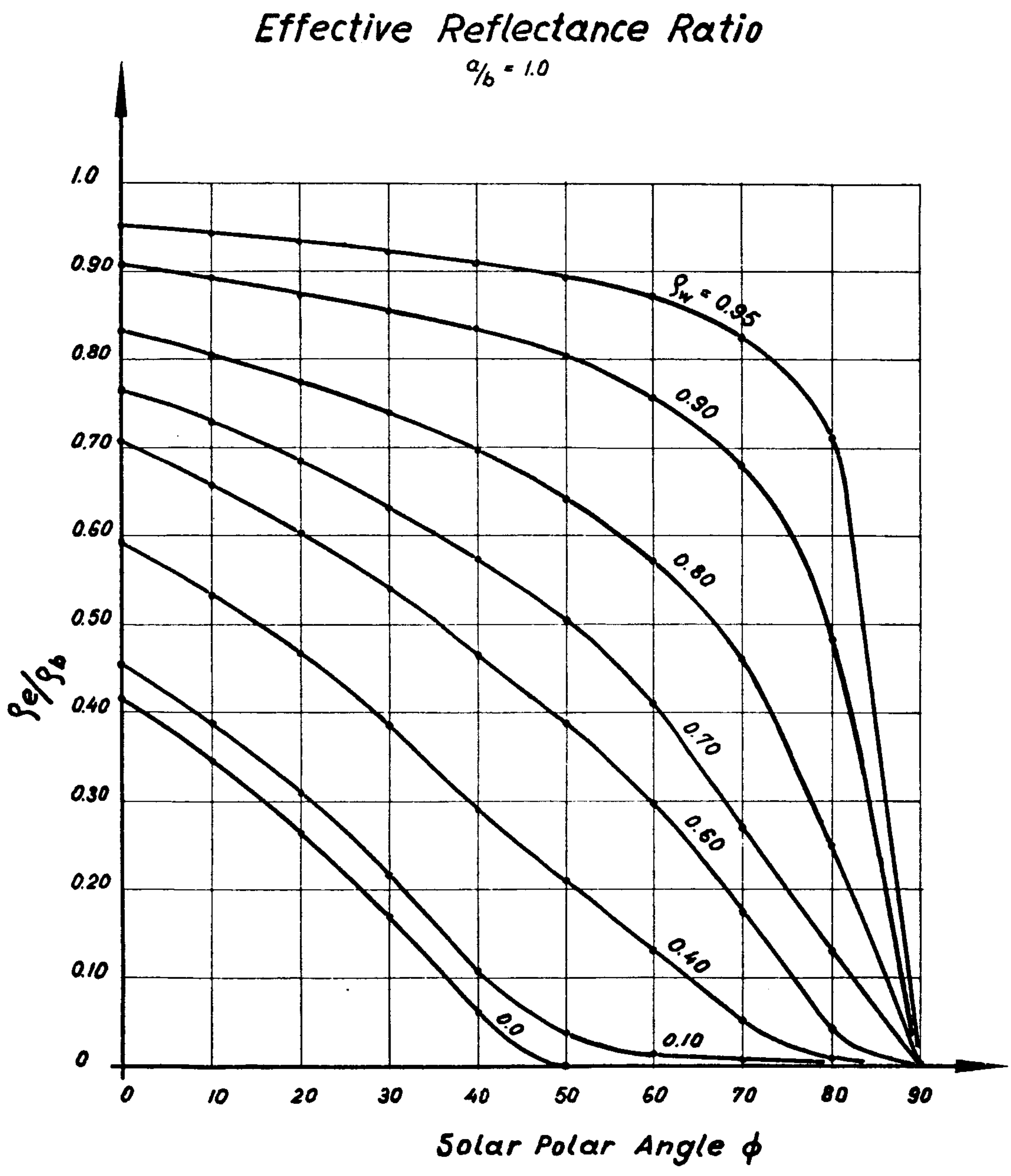
Effective Reflectance Ratio
a/b = 1.0
ρe/ρb
1.0
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0
ρw = 0.95
0.90
0.80
0.70
0.60
0.40
0.10
0.0
0
10
20
30
40
50
60
70
80
90
Solar Polar Angle φ

Figure 6.

Effective Reflectance Ratio

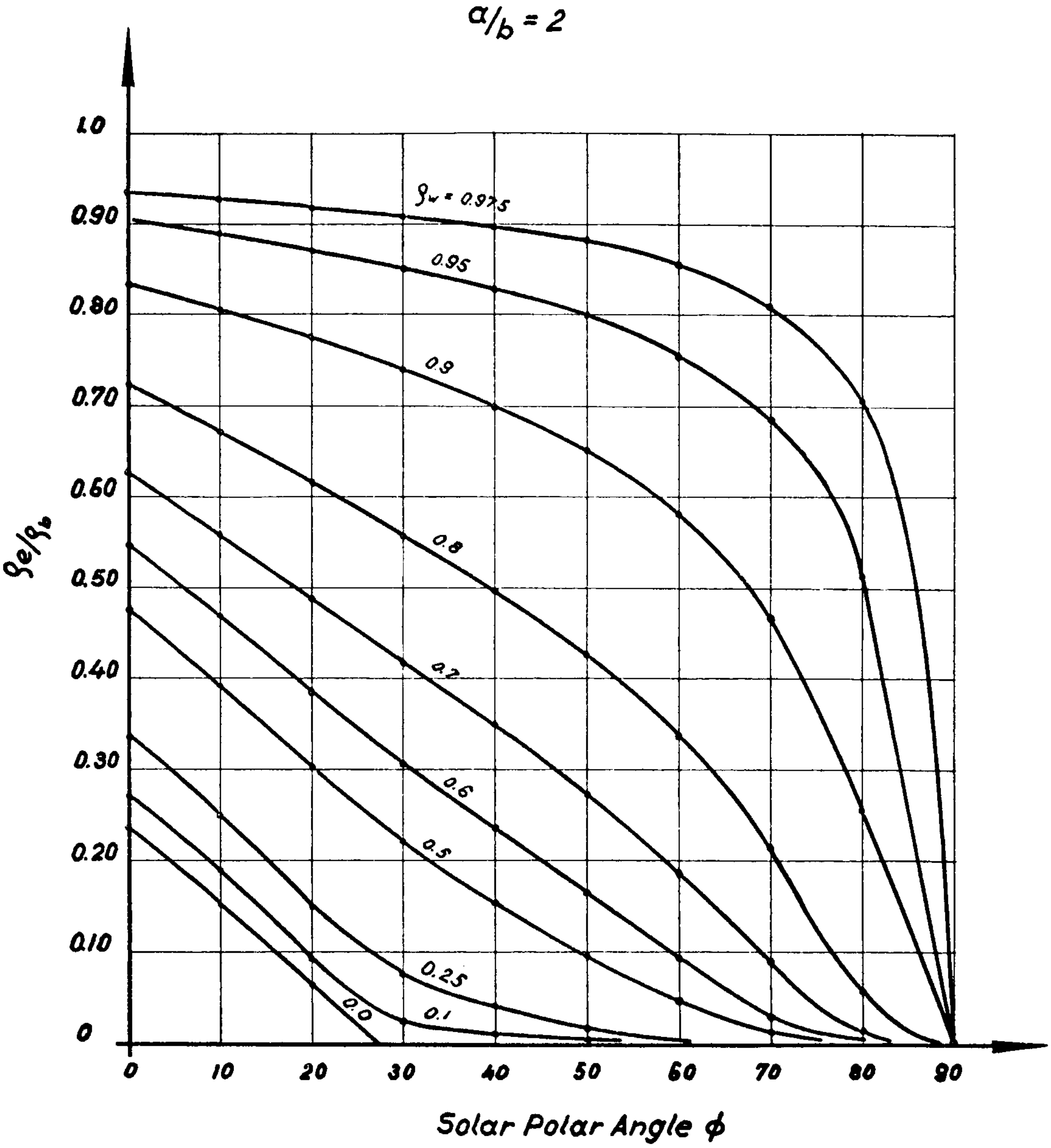

Figure 7.

monochromatic effective reflectance curve for walls of evaporated aluminum and base of Corning #7941 white paint is shown for two different angles of inclination in Figure 8. A tabular presentation of monochromatic effective reflectance values is given in Table 1.

Once the monochromatic curve is known for each angle of inclination, the total reflectance of the surface to solar irradiation can be calculated (ref. 5). The results are illustrated in Figure 9.

Calculation of ϵ'_T.

Assumptions

1) The fins always remain vertical.
2) The fins are thin enough so that they don't conduct any heat to or from the surface.
3) The slit between the adjacent thermostatic strips which form a fin is black.
4) The base surface emits energy diffusely.
5) The fins and base are all at the same uniform temperature.

The net heat flux from the spacecraft will be given by a modified form of equation (5) which takes into consideration variations of the solar polar angle ϕ.

$$q''(\phi) = \epsilon - \alpha_s \left(\frac{G_s \cos\phi}{\sigma T_s^4} \right) \ldots\ldots \qquad (18)$$

in which $\alpha_s = f(\phi, T_S)$ is the solar absorptance of the surface for a given solar polar angle and surface temperature, and $\epsilon = f(T)$, the total effective emittance of the surface at a specified temperature. Figure 1 indicates that the incoming energy from the sun may strike the surface and 1) enter the groove between the fins, 2) enter the slit formed by the adjacent thermostat elements, or 3) strike the top of the fins. The areas of the first two depend upon the temperature of the spacecraft surface because of the action of the fin, (as explained in the introduction).

The area of the groove (A_G) will be equal to the total area minus the area of the slit and fin top. The ratio of A_G/A_{TOT} will be the fraction of the surface which will allow the incoming radiation to strike the white base.

Because the fins are assumed to be infinitely long repeating sections:

$$\frac{A_G}{A_{TOT}} = 1 - \frac{2t}{b + 2t} - \frac{2(113 \times 10^{-7})(T_2 - T_1)\, a^2}{t(b + 2t)} \ldots\ldots \qquad (19)$$

in which $A_{TOT} = b + 2t$. (The distance between fins plus the thickness of the fins).

TABLE 1

MONOCHROMATIC EFFECTIVE REFLECTANCE, $\rho_{\lambda e}$, for a/b = 1

Wavelength	Monochromatic Wall Reflectance	Monochromatic Base Reflectance	Solar Polar Angle							
λ	$\rho_{\lambda w}$	$\rho_{\lambda b}$	0	10	20	30	40	50	60	70
.25	.95	.50	.475	.471	.466	.462	.455	.447	.435	.413
.30	.97	.76	.737	.733	.727	.719	.709	.698	.684	.668
.40	.92	.88	.814	.804	.792	.773	.754	.729	.699	.653
.50	.92	.91	.842	.832	.819	.800	.780	.754	.722	.675
.75	.842	.94	.812	.790	.766	.738	.705	.667	.602	.503
.80	.83	.94	.771	.743	.712	.673	.627	.577	.507	.390
.85	.843	.95	.823	.800	.776	.748	.715	.677	.612	.512
.90	.86	.95	.836	.817	.796	.769	.741	.703	.646	.552
1.0	.89	.94	.846	.832	.815	.795	.772	.742	.692	.611
1.5	.91	.88	.807	.794	.780	.764	.745	.720	.688	.634
2.0	.91	.75	.688	.677	.665	.651	.634	.613	.586	.541
2.5	.92	.69	.636	.624	.617	.605	.593	.575	.552	.507
3.0	.93	.16	.150	.148	.146	.143	.139	.135	.129	.123
3.5	.94	.38	.358	.355	.350	.346	.340	.333	.319	.300
4.0	.95	.50	.475	.471	.466	.462	.455	.448	.435	.413
4.5	.95	.20	.190	.188	.187	.185	.182	.179	.174	.165
5.0	.96	.08	.077	.0763	.0756	.0745	.0737	.0725	.0709	.0682
6.0	.96	.05	.0480	.0477	.0473	.0466	.0461	.0456	.0443	.0426
7.0	.96	.03	.0288	.0286	.0284	.0280	.0276	.0272	.0266	.0256
8.0	.96	.10	.0962	.0956	.0948	.0935	.0924	.0901	.0980	.0856
9.0	.96	.23	.221	.220	.218	.215	.213	.209	.205	.197
10.0	.96	.13	.125	.124	.123	.122	.120	.118	.116	.112
13.0	.97	.095	.0923	.0916	.0908	.0899	.0886	.0872	.0855	.0835
17.0	.97	.08	.0776	.0771	.0765	.0757	.0746	.0734	.0720	.0703
21.0	.97	.28	.271	.270	.268	.265	.261	.257	.252	.246

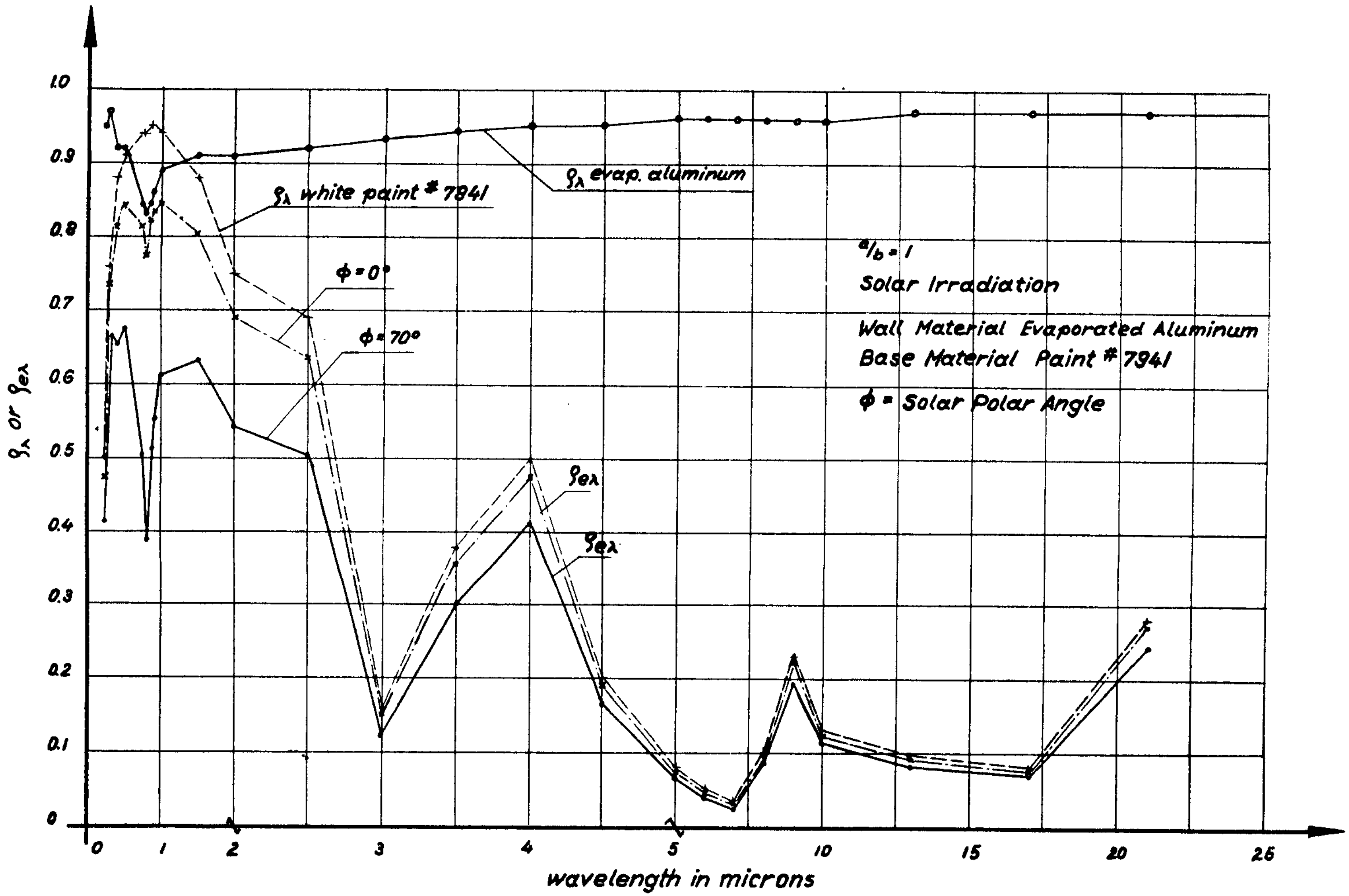

Figure 8. Effective Monochromatic Reflectance ρ_e of a Thermostatic Fin Surface with Fins in vertical Position.

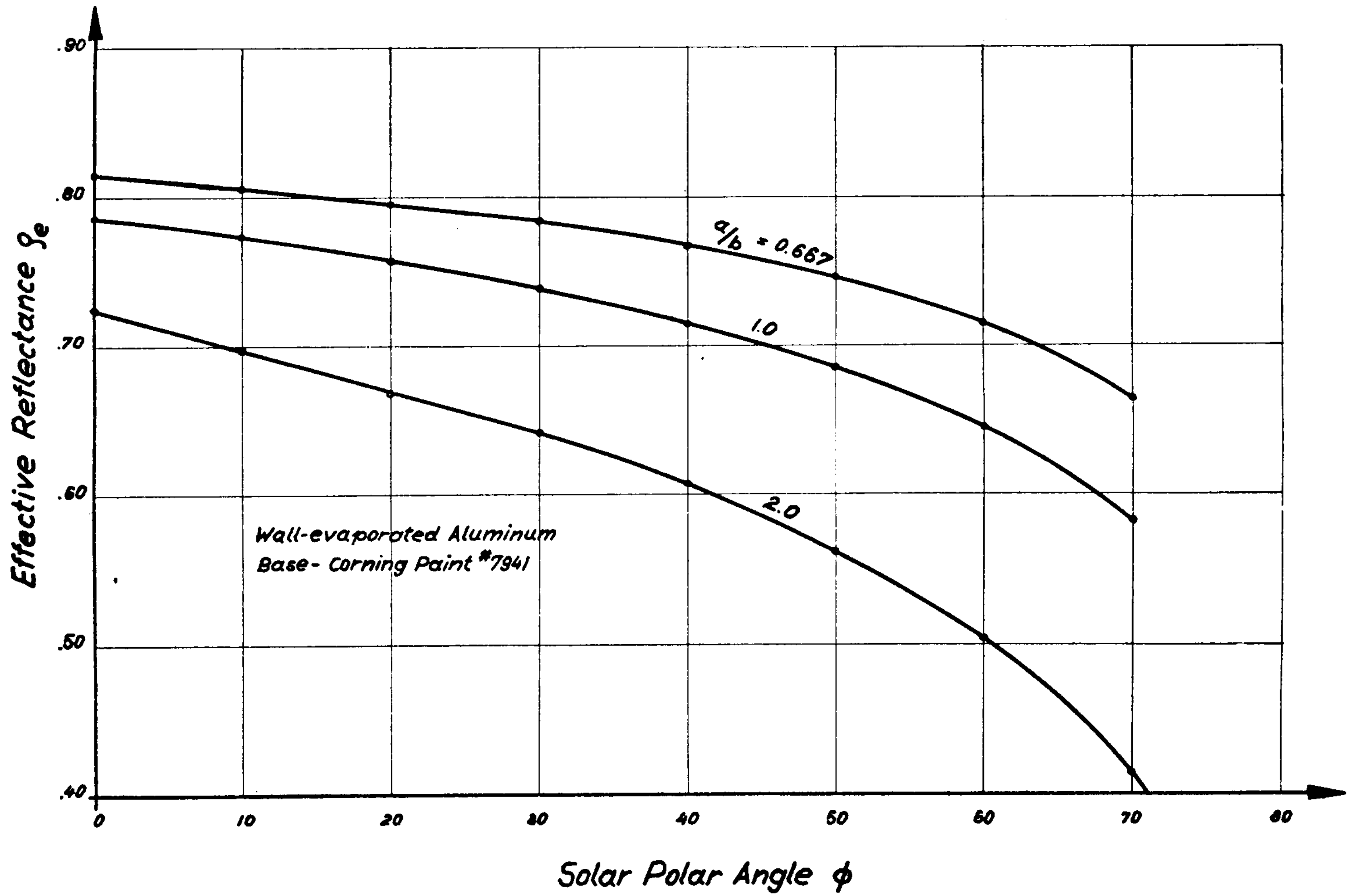

Figure 9. Effective Reflectance of a Specular Wall-Diffuse Base Groove.

The area of the slit A_{sL} is simply the distance between the adjacent thermostatic elements.

$$\frac{A_{sL}}{A_{TOT}} = \frac{2d}{A_{TOT}} = \frac{2(113 \times 10^{-7})\,(T_2 - T_1)\,a^2}{t(b + 2t)} \,. \tag{20}$$

The area of the top A_{TOT} is equal to twice the thickness of the thermostatic element.

$$\frac{A_{TOP}}{A_{TOT}} = \frac{2t}{b + 2t} \,. \tag{21}$$

Equations (19, 20, 21) are the fractions of the total area which have the radiant characteristics of the slit, groove or thermostatic fin top. The effective emissivity of the surface will therefore be equal to the sum of the emissivities of the three areas times their area fractions.

$$\varepsilon_e = \frac{A_{TOP}}{A_{TOT}} \varepsilon_{TOP} + \frac{A_{sL}}{A_{TOT}} \varepsilon_{sL} + \frac{A_G}{A_{TOT}} \varepsilon_G \,\cdots\cdot \tag{22}$$

and similarly for absorptance

$$\alpha_s = \frac{A_{TOP}}{A_{TOT}} \alpha_{TOP} + \frac{A_{sL}}{A_{TOT}} \alpha_{sL} + \frac{A_G}{A_{TOT}} \alpha_G \,. \tag{23}$$

In the calculations which were made for this report, the following assumptions were used in the evaluation of ε_e and α_e (22 and 23).

1) $\varepsilon_{TOP} = \alpha_{TOP} = .1$
2) $\varepsilon_{sL} = \alpha_{sL} = 1.0$
3) $\varepsilon_G = \varepsilon_{base} \times F_{bT-4} =$ constant
4) $\alpha_G = (1 - \rho_e(\emptyset))$ is independent of temperature

The last three assumptions are quite good when the temperature of the surface deviates only a few degrees from the temperature (T_2) at which the fins are perfectly vertical with respect to the white base surface. However, as the surface turns away from the sun and gets colder, the opening over the white groove becomes smaller. Therefore, the absorptance and emittance of the groove both approach one. At the same time, the small slit between the adjacent thermostatic fins is opening, decreasing both its emittance and absorptivity. The net heat flux calculated by

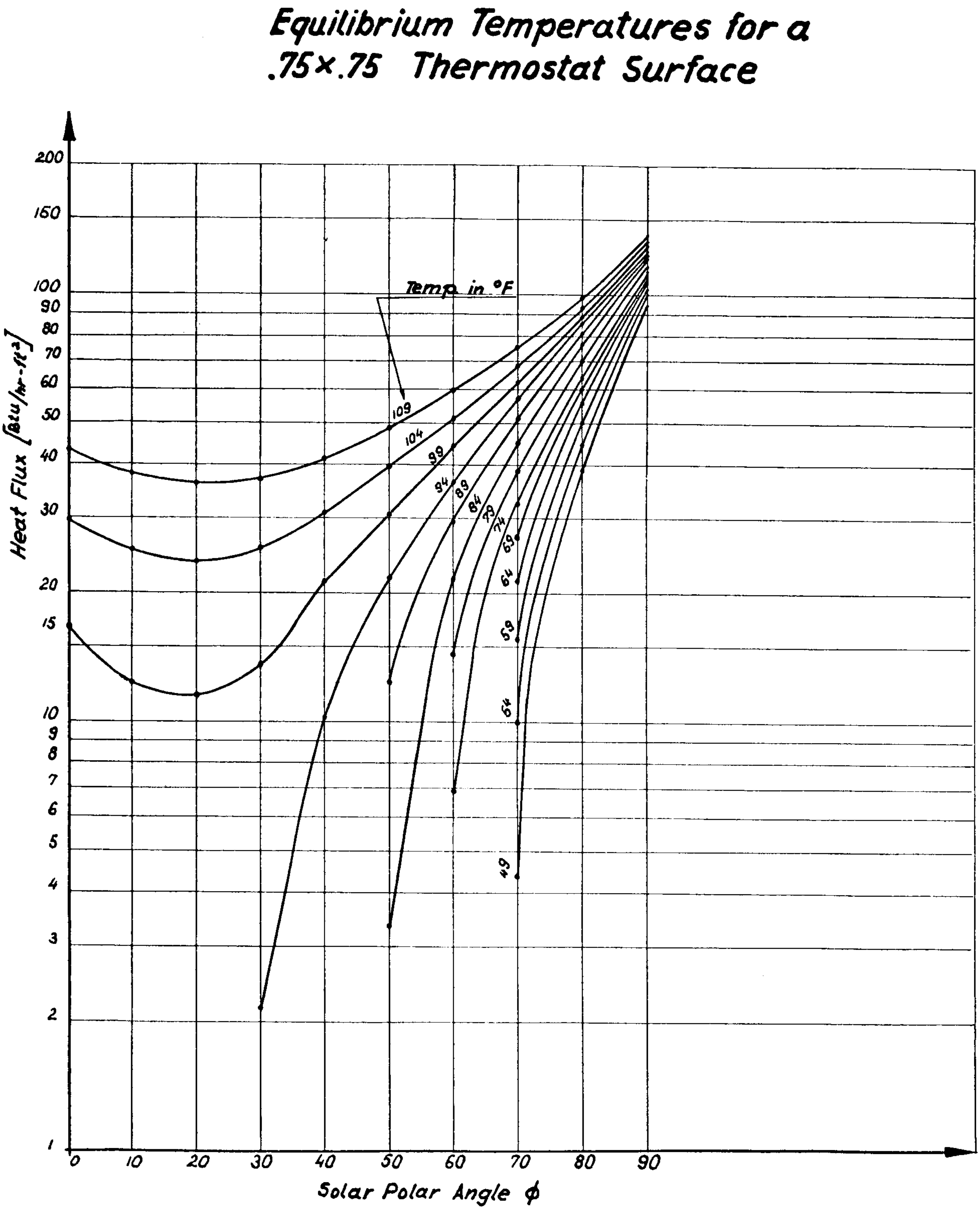
Equilibrium Temperatures for a
.75×.75 Thermostat Surface
Heat Flux [Btu/hr-ft²]
Solar Polar Angle ϕ
Temp. in °F
200
150
100
90
80
70
60
50
40
30
20
15
10
9
8
7
6
5
4
3
2
1
0
10
20
30
40
50
60
70
80
90
109
104
99
94
89
84
79
74
69
64
59
54
49

Figure 10.

Equilibrium Temperatures for a 2"x2" Thermostat Surface

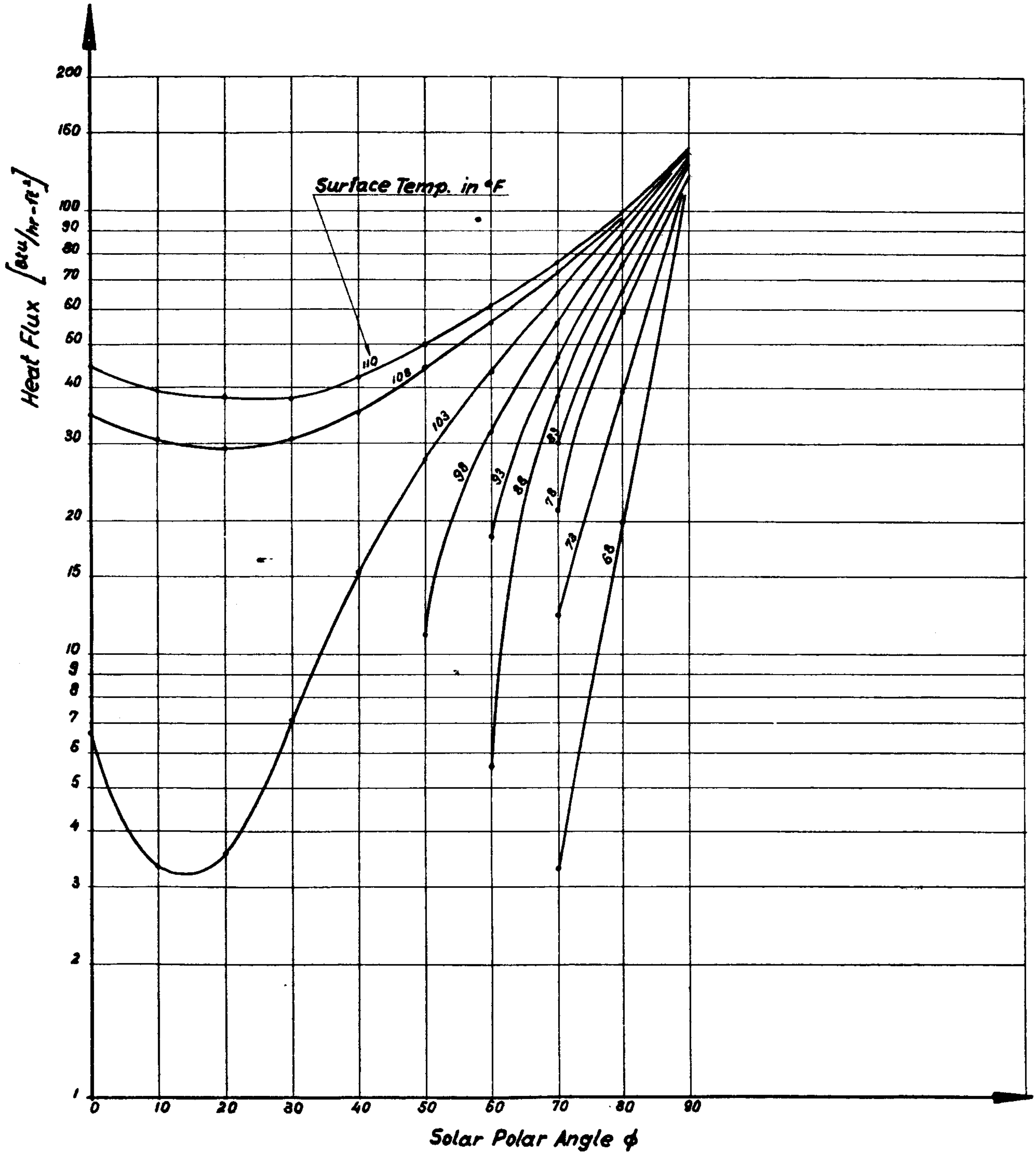

Figure 11.

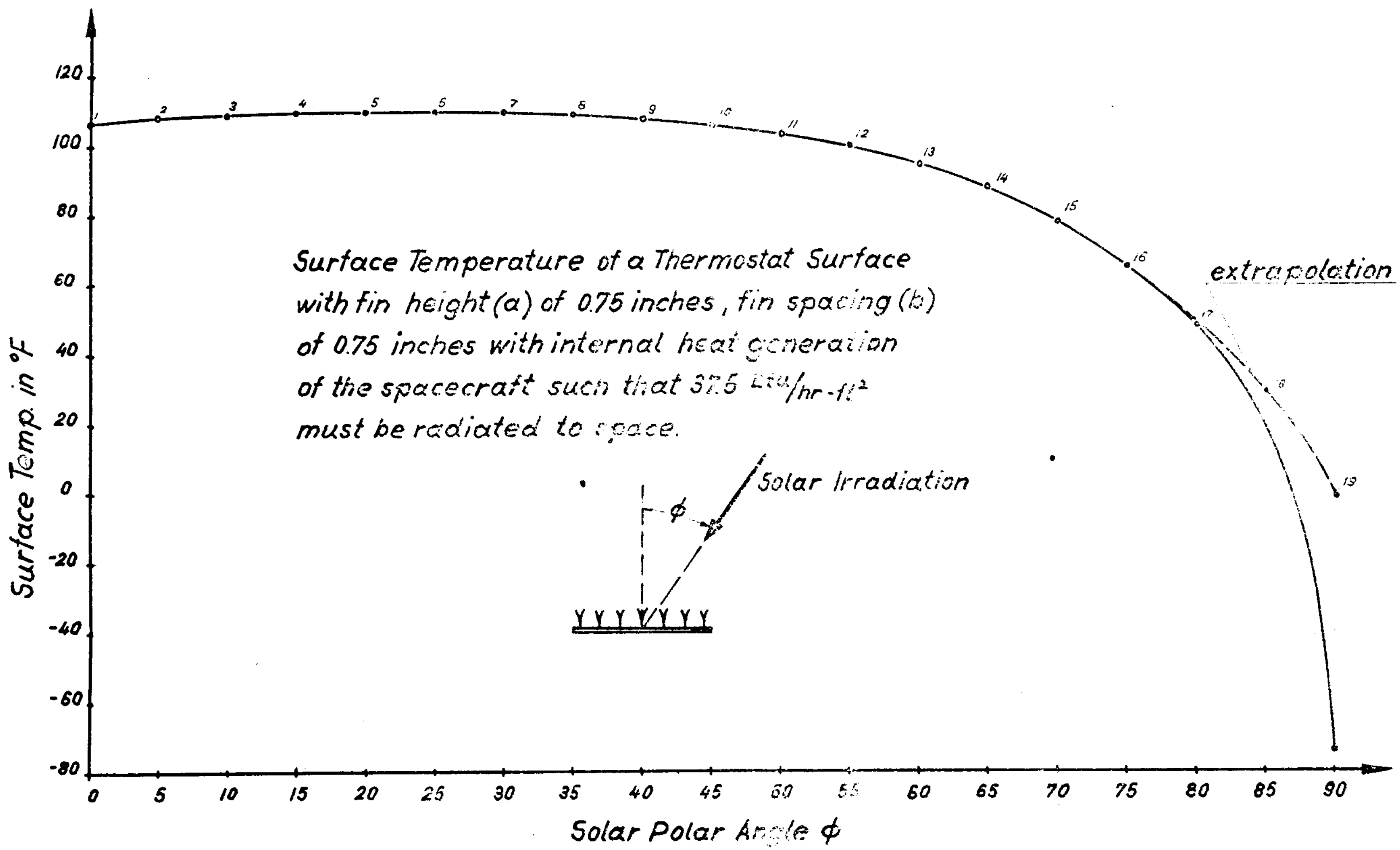
Surface Temperature of a Thermostat Surface
with fin height (a) of 0.75 inches, fin spacing (b)
of 0.75 inches with internal heat generation
of the spacecraft such that 37.5 Btu/hr-ft²
must be radiated to space.
Solar Irradiation
φ
extrapolation
Surface Temp. in °F
120
100
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90
Solar Polar Angle φ

Figure 12.

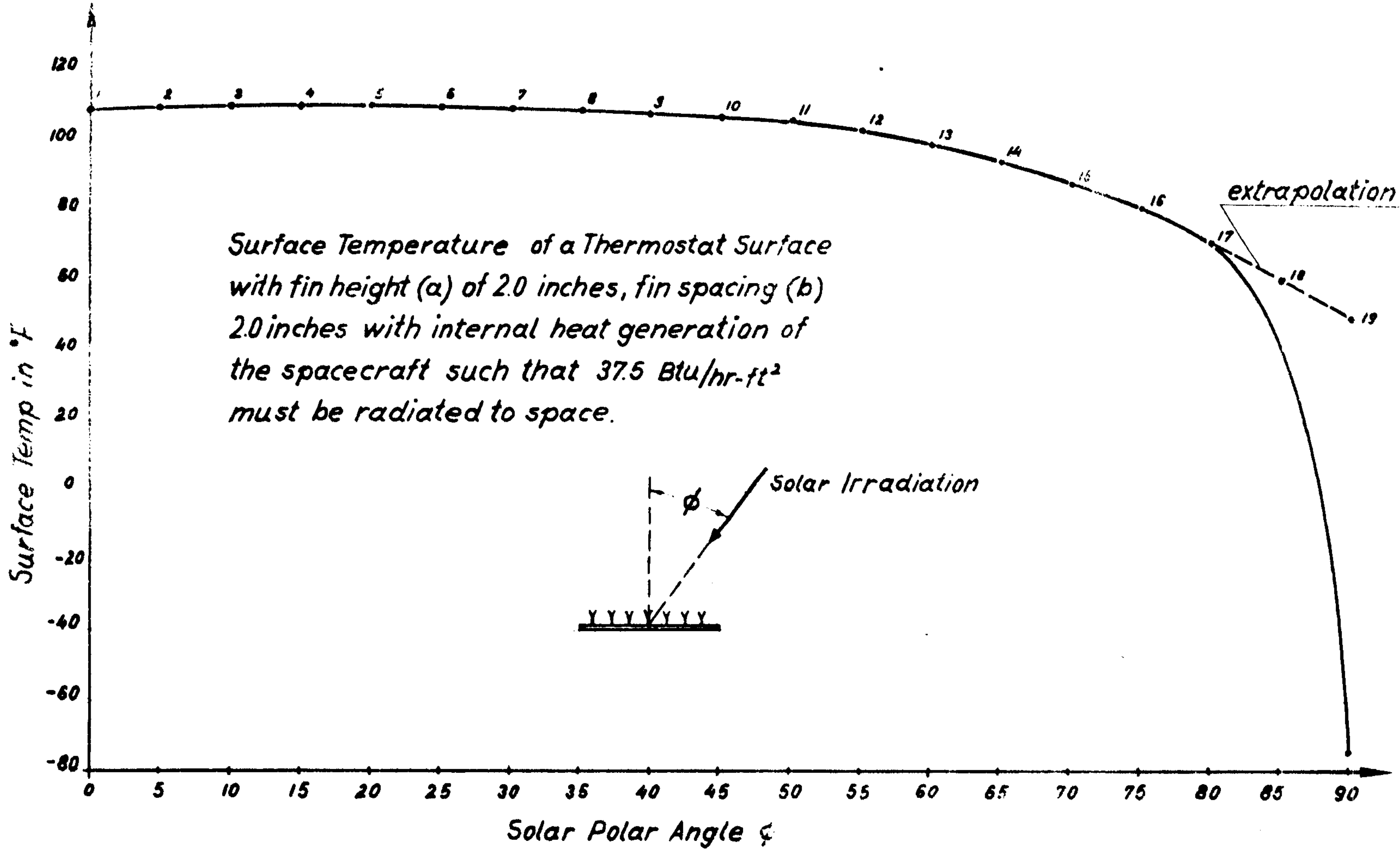
Surface Temperature of a Thermostat Surface with fin height (a) of 2.0 inches, fin spacing (b) 2.0 inches with internal heat generation of the spacecraft such that 37.5 Btu/hr-ft²
must be radiated to space.
Solar Irradiation
ϕ
extrapolation
Surface Temp in °F
Solar Polar Angle ϕ
120
100
80
60
40
20
0
-20
-40
-60
-80
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
85
90

Figure 13.

the use of equation (23) is shown in Figures 10 and 11. The equilibrium temperatures for surfaces with different size fins, but all with a/b ratios of one and net heat fluxes equal to 37.5 Btu/hr-ft^2 are shown in Figures 12 and 13. The dashed line in these figures represents an approximation to the correct equilibrium temperatures which will be obtained when the walls have deviated from their vertical position so that the emittance of the slit is low and the emittance of the groove is high.

RESULTS

As a result of the analysis work preceding, the design of a thermostatic finned surface for radiant energy control appears entirely feasible. Examination of the two sample curves, Figures 12 and 13, indicates what may be possible. These curves were prepared for a particular combination of base paint (Corning #7941 (ref. 2)) and aluminized fin surfaces. Many different coatings could be used in place of the two chosen, resulting in a wide variation of characteristics. However, assuming a surface is used with these two coating materials, the degree of temperature control is shown to be variable by variation of the fin length. As was expected, the longer (two inch) fin exhibits a more constant temperature characteristic. Actually, the temperature predicted for either fin length is essentially the same for solar polar angles from 0° to 45°. From 45° to 75°, the longer fin maintains a more uniform temperature. In the region from 75° to 90° (or complete shade) the analysis is obviously very much in error. This error may be examined qualitatively to determine the effect.

As an example, consider the two inch finned surface of Figure 13. The thermostatic material chosen will warp to a position in which the fin tops touch at 52°F. Under this condition, the average emittance of the surface will be the average for a V-groove surface with a surface material emittance equal to the emittance of the low expansion side of the fins. The fin material used in the analysis was "invar" on the low expansion side. Invar is approximately 36% nickle and 64% iron. It may be expected that the emittance of this material is near 0.1. With an emittance of 0.1 for the material the grooves will have an emittance of about 0.18 (ref. 4). Examination of the Stephen-Boltzmann equation, $q'' = \varepsilon_e \sigma T^4$ indicates that the surface temperature T_s must be approximately 130°F if q" is 37.5 Btu/hr-ft^2. Recalling that this was based on a temperature of 52°F, the conclusion is that the surface will be warmer than 52°F, but less than 130°F, since the fins will open to cool at any temperature above 52°F. Analysis for the temperature under these conditions is more difficult than the analysis presented since the fins form V-grooves with varying groove angles and the base-fin-opening enclosure becomes more difficult to analyze. This analysis work is being examined and will be forthcoming at a later date. Present information indicates that the surface temperature from 75° to 90° will be higher than the extrapolated temperature (for the two inch fins) but not above 110°F. Of course this result is exactly what is required to improve the overall temperature control characteristics for the finned surface.

CONCLUSIONS AND RECOMMENDATIONS

The finned surface proposed can be expected to maintain a uniform temperature on the surface of spacecraft within prescribed limits. For example, if fins two inches long with the prescribed characteristics are used, the surface temperature is expected to vary between 112°F and 90°F for solar polar angles from 0° to 70°. From angles of 70° to 90° (or shaded) the surface temperature should be between 90°F and some temperature higher than 52°F. As an estimate 70°F may be the minimum temperature experienced.

It is recommended that finned surfaces of the type described be constructed and tested in a space simulator. Such tests are required because of the many variables which were not included in the analysis. Also, variables in construction may occur which would alter the results of the analysis work. Furthermore, it is recommended that a design procedure (possibly digital computer oriented) be developed for the design of surface systems to be used on specific missions. The analysis work from this report may be used in the design, however, design procedures will be lengthy.

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November, 1963
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
Washington, D.C.