NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

WARTIME REPORT

ORIGINALLY ISSUED

January 1944 as
Advance Restricted Report 4A21

AN INVESTIGATION OF AIRCRAFT HEATERS

XV - THE EMISSIVITY OF SEVERAL MATERIALS

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NACA

WASHINGTON

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SUMMARY

The mean effective emissivity as a function of temperature for the surfaces of several metals and insulating materials has been determined. The surfaces are typical samples of the materials which are used in aircraft construction. A description and discussion of the mensuration technique is presented. The data are evaluated over a range of surface temperatures from approximately 110° F to approximately 350° F.

Over the range of temperatures investigated, it was found that the mean effective emissivities of the surfaces tested were approximately constant with temperature when viewed normal to the surface; the several emissivities ranged from approximately 0.05 to approximately 0.85. The color of a surface is not a criterion for estimating the emissivity at the wavelengths and temperatures under consideration; texture and chemical composition of the surface are probably more reliable criterions.

The result obtained has been termed the "mean effective emissivity," since it is a factor to be used in a particular equation involving temperatures determined by means of thermocouples mounted in a particular manner. This definition must be kept in mind in using the values of the emissivities given.

INTRODUCTION

A knowledge of the emissivities of the surfaces of materials used in various places on the airplane is needed when a complete heat balance on an airplane or any of its parts is undertaken. In many cases, as may be concluded if the complete thermal circuit is studied (reference 1), radiation provides the controlling element in the circuit. Large errors in the design of cabin insulation and of aircraft heaters may be made if the emissivities of the surfaces are not estimated closely.

It is the purpose of this report to present data on the mean effective emissivity as a function of temperature for the surfaces of some materials used in the airplane. The values were obtained by viewing the specimens normal to the surface. Further measurements on these and other materials over a greater range of temperatures, to include the determination of the variation of emissivity with angle, are anticipated.

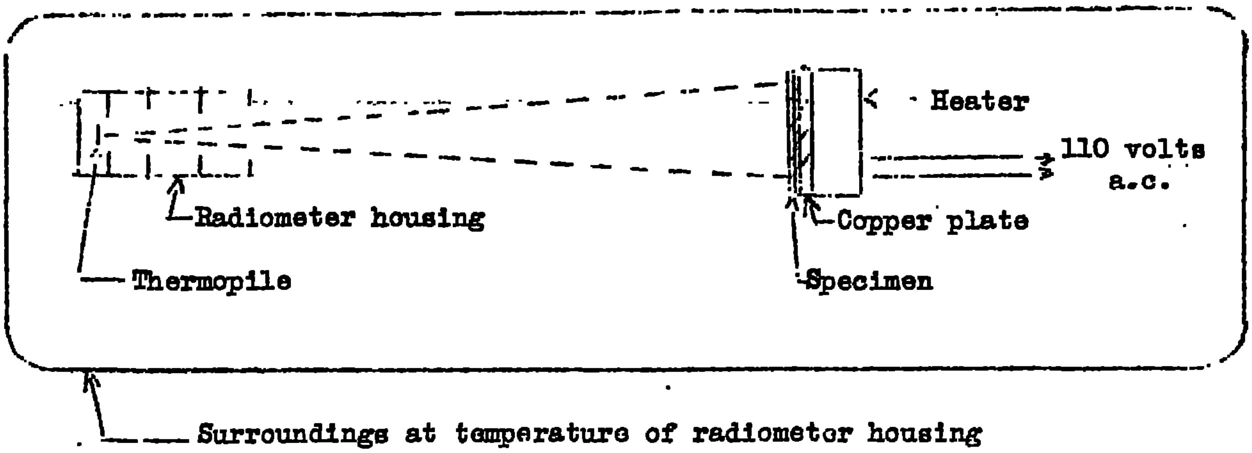
This program of research in the Spectro-Radiometric Laboratory of the Department of Mechanical Engineering of the University of California was conducted under the sponsorship and with the financial assistance of the National Advisory Committee for Aeronautics.

The authors wish to express their appreciation to Messrs. L. M. Grossman and H. F. Poppendiek for their assistance in obtaining the data, and to Messrs. H. Poeland and D. F. Sewoll for their aid in the construction of the apparatus.

The materials used in the investigations were obtained from the Douglas Aircraft Company, Santa Monica, California.

PROCEDURE AND APPARATUS

Emissivity measurements were made on samples of Inconel, 18-8 stainless steel, 24S-T alclad aluminum alloy, and a cloth covering of kapok insulation in the following manner. The test specimens were heated by contact with an electrically heated copper plate. The net exchange of energy by radiation between the heated specimen surface and a thermopile radiometer (reference 2) was measured. The temperature of the surface of the test specimen was measured by a thermocouple. From these measurements of the surface temperature and the net radiant energy exchange, a mean effective emissivity normal to the surface was calculated. (See appendix A.) The following sketch illustrates the experimental setup.



DISCUSSION OF RESULTS AND CONCLUDING REMARKS

The results of the tests are plotted in figures 1 to 4.

The data shown in figure 1 for 24S-T alclad aluminum alloy indicate that the mean effective emissivity for the painted surface is many times that of the unpainted surface. The camouflage-green paint possesses a higher mean effective emissivity than the zinc chromate paint, probably because of the rougher surface of the former. The dotted curve for the unpainted surface indicates that the experimental data were somewhat uncertain, although the magnitudes presented are probably accurate within 10 percent.

Reference to figure 2 reveals that oxidation of the surface of Inconel had little effect on the mean effective emissivity owing to its high corrosion-resistance characteristics.

Although the emissivity of untreated 18-8 stainless steel was not measured, it is believed to be a low value. Oxidation of the surface by heating in air to 1500° and to 1000° F and also by a solution of chromic and sulfuric acids probably increased the mean effective emissivity. A roughening of the surface (sand-blasting) also increased the emissivity, but not as much as the high temperature (1500° F) oxidation. (See fig. 3.)

The approximate thickness of the paint on the surfaces is listed in the following table:

Material	Approx. thickness range (microns)
Aluminum painted cloth	12 - 18
Green painted cloth	5 - 18
Painted metal	2 - 5

The emissivity of the cloth sample is lower when painted with the aluminum than when painted with the green paint, probably because of the reflecting characteristic of the metal in the paint. (See fig. 4.)

The mean effective emissivity of all of the metal surfaces measured are approximately independent of temperature between 100° and 300° F. The same is true for the cloth specimens between 100° and 250° F.

In using the emissivities reported here, the temperatures must be measured as follows:

Cloth surfaces: Small cuts are made in the cloth surface and thermocouples of No. 40 wire inserted in those cuts in such a manner that the thermocouples are within a few thousandths of an inch of the surface. The wires are held in place by means of cellulose acetate cement.

Metal surfaces: The thermocouple should be soldered to the surface with as small a soldered joint as possible.

University of California,
Berkeley, Calif., October 1943.

APPENDIX A

SYMBOLS

A_a area of surface a, ft^2

A_b area of surface b, ft^2

A_s area of surroundings, ft^2

C_1 proportionality constant between voltage generated by thermopile and absorbed power, $\frac{\text{millivolts}}{\text{Btu/hr}}$

$E_{I\lambda, T_a}$ emissive power of an ideal radiator at wavelength λ and temperature T_a, $\frac{\text{Btu}}{\text{hr ft}^2\text{ micron}}$

$E_{I\lambda, T_b}$ emissive power of an ideal radiator at wavelength λ and temperature T_b, $\frac{\text{Btu}}{\text{hr ft}^2\text{ micron}}$

$F_{b \leftarrow a}$ shape modulus, the fraction of energy originally leaving a perfectly diffusing surface a of uniform temperature which reaches a surface b before any reflections have taken place

$$= \frac{1}{A_a \pi} \int_{A_a} \int_{A_b} \frac{\cos \Phi_a \cos \Phi_b \, dA_b \, dA_a}{r^2}$$

(See references 3, pp. 11-12, 6, 7, and 8.)

$F_{s \leftarrow a}$ shape modulus, (same as $F_{b \leftarrow a}$, but refers to energy leaving a incident on s)

$F_{s \leftarrow b}$ shape modulus, (same as $F_{b \leftarrow a}$, but refers to energy leaving b incident on s)

$F_{a \leftarrow b}$ shape modulus, (same as $F_{b \leftarrow a}$, but refers to energy leaving b incident on a)

$F_{a \leftarrow s}$ shape modulus, (same as $F_{b \leftarrow a}$, but refers to energy leaving s incident on a)

$F_{b \leftarrow s}$ shape modulus, (same as $F_{b \leftarrow a}$, but refers to energy leaving s incident on b)

K calibration factor of radiometer used, Btu/hr ft^2 mv

mv electromotive force generated by thermopile element of radiometer, millivolts

q_{net} net exchange of radiant power at one body, Btu/hr

r distance between a point on surface a and a point on surface b, ft

T_a absolute temperature of surface a, $^\circ$R

T_b absolute temperature of surface b, °R

T_s absolute temperature of surface s, °R

$\epsilon_{a_{\lambda,T_a}}$ monochromatic emissivity of surface a at wavelength λ and temperature T_a

$\epsilon_{b_{\lambda,T_b}}$ monochromatic emissivity of surface b at wavelength λ and temperature T_b

$\epsilon_{s_{\lambda,T_s}}$ monochromatic emissivity of surface s at wavelength λ and temperature T_s

$\epsilon_{a_{me_{T_a}}}$ mean effective emissivity of surface a at temperature T_a

$\epsilon_{b_{me_{T_b}}}$ mean effective emissivity of surface b at temperature T_b

ϕ_a angle between a ray to a point on surface a, and the normal to that point

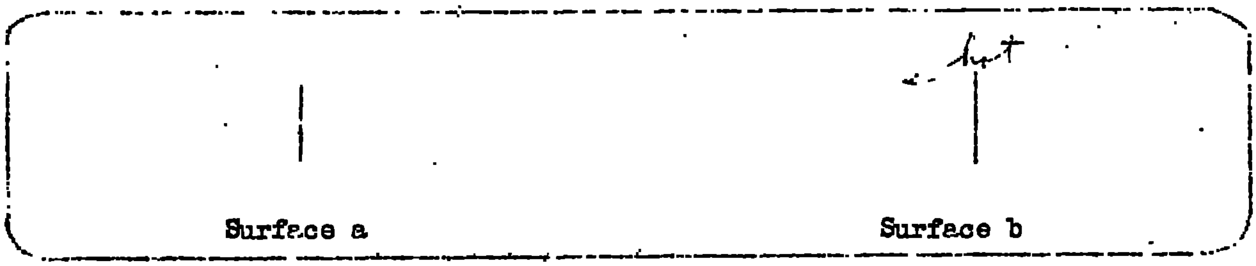
ϕ_b angle between a ray to a point on surface b, and the normal to that point

λ wavelength, microns

$d\lambda$ differential wavelength, microns

In order to calculate the heat transfer from a surface by radiation, the complete system must be considered in the analysis. This statement is best illustrated by the following example:

A surface at a temperature T_a and having a monochromatic emissivity $\epsilon_{a_{\lambda,T_a}}$ (emissivity at wavelength λ and temperature T_a) is in a large enclosure and is being irradiated by a hot surface at a temperature T_b and having a monochromatic emissivity $\epsilon_{b_{\lambda,T_b}}$. The surroundings are at a uniform temperature equal to T_s. The areas are represented by A_a and A_b, the area of the surroundings being A_s; A_a and A_b are sufficiently small and far apart that all points on A_a may be considered equidistant from all points on A_b and that no interreflections take place. All surfaces are opaque and perfectly diffuse. The sketch illustrates the system:



Surroundings s

	Surface a	Surface b	Surroundings s
Area	A_a	A_b	A_s
Monochromatic emissivity	$\epsilon_{a\lambda,T_a}$	$\epsilon_{b\lambda,T_b}$	$\epsilon_{s\lambda,T_s} = 1$
Temperature	T_a	T_b	T_s
Monochromatic emissive power	$\epsilon_{a\lambda,T_a} \times E_{I\lambda,T_a}$	$\epsilon_{b\lambda,T_b} \times E_{I\lambda,T_b}$	$E_{I\lambda,T_s}$

Due to the fact that the surroundings are large compared to the radiating surfaces a and b, the surroundings radiate to those surfaces as if the surroundings had an emissivity of unity (reference 3).

The net amount of power absorbed by surface a is desired. A radiation heat balance on surface a is accomplished - that is, the difference between all absorbed and radiated power is obtained. The absorbed power is equal to the incident power times the absorptivity. The monochromatic absorptivity is equal to the monochromatic emissivity (reference 4). The power absorbed at a is equal to the sum of the following terms:

Emissivity of surface b at wavelength λ and Temp. T_b — Emissive power of black body at wavelength λ and temperature T_b — Radiating area — Shape factor — Emissivity of absorbing surface at wavelength λ and temp. T_a = absorptivity of absorbing surface at wavelength λ and temp. T_a by Kirchhoff's law.

$$\int_0^\infty \epsilon_{b_{\lambda,T_b}} \underbrace{E_{I_{\lambda,T_b}} A_b}_{\text{Integral of this product is energy radiated by a black body at temp. } T_b \text{ of area } A_b} F_{a\leftarrow b} \, \epsilon_{a_{\lambda,T_a}} \, d\lambda$$

power radiated to a from b and absorbed at a. (1)

$$\int_0^\infty \epsilon_{s_{\lambda,T_s}} E_{I_{\lambda,T_s}} A_s F_{a\leftarrow s} \, \epsilon_{a_{\lambda,T_a}} \, d\lambda$$

power radiated to a from s and absorbed at a (2)

$$\int_0^\infty \epsilon_{s_{\lambda,T_s}} E_{I_{\lambda,T_s}} A_s F_{b\leftarrow s} \left(1-\epsilon_{b_{\lambda,T_b}}\right) F_{a\leftarrow b} \, \epsilon_{a_{\lambda,T_a}} \, d\lambda$$

power radiated to b from s and reflected to a and absorbed at a (3)

The power actually leaving a is equal to the power absorbed by surface b from a plus the power absorbed by surface s from a. If there were any other absorbing bodies in the system, the power absorbed by them from a would be added.

The power leaving a is equal to the sum of the following terms:

$$\int_0^\infty \epsilon_{a_{\lambda,T_a}} E_{I_{\lambda,T_a}} A_a F_{b\leftarrow a} \, \epsilon_{b_{\lambda,T_b}} \, d\lambda$$

power radiated to b from a and absorbed at b (4)

$$\int_0^\infty \epsilon_{a_{\lambda,T_a}} E_{I_{\lambda,T_a}} A_a F_{b\leftarrow a} \left(1-\epsilon_{b_{\lambda,T_b}}\right) F_{s\leftarrow b} \, \epsilon_{s_{\lambda,T_s}} \, d\lambda$$

power radiated to b from a and reflected to s and absorbed by s (5)

$$\int_0^\infty \epsilon_{a_{\lambda,T_a}} E_{I_{\lambda,T_a}} A_a F_{s\leftarrow a} \, \epsilon_{s_{\lambda,T_s}} \, d\lambda$$

power radiated directly to s from a and absorbed at s (6)

Further terms can be written which will account for interreflections, but the effect of this phenomenon will be postulated as negligibly small.

The net power absorbed at a is equal to

$$\left[(1) + (2) + (3)\right] - \left[(4) + (5) + (6)\right] \qquad (7)$$

Combining the various terms and utilizing the reciprocity relation (reference 3, p. 12),

$$A_b F_{a \leftarrow b} = A_a F_{b \leftarrow a},$$

$$A_s F_{a \leftarrow s} = A_a F_{s \leftarrow a}, \tag{8}$$

$$A_b F_{b \leftarrow s} F_{a \leftarrow b} = A_a F_{s \leftarrow b} F_{b \leftarrow a};$$

the expression

$$\begin{aligned} q_{net} &\text{ (net heat transfer rate)} \\ &= A_a F_{b \leftarrow a} \int_0^\infty \epsilon_{a_{\lambda, T_a}} \epsilon_{b_{\lambda, T_b}} \left[E_{I_{\lambda, T_a}} - E_{I_{\lambda, T_b}} \right] d\lambda \\ &\quad + A_a F_{s \leftarrow a} \int_0^\infty \epsilon_{a_{\lambda, T_a}} \left[E_{I_{\lambda, T_a}} - E_{I_{\lambda, T_s}} \right] d\lambda \\ &\quad + A_a F_{s \leftarrow b} \int_0^\infty \epsilon_{a_{\lambda, T_a}} \left(1 - \epsilon_{b_{\lambda, T_s}} \right) \left[E_{I_{\lambda, T_a}} - E_{I_{\lambda, T_s}} \right] d\lambda \end{aligned} \tag{9}$$

is obtained.

In general, all the variables in this equation would have to be known in order to obtain an accurate result. A close approximation to the correct result may be obtained by replacing the monochromatic emissivities, $\epsilon_{a_{\lambda, T_a}}$ and $\epsilon_{b_{\lambda, T_b}}$, used in equations (1) to (9) by constants (mean effective emissivities) which are obtained by averaging $\epsilon_{b_{\lambda, T_b}}$ and $\epsilon_{a_{\lambda, T_a}}$ with respect to $E_{I_{\lambda, T_a}}$, $E_{I_{\lambda, T_b}}$, and $E_{I_{\lambda, T_s}}$ over the wavelengths involved. These mean effective emissivities $\epsilon_{a_{me_{T_a}}}$ and $\epsilon_{b_{me_{T_b}}}$ are defined in such a manner as to yield the same result (q_{net}) for the temperatures T_a, T_b, and T_s. These values are given in this report. Since the values of ϵ_{me_T} (mean effective emissivity of any body at a temperature T) are averages, it must be remembered that they are averaged with respect to certain variables, and consequently are to be used only with those variables over the range that the averages were taken.

For the case in which $T_a = T_s$ equation (9) becomes

$$q_{net} = A_a F_{b\leftarrow a} \int_0^\infty \epsilon_{a\lambda,T_a} \epsilon_{b\lambda,T_b} \left[E_{I\lambda,T_a} - E_{I\lambda,T_b} \right] d\lambda \qquad (10)$$

and replacing $\epsilon_{a\lambda,T_a}$ and $\epsilon_{b\lambda,T_b}$ by $\epsilon_{a_{meT_a}}$ and $\epsilon_{b_{meT_b}}$ equation (10) becomes

$$q_{net} = A_a F_{b\leftarrow a} \epsilon_{a_{meT_a}} \epsilon_{b_{meT_b}} \int_0^\infty \left(E_{I_{\lambda,T_a}} - E_{I_{\lambda,T_b}} \right) d\lambda \qquad (11)$$

and, since (reference 3, p. 12)

$$\int_0^\infty E_{I_{\lambda,T}} \, d\lambda = \sigma T^4$$

$$q_{net} = A_a F_{b\leftarrow a} \epsilon_{a_{meT_a}} \epsilon_{b_{meT_b}} \sigma \left[T_a^4 - T_b^4 \right] \qquad (12)$$

The emissivity measurements were made under conditions satisfying equations (10) and (12). The measurements were made as follows:

The thermopile radiometer (reference 2) was used to measure the net interchange by radiation (q_{net}) between the thermopile receiver element and the test surface. It has been shown (reference 2) that the power exchange by radiation is directly proportional to the electro-motive force generated by the thermopile as determined by a potentiometer. Consequently, since the housing and surroundings are at the temperature of the receiver element,

$$q_{net} = C_1(mv) = A_a F_{b\leftarrow a} \epsilon_{a_{meT_a}} \epsilon_{b_{meT_b}} \sigma \left(T_a^4 - T_b^4 \right) \qquad (13)$$

In equation (13), C_1 is a proportionality factor between (q_{net}) and the electromotive force generated in millivolts. T_a and $\epsilon_{a_{meT_a}}$ now refer to the radiometer receiver element, and T_b and $\epsilon_{b_{meT_b}}$ to the test specimen. Although data have not been obtained for the complete spectrum, sufficient experiments have been performed to indicate that $\epsilon_{a_{meT_a}}$ (the mean effective emissivity of the radiometer receiver element) is constant for the temperature ranges used. Solving equation (13) for $\epsilon_{b_{meT_b}}$ (the mean effective emissivity of the test specimen) results in the equation

$$\epsilon_{b_{meT_b}} = \left(\frac{C_1}{\epsilon_{a_{meT_a}} A_a}\right) \frac{(mv)}{F_{b \leftarrow a}\, \sigma\, (T_a^4 - T_b^4)} \qquad (14)$$

and, setting

$$\frac{C_1}{\epsilon_{a_{meT_a}} A_a} = K,$$

$$\epsilon_{b_{meT_b}} = \frac{K\,(mv)}{F_{b \leftarrow a}\, \sigma\, (T_a^4 - T_b^4)} \qquad (15)$$

K is obtained by calibration with a radiation standard.

Comparison of equations (10), (13), and (14) shows that (taking $\epsilon_{a\lambda, T_a}$ of the radiometer receiver element as constant with wavelength and equal to $\epsilon_{a_{meT_a}}$)

$$\epsilon_{b_{meT_b}} = \frac{\int_0^\infty \epsilon_{b\lambda, T_b} \left[E_{I\lambda, T_a} - E_{I\lambda, T_b} \right] d\lambda}{\sigma\, (T_a^4 - T_b^4)} \qquad (16)$$

Thus, equation (16) shows that the mean effective emissivity of a material ($\epsilon_{b_{meT_b}}$) is a function of $\epsilon_{b\lambda, T_b}$, T_a, and T_b. In the measurements described, T_a was held at room temperature, while T_b was varied. Thus, the values obtained are for varying specimen temperatures (T_b), but must be used with the same value of T_a as used in the experiments. That is, in computing radiant heat transfer from a surface, the values of the mean effective emissivities (ϵ_{me_T}) as obtained from the curves given in this report may be used to a high degree of accuracy only if the radiation computed is to surfaces at ordinary room temperature. Actually, if the mean effective emissivity of the surface does not vary much with temperature, radiation to surfaces at other temperatures can be estimated to a good degree of approximation by using the same mean effective emissivity. The allowable variation in T_a may be estimated by inspection of the curves (figs. 1 to 4). If the slope of the ϵ_{me_T} against T curve is small, or zero, it is probable that the values of mean effective emissivity given by these curves are applicable over a wide range of values of the temperature of the other radiating surfaces in the system.

For example, the curve for sand-blasted 18-8 stainless steel reveals that the values of mean effective emissivity given are probably applicable in a system in which the temperature of the other radiating surfaces differ considerably from room temperature; the curve for 24S-T alclad painted with camouflage-green paint cannot be used with accuracy in a system in which the temperatures of the other radiating surfaces differ from the usual room temperature by a large amount.

It should be emphasized that in any application of the thermopile radiometer a complete analysis of the system would be necessary, and that the conditions which obtain in the application described previously may not hold in another system.

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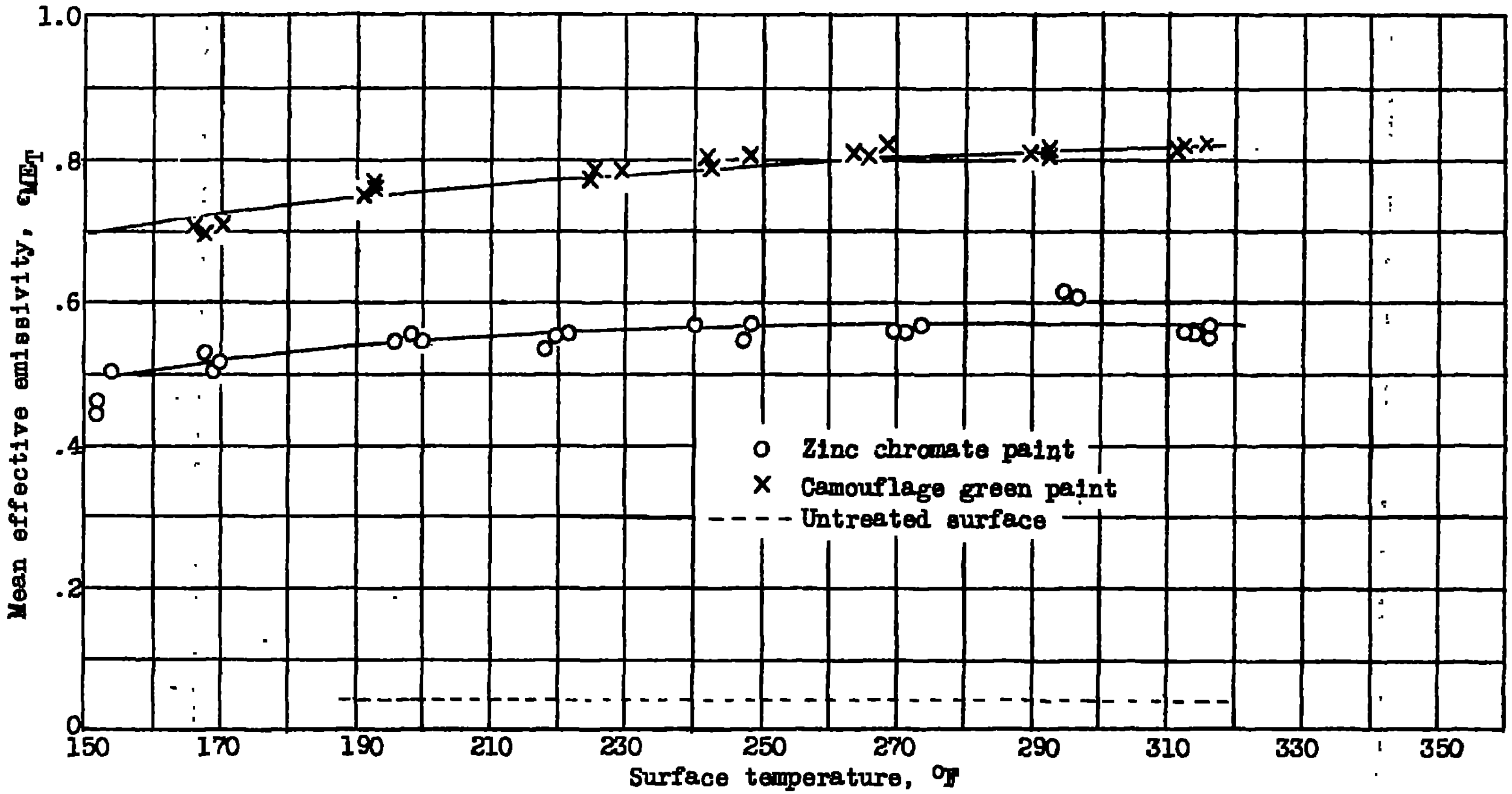

Figure 1.- Emissivity as a function of temperature for painted surfaces of 24 S-T alclad. (Measured in a direction perpendicular to the plane of the surface).

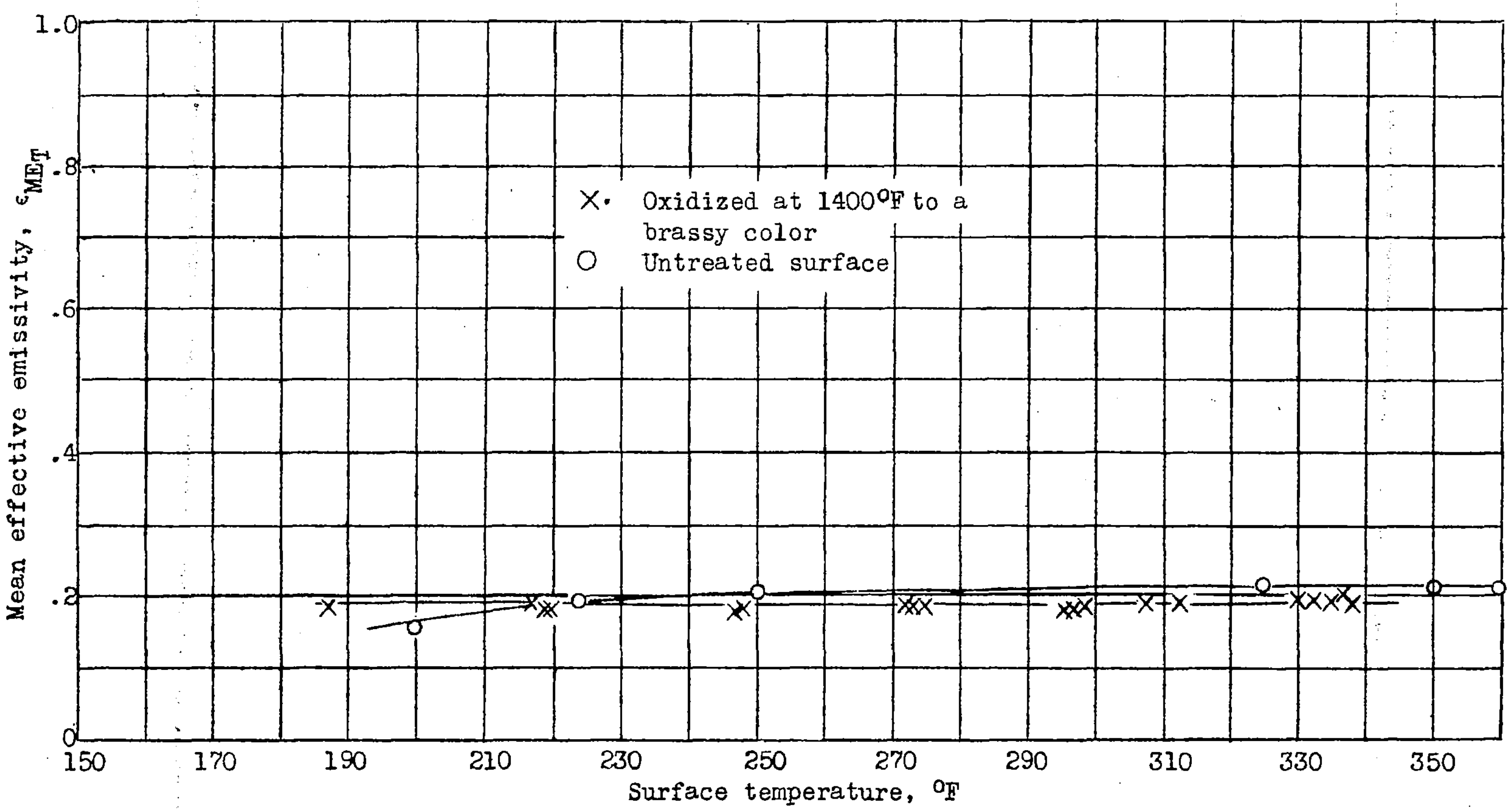

Figure 2.- Emissivity of Inconel as a function of temperature. (Measured in a direction perpendicular to the plane of the surface).

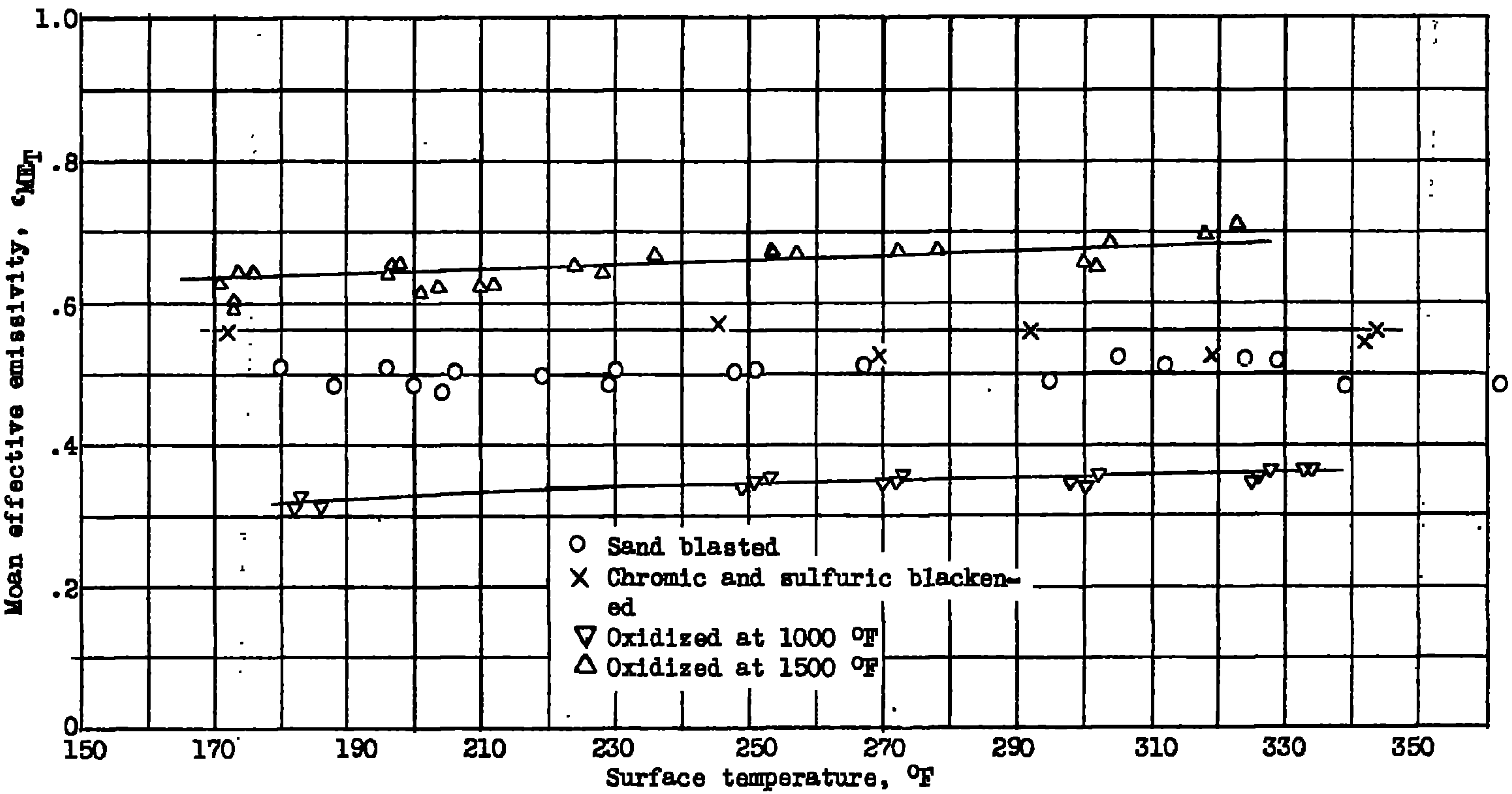

Figure 3.- Emissivity of 18-8 stainless steel as a function of temperature. (Measured in a direction perpendicular to the plane of the surface).

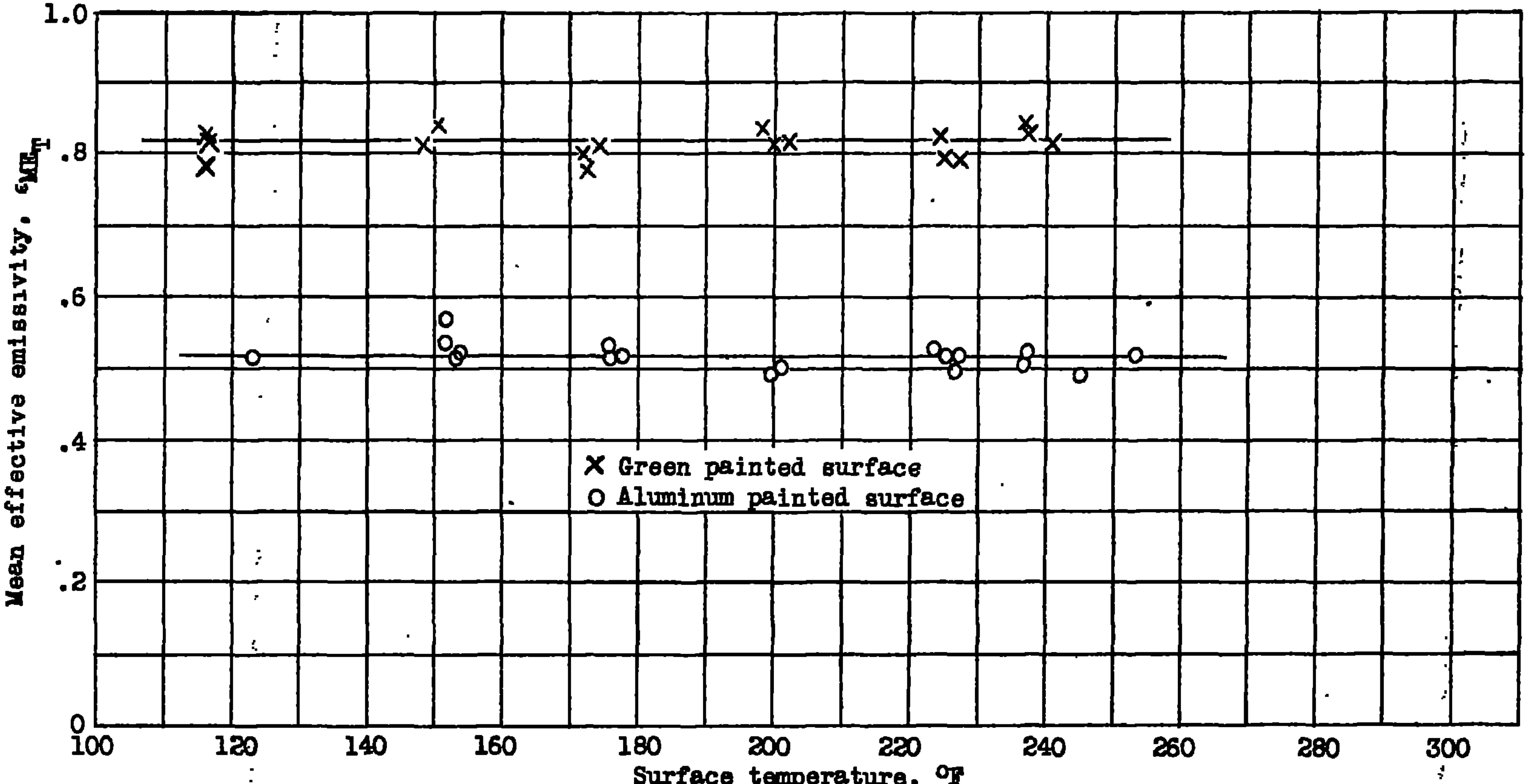

Figure 4.- Emissivity as a function of temperature for the surface of cabin insulating material. (Measured in a direction perpendicular to the plane of the surface).