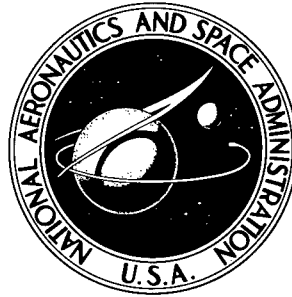


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OF ABSORPTANCE TO EMITTANCE

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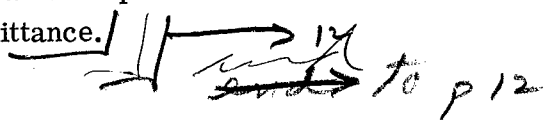
# METHOD FOR ESTIMATING RATIO OF ABSORPTANCE TO EMITTANCE

by Robert R. Hibbard

Lewis Research Center

## SUMMARY

A graphical method is presented for estimating the values of the ratio of <sup>TP</sup> absorptance to emittance  $\alpha/\epsilon$  that can be achieved with surfaces having a high degree of spectral selectivity. The ratio of source to surface temperature is the parameter in the graphs. In principle, the results of the calculations presented are general and apply for any source or surface temperature. In practice, the ratios of absorptance to emittance so estimated can be used in radiant-heat-transfer calculations involving space vehicles. In this case  $\alpha$  becomes  $\alpha_s$ , the total normal absorptance of a surface to solar radiation, and  $\epsilon$  is the total hemispherical emittance.

*Handwritten note:*  to p 12

## INTRODUCTION

In environments where heat transfer to or from a surface is entirely or primarily through radiation, a knowledge of the surface absorptance  $\alpha$  and the surface emittance  $\epsilon$  is necessary for heat-transfer calculations. There are conditions, however, where only the ratio of absorptance to emittance  $\alpha/\epsilon$  need be known to calculate the temperature or performance of a system; the individual values of  $\alpha$  and  $\epsilon$  need not be used. These are conditions where the internal heat fluxes to or from the surface are either zero or small compared with the external, radiant heat fluxes. The principal example is the space vehicle exposed to sunlight. In this case,  $\alpha$  becomes the total directional absorptance of solar radiation  $\alpha_s$ . For example, the boiloff loss of cryogenic propellants from a well-insulated tank in space is directly proportional to the ratio  $\alpha_s/\epsilon$  of the external surface of the tank and is independent of the value of  $\alpha_s$  (ref. 1).

Gray surfaces are those for which both the monochromatic absorptance  $\alpha_\lambda$  and the monochromatic emittance  $\epsilon_\lambda$  are invariant with wavelength. For perfectly diffuse surfaces,  $\alpha_\lambda = \epsilon_\lambda$ , and therefore, for gray diffuse surfaces,  $\alpha = \alpha_\lambda = \epsilon_\lambda = \epsilon$  and

$\alpha/\epsilon = 1.0$ . This is not the case for most materials. Values of  $\alpha_s/\epsilon$  for metals are greater than unity because their monochromatic absorptance and emittance decrease with increasing wavelength  $\lambda$  (as shown, e. g., in ref. 2). Therefore,  $\alpha_s$  is greater for the relatively short wavelength radiation from the Sun than is  $\epsilon$  for the longer wavelength radiation emitted from the much colder surface. Semiconductors are similar to metals in that their  $\alpha_s/\epsilon$  is greater than 1. Nonconductors have  $\alpha_s/\epsilon$  values less than unity because  $\alpha_\lambda$  and  $\epsilon_\lambda$  increase with increasing wavelength for this class of compounds.

Considerable effort is now being aimed at producing surfaces having ratios either as high or as low as possible. High surface temperatures result from high values of  $\alpha_s/\epsilon$  and are most effective in increasing the performance of flat-plate collectors of solar energy (see, e. g., ref. 3). Surfaces having low values for this ratio give low temperatures and might be used, for example, on the previously mentioned cryogenic tanks.

For any given surface with spectral properties described in terms of  $\alpha_\lambda$  as a function of wavelength and for any given source temperature or surface temperature, the values of  $\alpha$ ,  $\epsilon$ , and  $\alpha/\epsilon$  can be calculated. It was observed, however, that a product term  $\lambda_c T$  can be used to develop a series of plots from which  $\alpha/\epsilon$  can be read directly, provided the source is a gray body or a blackbody. The spectral quality of the surface is characterized by  $\lambda_c$ , which is described later; the temperature  $T$  may be either the source temperature  $T_1$  or the surface temperature  $T_2$ . The ratio  $T_1/T_2$  is a parameter in these plots.

While such curves may be used in estimating the  $\alpha/\epsilon$  of spectrally selective surfaces, their greatest value may be in estimating the maximum and minimum values of this ratio that may be achieved. These limiting values of  $\alpha/\epsilon$  can then be used to estimate the ultimate performance of those systems where the internal heat transfer is small relative to that received and radiated from the external surfaces.

Presented herein are figures that can be used to estimate  $\alpha/\epsilon$ . These figures are based on the temperature of the radiation source (usually the Sun) and on a simplified but realistic description of spectrally selective surfaces.

## SYMBOLS

A	area
C	solar radiant flux, W/sq cm
$F_{\lambda, T}$	fraction of total energy radiated by blackbody at temperature $T$ at all wavelengths shorter than $\lambda$
T	temperature, $^{\circ}\text{K}$

$T_1$	temperature of radiation source, $^{\circ}\text{K}$
$T_2$	temperature of radiating surface, $^{\circ}\text{K}$
$W_{T,B}$	incident radiant flux per unit area from blackbody at temperature $T$ , W/sq cm
$W_{\lambda,T,B}$	incident radiant flux per unit area per unit increment of wavelength from blackbody at temperature $T$ , (W/sq cm)/ $\mu$
$\alpha$	total absorptance of surface
$\alpha_s$	total directional absorptance to solar radiation
$\alpha_{\lambda}$	monochromatic absorptance
$\epsilon$	total emittance of surface
$\epsilon_{\lambda}$	monochromatic emittance
$\lambda$	wavelength, $\mu$
$\lambda_c$	cutoff wavelength of spectrally selective surface, $\mu$
$\lambda_0$	any given wavelength, $\mu$
$\sigma$	Stefan-Boltzmann constant, (W/sq cm)/ $^{\circ}\text{K}^4$

## PROCEDURE AND RESULTS

An ideal spectrally selective surface is one for which the monochromatic absorptance  $\alpha_{\lambda}$  (and the emittance  $\epsilon_{\lambda}$ ) is unity over a span of wavelengths and changes abruptly to zero over the rest of the span. Figure 1 shows this behavior for the two types of ideal spectral surfaces, types A and B. The type A surface with the high value for  $\alpha_{\lambda}$  and  $\epsilon_{\lambda}$  at short wavelengths is a more powerful absorber for high-temperature radiation than it is an emitter for lower temperature radiation; therefore,  $\alpha/\epsilon$  is greater than unity. Conversely, for the type B surface  $\alpha/\epsilon$  is less than unity.

While the type A and B surfaces are ideal in spectral selectivity, it is likely that more practical surfaces are those where a step change in  $\alpha_{\lambda}$  is between 0.95 and 0.05. These are shown in figure 1 as type C and D surfaces. Type C surfaces with this degree of spectral selectivity have been approached, for example, by coating molybdenum with tantalum oxide. The spectral response of this material is shown in figure 2 as the solid curve (data from ref. 4). Many nonconductors show sharp changes in spectral emittance of the opposite or D type. An example is the spectral emittance curve for magnesium carbonate (from ref. 5) shown as the dashed curve in figure 2.

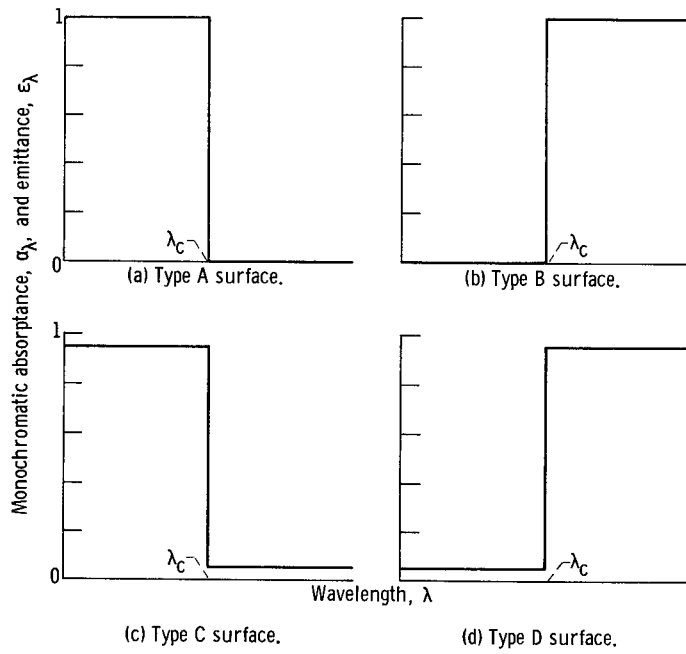


Figure 1. - Absorptance and emittance of ideal spectrally selective surfaces.

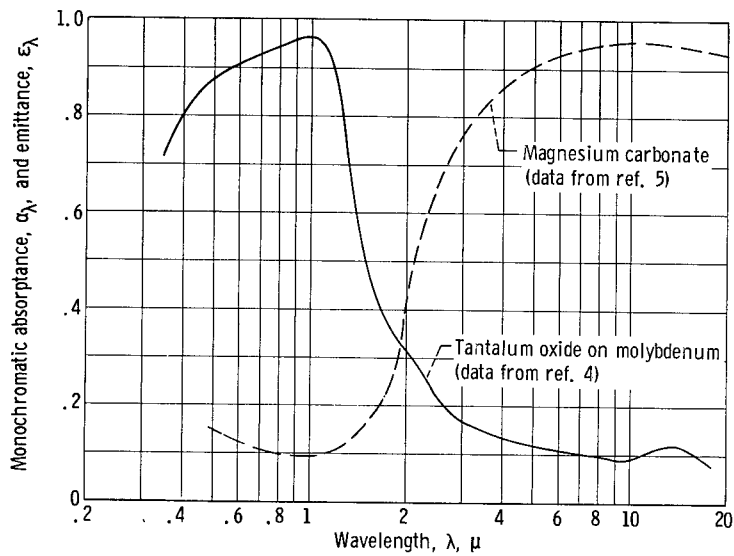


Figure 2. - Absorptance and emittance of two spectrally selective surfaces.

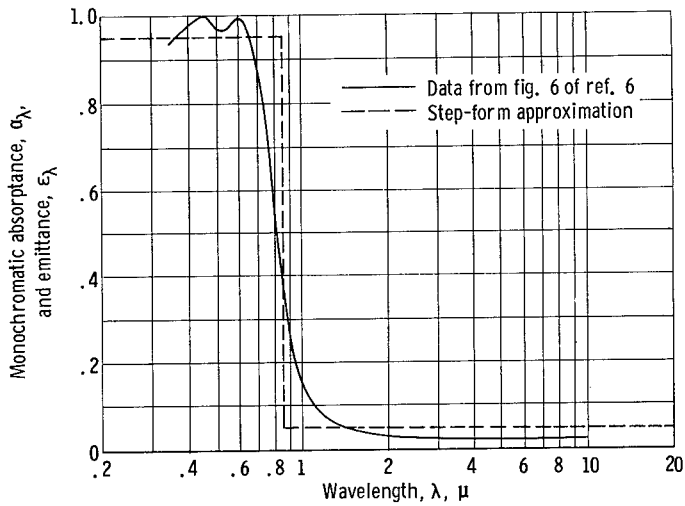


Figure 3. - Spectral absorptance and emittance of copper - germanium - silicon monoxide filter.

The highest degree of spectral selectivity is obtained with multilayer, interference-type surfaces like that shown in figure 3 (data from ref. 6). Figure 6 of reference 6 presents spectral reflectance as a function of wavelength. It was assumed that this filter could be backed by a black surface so that the spectral absorptance or emittance would be equal to 1 minus the spectral reflectance. It is recognized that there will be strong directional effects for such a composite surface, that the total absorptance will vary

with the angle of the incident radiation, and that the total emittance (hemispherical) cannot be easily calculated from spectral values. Nevertheless, it is assumed that this approaches a type C surface with an abrupt change in  $\alpha_\lambda$  or  $\epsilon_\lambda$  at 0.85 micron.

The spectrally selective surfaces shown in figures 1 to 3 can be characterized by the wavelength at which the spectral absorptance or emittance changes abruptly from a high to a low value. The wavelength of this step change in absorptance or emittance is termed  $\lambda_c$  herein and is used in the subsequent development.

The absorptance of a surface is a function of both the spectral selectivity of the surface and the source temperature or the spectral distribution of the incident flux. If the source is a blackbody, the surface absorptance is given by

$$\alpha = \frac{\int_0^{\infty} \alpha_\lambda W_{\lambda, T_1, B} d\lambda}{W_{T_1, B}} \quad (1)$$

The values of  $W_{\lambda, T_1, B}$  and  $W_{T_1, B}$  can be calculated for the incident radiation from a source at temperature  $T_1$  from the Planck and Stefan-Boltzmann equations, respectively. In a similar way the emittance of a surface is given by

$$\epsilon = \frac{\int_0^{\infty} \epsilon_\lambda W_{\lambda, T_2, B} d\lambda}{W_{T_2, B}} \quad (2)$$

where the temperature  $T_2$  refers to the temperature of the surface.

However, the fraction of the total energy radiated by a blackbody at all wavelengths shorter than a given value  $\lambda_0$  is a unique function of the product of wavelength and temperature  $\lambda_0 T$ . This fraction is defined as

$$F_{\lambda, T} \equiv \frac{\int_0^{\lambda_0} W_{\lambda, T, B} d\lambda}{W_{T, B}}$$

and tables of its values as a function of  $\lambda T$  were developed by Lowan and Branch (ref. 7) and can be found in standard references on radiative processes (e.g., ref. 8). The fraction at a wavelength larger than  $\lambda_0$  is then

$$\frac{\int_{\lambda_0}^{\infty} W_{\lambda, T, B} d\lambda}{W_{T, B}} = 1 - F_{\lambda, T}$$

If a surface has a high degree of spectral selectivity so that the monochromatic absorptance  $\alpha_\lambda$  is substantially a constant value from  $\lambda = 0$  to  $\lambda_0 = \lambda_c$  and a second constant value from  $\lambda_0 = \lambda_c$  to  $\lambda = \infty$ , the  $\alpha_\lambda$  term can be taken outside the integral in equation (1). The absorptance can then be calculated from

$$\alpha = \left( \alpha_{0-\lambda_c} F_{\lambda_c, T} \right) + \alpha_{\lambda_c-\infty} \left( 1 - F_{\lambda_c, T} \right) \quad (3)$$

by using values of  $F_{\lambda, T}$  as a function of  $\lambda T$  taken from tables (e.g., ref. 8). Equation (2) can be similarly modified so that the emittance can be calculated from

$$\epsilon = \left( \epsilon_{0-\lambda_c} F_{\lambda_c, T} \right) + \epsilon_{\lambda_c-\infty} \left( 1 - F_{\lambda_c, T} \right) \quad (4)$$

The source temperature is used in determining the absorptance by equation (3), and the surface temperature is used with equation (4) for emittance.

Since  $\alpha_{0-\lambda_c} = \epsilon_{0-\lambda_c}$  and  $\alpha_{\lambda_c-\infty} = \epsilon_{\lambda_c-\infty}$ , numerical values for these quantities

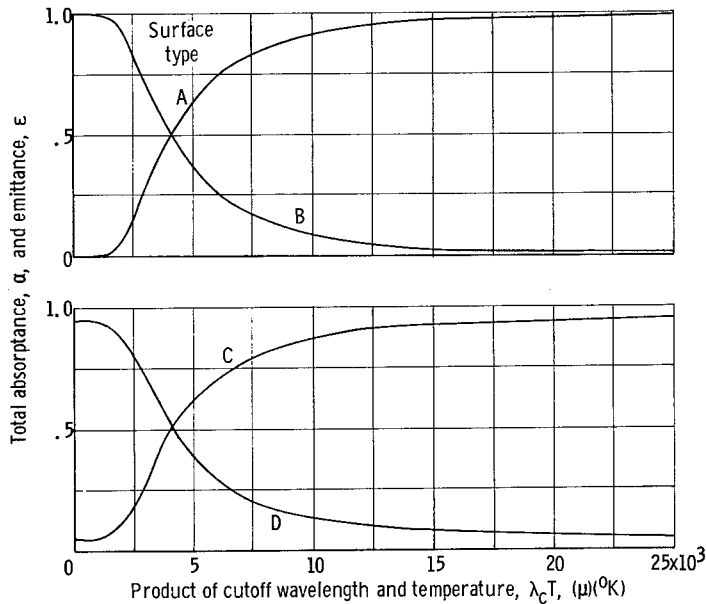


Figure 4. - Total absorptance and emittance for ideal spectrally selective surfaces.

can be used interchangeably in equations (3) and (4).

Equations (3) and (4) have been used to calculate the absorptance or emittance of ideal spectrally selective surfaces for various values of  $\lambda_c T$ . These are plotted in figure 4 for the four surfaces of figure 1. Figure 4 can be used to estimate  $\alpha$  or  $\epsilon$  for any surface where the monochromatic absorptance and emittance approach the step functions shown in figure 1 and where the source and the surface temperature are known. For example, if the surface shown in figure 3 is assumed to be equivalent to one having

$\alpha_\lambda = \epsilon_\lambda = 0.95$  at all wavelengths shorter than 0.85 micron, and  $\alpha_\lambda = \epsilon_\lambda = 0.05$  at all wavelengths longer than 0.85 micron (the dotted line in fig. 3), and if the incident radiation is from the Sun or a  $6000^\circ \text{K}$  blackbody, then  $\lambda_c T_1 = (0.85 \mu)(6000^\circ \text{K}) = 5100 (\mu)(^\circ \text{K})$ . Figure 4 gives a total absorptance of 0.63 for these conditions (type C surface). Similarly, if the same surface is at  $500^\circ \text{K}$ , the  $\lambda_c T_2$  value is  $425 (\mu)(^\circ \text{K})$  and the total emittance value of 0.05 can be read from figure 4 (type C surface). The  $\alpha/\epsilon$  for this surface and these temperatures is  $0.63/0.05 = 12.6$ .

The example just given indicates that it is also possible to plot  $\alpha/\epsilon$  as a function of  $\lambda_c T$  by using temperature ratios as parameters. The example of  $\alpha/\epsilon = 12.6$  for a temperature ratio  $T_1/T_2$  of  $6000/500 = 12.0$  and a  $\lambda_c T_1$  of  $5100 (\mu)(^\circ \text{K})$  would be one point in developing the curves. Curves could also be developed based on a  $\lambda_c T_2$  of  $425 (\mu)(^\circ \text{K})$  in the preceding example by using the surface rather than the source temperature as the reference value.

Such curves were developed by using the source temperature  $T_1$  in the  $\lambda_c T$  term since most of the work in this area is related to sunlit systems where  $6000^\circ \text{K}$  can be used as  $T_1$ . The alternative of using the surface temperature would be less convenient since the surface temperature is often unknown and may be the quantity that is to be calculated after  $\alpha/\epsilon$  is established. The surface temperature  $T_2$  must still be estimated to determine the temperature-ratio parameter, but, for a sunlit surface operating below  $500^\circ \text{K}$  ( $T_1/T_2 > 12$ ), the results are relatively insensitive to changes in  $T_2$ .

Calculated  $\alpha/\epsilon$  values are presented in figures 5(a) and (b) as a function of  $\lambda_c T_1$  for ideal spectrally selective surfaces, that is, those with a step change in  $\alpha_\lambda$  from

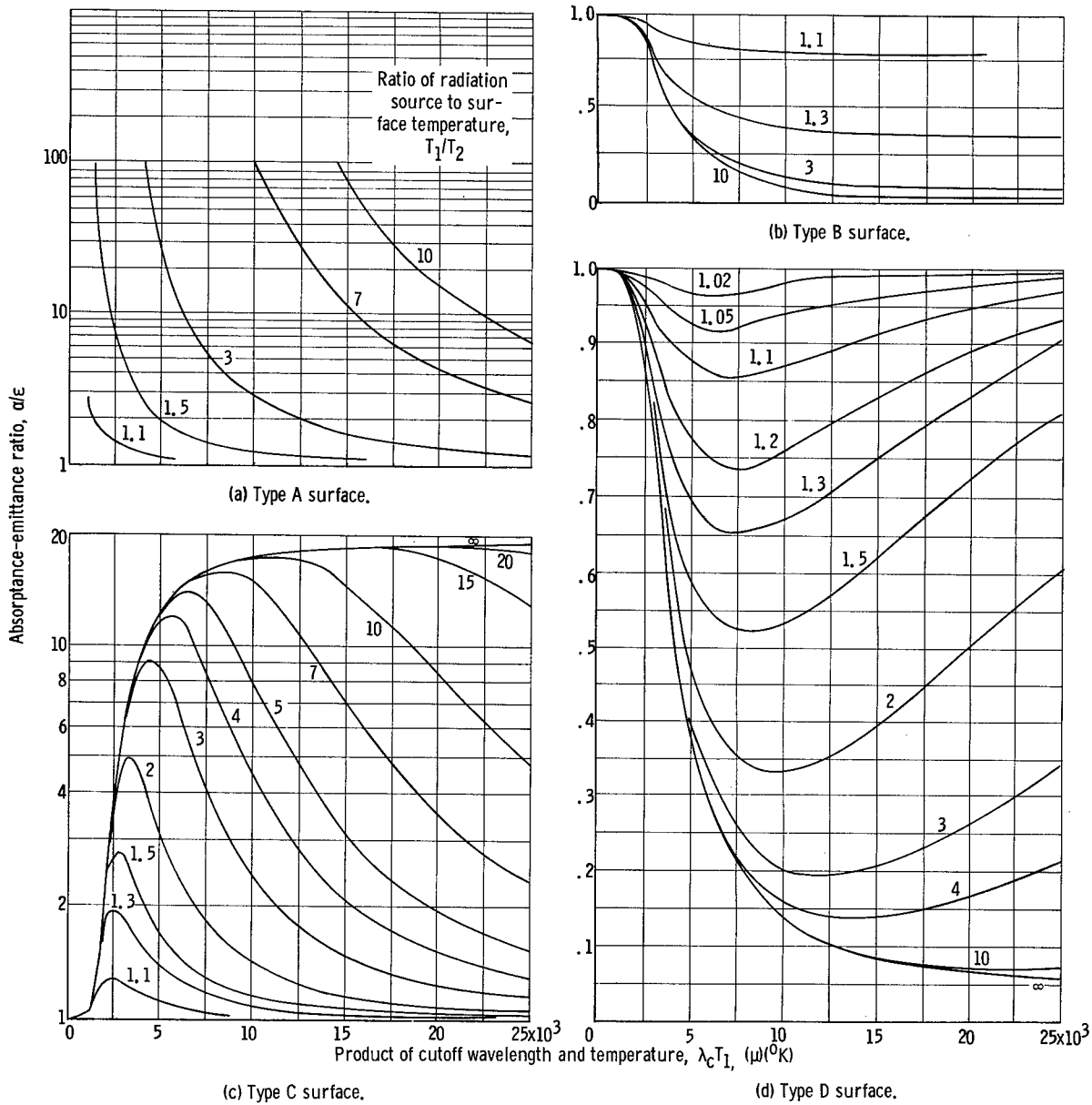


Figure 5. - Absorbance-emittance ratio for spectrally selective surfaces as function of wavelength-temperature product and temperature ratio.

1.0 to 0.0;  $T_1/T_2$  is the parameter in these curves.

For the type A surface,  $\alpha/\epsilon$  increases continuously both with decreasing  $\lambda_c T_1$  and with increasing  $T_1/T_2$  (fig. 5(a)). Very high values for  $\alpha/\epsilon$  would be achieved with surfaces having  $\lambda_c$  at short wavelengths so that  $\lambda_c T_1$  would be small.

For the type B surface,  $\alpha/\epsilon$  decreases both with increasing  $\lambda_c T_1$  and with increasing  $T_1/T_2$  (fig. 5(b)), and  $\alpha/\epsilon$  approaches zero as a limit with increasing  $T_1/T_2$ . The results shown in figures 5(a) and (b), however, are largely academic because

surfaces with this degree of spectral selectivity are not presently attainable. A more realistic degree of spectral selectivity is seen in the type C and D surfaces, where  $\alpha_\lambda$  and  $\epsilon_\lambda$  change from 0.95 to 0.05. Calculated values for  $\alpha/\epsilon$  are presented in figures 5(c) and (d) for these types of surfaces.

When the results for type A and C surfaces (figs. 5(a) and (c)) are compared, it can be seen that curves of quite different shape are obtained. For the type C surfaces  $\alpha/\epsilon$  does not increase continuously with decreasing  $\lambda_c T$  but reaches a maximum value for each temperature ratio. At lower temperature ratios these maximums are a quite sharp function of  $\lambda_c T_1$  and show that there is an optimum value of  $\lambda_c$  for any given source temperature. Figure 5(c) can be used, therefore, as a guide in developing a surface coating for any particular mission. At higher temperature ratios, the maximum  $\alpha/\epsilon$  is a less sensitive function of  $\lambda_c T_1$ .

The theoretical upper limit of  $\alpha/\epsilon$  that can be achieved with a type C surface is 19.0, and this only for very high temperature ratios and large values of  $\lambda_c T_1$  beyond those shown in figure 5(c). The practical upper limit is about 18, as shown for the range of  $\lambda_c T_1$  and  $T_1/T_2$  encompassed by this figure.

The type D surface (fig. 5(d)) also gives curves quite differently shaped from those for the ideal type B surface of figure 5(b). Minimum values of  $\alpha/\epsilon$  are shown as a function of  $\lambda_c T$ , and these minimums are sharpest at low values of  $T_1/T_2$ . The lowest  $\alpha/\epsilon$  possible for a type D surface is 0.053, and this only for  $\lambda_c T_1$  greater than that shown in figure 5(d). A more reasonable lower limit is about 0.070, as shown in this figure.

## EXAMPLES

The following cases are presented as examples of the use of the curves presented herein. Figures 5(c) and (d) are used in these illustrations since they are based on spectrally selective surfaces that may be attained in practice.

Case I. - What are the maximum and minimum values of  $\alpha_s/\epsilon$  that may be achieved for the sunlit surface of a space vehicle at the orbit distance of the Earth from the Sun? The surface temperature will be about  $300^\circ\text{K}$ , so that the temperature ratio will be  $6000/300$  or 20. The maximum  $\alpha_s/\epsilon$  therefore will be about 18 (fig. 5(c)), and the minimum about 0.07 (fig. 5(d)). In this case it makes little difference whether the vehicle temperature is below  $300^\circ\text{K}$  ( $T_1/T_2 > 20$ ) or as high as  $600^\circ\text{K}$  ( $T_1/T_2 = 10$ ); substantially the same limiting values of  $\alpha_s/\epsilon$  will be obtained.

Case II. - Similarly, what are the maximum and minimum values of  $\alpha/\epsilon$  for surfaces where the temperature ratio is 1.1? An example might be a relatively low temperature experiment operating in a hard vacuum with small temperature differences be-

tween adjacent surfaces. In this case the maximum and minimum  $\alpha/\epsilon$  may be 1.3 and 0.85, respectively, from figures 5(c) and (d).

Case III. - What is the minimum  $\alpha_s/\epsilon$  and the minimum temperature that may be achieved for a spherical body at 0.1 astronomical unit (Earth orbital distance) from the Sun? If it is assumed that the body is isothermal and that there is no heat source other than the Sun, the equilibrium temperature can be calculated from

$$T_2 = \left( \frac{C}{4\sigma} \frac{\alpha_s}{\epsilon} \right)^{1/4} \quad (5)$$

where  $C$ , the solar flux, is 13.5 watts per square centimeter at 0.1 astronomical unit and the constant 4 is due to the radiating surface area of a sphere being four times greater than its projected or absorbing area. Equation (5) is a simple derivation for the conditions of equal flux absorption and reradiation, where  $C\alpha_s A = \epsilon\sigma T_2^4 A$ . The temperature for a gray body ( $\alpha_s/\epsilon = 1.0$ ) is  $878^\circ$  K from equation (5) but would be considerably less for a low  $\alpha_s/\epsilon$  surface;  $600^\circ$  K can be used for the first approximation. For a  $600^\circ$  K surface the temperature ratio will be 10, and figure 5(d) indicates that an  $\alpha_s/\epsilon$  of 0.07 may be achieved. Inserting this value in equation (5) gives a temperature of  $451^\circ$  K. No further iteration is required since the minimum  $\alpha_s/\epsilon$  taken from figure 5(d) for this temperature ratio ( $T_1/T_2 = 13$ ) is substantially the same as that for the first approximation, where  $T_1/T_2 = 10$ .

Case IV. - What is the maximum  $\alpha_s/\epsilon$  and the maximum temperature that may be achieved under the conditions of case III? As a first approximation, assume a temperature of  $1000^\circ$  K so that  $T_1/T_2 = 6$  and the maximum  $\alpha_s/\epsilon$  is about 14 (fig. 5(c)). This value of  $\alpha_s/\epsilon$  results in a temperature of  $1700^\circ$  K and a temperature ratio of 3.5. The second approximation must start with a temperature ratio between 3.5 and 6.0 but much closer to the lower value. A ratio of 3.75 is taken where the maximum  $\alpha_s/\epsilon$  is approximately 11.0. This approximation results in a temperature of  $1600^\circ$  K or a temperature ratio of 3.75. No further iterations are required.

Case V. - At what wavelength should the monochromatic absorptance or emittance of the surface change from a high to a low value to achieve the maximum  $\alpha_s/\epsilon$  desired under the conditions of case IV? The temperature ratio was found to be about 3.75 in case IV, and figure 5(c) shows that the maximum  $\alpha_s/\epsilon$  is obtained at a  $\lambda_c T_1$  value of about  $5500 (\mu)(^\circ\text{K})$ . Since  $T_1$  is  $6000^\circ$  K, the wavelength  $\lambda_c$  is 0.917 micron. In other words, a spectrally selective surface should be sought for which the monochromatic absorptance or emittance is as high as possible at wavelengths less than 0.9 micron and as low as possible at longer wavelengths.

TABLE I. - COMPARISON OF MEASURED  
AND ESTIMATED ABSORPTANCE-  
EMITTANCE RATIOS

Surface temperature, $T_2$ , °K	Ratio of source to surface temperature, $T_1/T_2$	Data from ref. 4			$\alpha_s/\epsilon$ predicted from fig. 5(c)
		Total absorptance, $\alpha_s$	Total emittance, $\epsilon$	$\alpha_s/\epsilon$	
298	20	0.83	0.051	16.3	17
533	11.2	.79	.058	13.6	17
819	7.3	.68	.078	8.7	16

## COMPARISON WITH PRESENT STATE OF THE ART

Figures 5(c) and (d) show the  $\alpha/\epsilon$  values that can be obtained with various ratios of source to surface temperature. These are based on a somewhat idealized description of surface spectral selectivity, and it is interesting to compare these predictions with what has been achieved to date. While no exhaustive literature search has been made, data are available from

two recent reports that indicate the present state of the art in this regard.

Highest values of  $\alpha/\epsilon$  are obtained by coating a good reflector (a polished metal) with a selective absorber for short-wavelength radiation, for example, by coating molybdenum with tantalum oxide (see solid curve in fig. 2).

Solar absorptance and emittance data are given for several surface temperatures in reference 4 for tantalum oxide on molybdenum. These are listed in table I, and  $\alpha_s/\epsilon$  values are compared with those predicted by the present analysis. The source (Sun) temperature was taken as 6000° K,  $\lambda_c$  as 1.5 microns, and  $\lambda_c T_1$  as 9000 ( $\mu$ )(°K).

It can be seen that the predicted  $\alpha_s/\epsilon$  closely approaches the experimental value at high temperature ratios. At the lower temperature ratios (higher surface temperatures), however, the predicted values are well above those determined experimentally. The difference is largely due to a decrease in  $\alpha_\lambda$  at the shorter wavelengths for this material when its temperature is raised from room temperature to 819° K. These data are not shown herein but are clearly shown in figure 12 of reference 4. The surface therefore falls short of being a type C surface at high temperatures in that  $\alpha_\lambda$  is less than 0.95 at short wavelengths.

As for surfaces with very low  $\alpha_s/\epsilon$  values, total absorptance and emittance were not given for the magnesium carbonate used in figure 2 as an example of a type D material. An  $\alpha_s/\epsilon$  of 0.17, however, has been reported (ref. 9) for a surface painted with calcium silicate pigment in a sodium silicate vehicle. The latter painted surface should have a spectral response similar to that of magnesium carbonate in that  $\alpha_\lambda$  should be low at shorter wavelengths. If the paint is assumed to have a  $\lambda_c$  of 2 microns, the value for magnesium carbonate, then  $\lambda_c T_1 = 12\,000$  ( $\mu$ )(°K). Figure 5(d) predicts an  $\alpha_s/\epsilon$  of 0.11 for temperature ratios of 10 or greater. This predicted value for  $\alpha_s/\epsilon$  is somewhat lower than the experimental value of 0.17 and suggests that further work is

needed to develop a surface to achieve minimum  $\alpha_s/\epsilon$  values.

To this point the discussion has largely been concerned with the possibilities of achieving a high degree of spectral selectivity through having  $\alpha_\lambda$  or  $\epsilon_\lambda$  at high values over one range of wavelengths and at low values over another. The requirements for having a sharp break from one value to another have not been discussed. The importance of this latter factor depends strongly on the temperature ratio of the system, as shown in the following examples.

Consider a system with a temperature ratio  $T_1/T_2$  of 20. At this ratio, 98 percent of the energy radiated from a black or gray source at  $T_1$  is at  $\lambda T_1$  less than  $17.7 \times 10^3$  ( $\mu$ )( $^\circ\text{K}$ ) and 98 percent of the energy radiated from a similar surface at  $T_2$  is at  $\lambda T_1$  greater than  $32.0 \times 10^3$  ( $\mu$ )( $^\circ\text{K}$ ). For  $\lambda T_1$  values between  $17.7 \times 10^3$  and  $32.0 \times 10^3$  ( $\mu$ )( $^\circ\text{K}$ ) there is very little energy radiated from either source or surface. Therefore, the values for  $\alpha_\lambda$  and  $\epsilon_\lambda$  that a surface has in this range have very little influence on  $\alpha$ ,  $\epsilon$ , or  $\alpha/\epsilon$ . The surface can have a sharp break at the  $\lambda_c$  that gives a  $\lambda_c T_1$  product anywhere between  $17.7 \times 10^3$  and  $32.0 \times 10^3$  ( $\mu$ )( $^\circ\text{K}$ ), or there can be a slow transition between high and low values of  $\alpha_\lambda$  in this range without significantly changing the performance of the surface.

If the temperature ratio is reduced to 10, 98 percent of the source energy is still at  $\lambda T_1$  less than  $17.7 \times 10^3$  ( $\mu$ )( $^\circ\text{K}$ ), but 3.5 percent of the energy of the surface is also found below this value. Therefore, at  $T_1/T_2 = 10$ , there is a small overlap in the spectral distribution from source and surface, and this overlap increases as the temperature ratio decreases. At the lower temperature ratios it becomes increasingly important to have  $\lambda_c$  at the proper wavelength and for  $\alpha_\lambda$  to change value as abruptly as possible.

The shape of the curves in figures 5(c) and (d) give quantitative confirmation to the preceding statements. Sharp maximums and minimums are shown for the lower values of  $T_1/T_2$ , but at the higher temperature ratios these maximums and minimums are a less sensitive function of  $\lambda T_1$ .

### CONCLUDING REMARKS

It has been shown that the product of  $\lambda_c$ , a term characterizing the spectral quality of a surface, and  $T$ , the temperature of a black or gray radiation source, can be used to develop a series of completely general curves from which values for the ratio of absorptance to emittance  $\alpha/\epsilon$  can be read directly. Such curves were developed for surfaces with two degrees of spectral selectivity, those representing a theoretical limit and those that may be within reach experimentally.

The latter curves indicate that the maximum  $\alpha/\epsilon$  that is likely to be attained is about 18, and the minimum is about 0.070. These maximums and minimums are

attainable only at high values of the ratio of radiation source to surface temperature. At lower values of this temperature ratio,  $\alpha/\epsilon$  will be much closer to unity.

Examples are given to show both the use of these curves and the degree to which predicted values have been approached in practice.

*Send - WDC*

Lewis Research Center,  
National Aeronautics and Space Administration,  
Cleveland, Ohio, February 12, 1965.

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