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TECHNICAL NOTE 4121

THEORY AND APPARATUS FOR MEASUREMENT OF EMISSIVITY FOR RADIATIVE COOLING OF HYPERSONIC AIRCRAFT WITH DATA FOR INCONEL AND INCONEL X

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SUMMARY

Calculations of the amount of cooling attainable by radiation at Mach numbers up to 11 and altitudes up to 100,000 feet are presented for a flat plate with turbulent boundary layer and alined with the wind. These calculations show the utility of radiation as a means of cooling high supersonic and hypersonic aircraft under aerodynamic heating and the need for measurements of the total hemispherical emissivity of surfaces suitable for use on aircraft. The theory underlying the investigation and measurement of total hemispherical emissivity is presented. Readily duplicable apparatus suitable for performing the requisite measurements on a large variety of surfaces is described. The method of calibration and the techniques are given for using the apparatus to investigate the stability of the emissivity of surfaces, for measuring the total emissivity as a function of angle to the surface, and for measuring the total hemispherical emissivity of stable surfaces as a function of temperature. It is shown that on both Inconel and Inconel X, cleaned to bare metal, there can be produced by heating in air thin, smooth, adherent oxide coatings that do not flake off under rapid heating and cooling, are resistant to mild abrasion, emit diffusely, and have stable emissive characteristics at temperatures up to 2,000° F. The total hemispherical emissivity of the Inconel coating was found to vary from 0.69 at 600° F to 0.82 at 1,800° F and that of Inconel X from 0.89 at 600° F to 0.92 at 1,800° F.

INTRODUCTION

Cooling by radiation, either alone or in combination with insulation or other cooling methods, is one of the most promising means of keeping the temperatures resulting from aerodynamic heating of high supersonic and hypersonic (above a Mach number of 5) aircraft within structurally tolerable limits. The effectiveness of cooling by radiation is illustrated in figure 1 in which is plotted against flight Mach number the equilibrium

temperature attained at a point 2 feet from the leading edge of a flat surface parallel to the wind, assuming a turbulent boundary layer. The curves were calculated by equating the rate of heat loss from the surface by radiation to the rate of heat input to the surface by aerodynamic heating, with the turbulent-boundary-layer heat-transfer coefficients given by reference 1. Curves are shown for flight at sea level, at a 50,000-foot altitude, and at a 100,000-foot altitude, based upon the air temperature and density values of references 2 and 3. Two curves are given for each altitude: one for the case of zero surface emissivity, representing no loss of heat by radiation; and the other for the case of a surface total hemispherical emissivity of unity, representing the maximum possible cooling by radiation. It is apparent from figure 1 that radiation becomes a powerful means of cooling at the higher supersonic speeds and at hypersonic speeds and that, with increase in altitude, the temperature reduction produced by radiative cooling increases markedly. Had a laminar boundary layer been assumed, appreciably larger reductions in temperature would have been shown because the laminar-boundary-layer heat-transfer coefficients are much lower than those of the turbulent boundary layer. Since the rate of loss of heat by radiation is directly proportional to the total hemispherical emissivity of the surface, it is apparent that practical interest lies in development of surfaces having the highest possible value of total hemispherical emissivity in order to achieve the maximum radiative cooling.

Much of the attractiveness of radiative cooling stems from its inherent simplicity, reliability, and low weight as compared with other methods of cooling. Emissivity is a property of the surface of a body, so that materials that are poor radiators, such as most metals, may be coated with a thin layer of material of high emissivity and thus be made good radiators. The feasibility of this depends upon the development of strongly adherent, stable, and aerodynamically smooth coatings of high emissivity capable of withstanding elevated temperatures and rapid rates of change of temperature. The research herein reported shows that such coatings can be produced upon Inconel and Inconel X. It is therefore not unreasonable to hope that similar coatings might also be produced on other materials or that thin coatings of Inconel might be applied to other materials.

Although many data on the emissivity of surfaces are to be found in technical literature, the data are in large measure unsuited for application to the radiative cooling of aircraft. The information is often given only for a single temperature, whereas the emissivity of metal surfaces in particular is known to vary appreciably with temperature and time at temperature, partly because of progressive oxidation of the surface at elevated temperatures in air. The literature affords little information regarding the chemistry of coatings of high emissivity, their mechanical properties such as smoothness and adherence, their stability, and their

resistance to cracking and flaking off under repeated heating and cooling at rapid rates.

In view of these considerations, the Pilotless Aircraft Research Division of the Langley Aeronautical Laboratory has begun the investigation of high-emissivity surfaces from the viewpoint of their application to the cooling of supersonic and hypersonic aircraft. Apparatus suitable for such research was not found to be commercially available. Accordingly, appropriate apparatus, described herein, was designed after study of the types of apparatus heretofore employed. Most previous investigations of emissivity have employed either the "filament-in-vacuum" apparatus or the "reference-black-body" apparatus. In the filament-in-vacuum apparatus, the total hemispherical emissivity is derived from measurements of the power input to an electrically heated wire specimen in a vacuum because the wire specimen loses energy primarily as radiation. The variation of the electrical resistance of the wire with temperature is usually employed to determine the temperature of the radiating wire. For many materials the resistance is found not to be a unique function of temperature with the result that reliable determination of the temperature presents difficulties. In the reference-black-body method, the emissivity is determined by comparison of the intensity of the radiation emitted by the test specimen with that emitted by a body of known emissivity, which comparison body is usually a black body of unit emissivity. In this method the principal difficulty is the construction of the reference black body, and reliance is placed primarily upon theory that it is a black body. However, the method is suitable for investigating the variation of the emissivity with time at elevated temperature of a large variety of materials when heated in air and accordingly was selected as being the most suitable method for the purposes here intended. Insofar as possible, commercially available components were used in construction of the apparatus in order that the apparatus may be readily and economically duplicated by others, in consideration of the rapidly expanding need for emissivity data. The theory underlying the operation and design of the apparatus is given.

Investigations of the total hemispherical emissivity of Inconel and Inconel X are reported in view not only of the importance of the data, but also as examples of the methods of performing such investigations with the apparatus. Some other recent measurements of the emissivity of Inconel are reported in reference 4 by a modification of the filament-in-vacuum method and in reference 5 by the reference-black-body method. In both instances repeatable results were not obtained, indicating the desirability of further investigation.

SYMBOLS AND ABBREVIATIONS

Symbols

A	area, sq ft
d	diameter of circular surface, ft
f	radiation flux, Btu/(sq ft)(sec)
P	point on surface of hemisphere of radius r
Q	quantity of radiant energy, Btu
R	rate of radiant energy emission, Btu/sec
r	radius of hemisphere, ft
S	area of hemisphere of radius r, sq ft
T	absolute temperature, $^{\circ}R$
X,Y,Z	Cartesian coordinate axes
ϵ	total hemispherical emissivity
λ	wavelength, microns
σ	Stefan-Boltzmann radiation constant, Btu/($^{\circ}R^4$)(sq ft)(sec)
ϕ	elevation angle measured from normal to surface, radians
ψ	azimuth angle, radians

Subscripts:

b	black body
0	at $\phi = 0$
u	surface of unknown emissivity

Abbreviations

A	ammeter

amp	ampere
B	battery
B_s	standard cell
cps	cycles per second
C.J.	cold junction
G	galvanometer
H.J.	hot junction
v	volt

THEORY OF MEASUREMENT OF TOTAL HEMISPHERICAL EMISSIVITY

Preface

In this section is presented the theory underlying the experimental apparatus and techniques employed to measure the total hemispherical emissivity of surfaces. The theory, although not new, is presented in moderate detail for the convenience of the reader because it is not readily available inasmuch as it is scattered through a large quantity of technical literature in which there exists neither consistency of terminology nor clear distinction between the older empirical theories and the modern concepts. The theory as presented herein is based upon modern concepts with a compatible and consistent terminology.

Total Hemispherical Emissivity

The modern quantum theory of thermal radiation developed by Planck yields all the earlier developed laws of thermal radiation (ref. 6), including the Stefan-Boltzmann law. The Stefan-Boltzmann law, in conformity with Planck's law, gives the quantity of energy Q emitted as thermal radiation by a surface as

$$Q = \epsilon\sigma T^4 At \tag{1}$$

In equation (1), ϵ is the total hemispherical emissivity of the surface, σ is the Stefan-Boltzmann radiation constant, T is the absolute temperature of the surface, A is the area of the surface, and t is the length of time during which radiation occurs.

The dimensionless coefficient ϵ is termed the total hemispherical emissivity to indicate that it applies to the total radiation of all wavelengths emitted from any element of surface in all directions from the surface over the entire solid angle of a hemisphere. It is the efficiency of the surface as an emitter of thermal radiation. A surface which emits the theoretical maximum amount of energy is termed a "black body" and has a total hemispherical emissivity of unity. Conversely, a surface which emits no thermal radiation is termed a "white body" and has a total hemispherical emissivity of zero. Actual surfaces lie between these theoretical extremes.

Early investigations of the thermal radiation of actual surfaces gave rise to the concept of the "gray body." A gray body is visualized as an assemblage of infinitesimally small areas, some of which are black bodies and the remainder of which are white bodies. By varying the proportion of black areas to white areas, it is theoretically possible to obtain on a macroscopic scale gray bodies having any value of total hemispherical emissivity between the theoretical extremes of zero and unity. Implicit in the concept of gray bodies is that their spectral hemispherical emissivity, that is, their efficiency as radiators at any given wavelength, is a constant independent of wavelength. Since the total hemispherical emissivity is simply the summation of the spectral hemispherical emissivity over all wavelengths emitted, the total hemispherical emissivity of a gray body is a constant. Later investigations have disclosed that the spectral hemispherical emissivity of actual surfaces frequently varies with wavelength. Since the range of wavelengths emitted varies with temperature, the total hemispherical emissivity of actual surfaces must be regarded as a coefficient which may vary with temperature. Accordingly, real surfaces cannot be regarded as gray bodies as has been done frequently in the past. Throughout this report the total hemispherical emissivity ϵ of actual surfaces is regarded in this more modern view as being a coefficient that may vary with temperature.

General Outline of Method of Measurement of Total Hemispherical Emissivity

From equation (1), the rate of emission R of thermal radiation from any surface is

$$R = \frac{Q}{t} = \epsilon\sigma T^4 A \tag{2}$$

From equation (2) the total hemispherical emissivity ϵ is

$$\epsilon = \frac{R}{\sigma T^4 A} \tag{3}$$

Accordingly, ϵ may be experimentally evaluated if R, T, and A can be measured. No difficulty is encountered in measuring the absolute temperature T and the area A of a radiating surface. However, it is difficult to devise apparatus capable of measuring the absolute value of the rate of emission R.

Theoretically, a cavity having a small opening emits black-body radiation through its opening when the inner surfaces of the cavity are at uniform temperature (ref. 7, pp. 24 to 26). Such a black-body-radiation source affords a standard of comparison against which the rate of emission of a surface of unknown total hemispherical emissivity may be measured. With the comparison black body denoted by the subscript b and the surface of unknown total hemispherical emissivity by the subscript u, the ratio of their emissivities is obtained from equation (3) as

$$\frac{\epsilon_u}{\epsilon_b} = \frac{R_u}{R_b} \frac{T_b^4 A_b}{T_u^4 A_u}$$

Because the total hemispherical emissivity of a black body is unity, this equation reduces to

$$\epsilon_u = \frac{R_u}{R_b} \frac{T_b^4 A_b}{T_u^4 A_u} \tag{4}$$

The method of determination of the total hemispherical emissivity by comparison with a black body, as expressed by equation (4), is the basis of the technique herein employed. If the temperatures and the areas of the unknown surface and the black body are made equal, equation (4) reduces further to

$$\epsilon_u = \frac{R_u}{R_b} \tag{5}$$

when

$$T_b = T_u$$

$$A_b = A_u$$

under which conditions the method becomes simply the determination of the ratio of the rates of emission R_u/R_b.

Relation Between Rate of Emission and Radiant Flux

A relationship exists between the rate of emission R, required in equation (4) or (5), and the radiation flux f at a distance from the emitting surface. This relationship may be developed as follows.

Let there be located, as shown in figure 2, a circular surface of area A with its center at the origin of the Cartesian coordinate axes X, Y, and Z and lying in the XY-plane. Let there be circumscribed about the circular surface a hemisphere whose center is at the origin of the coordinate axes and whose radius r is large in comparison with the diameter of the circular surface.

In accordance with the law of the conservation of energy, any radiation emitted from the circular surface must pass through the surface of the hemisphere. Therefore, if f denotes the radiation flux at the surface of the hemisphere, that is, the quantity of radiant energy per unit of area per unit of time, the integral of the flux over the surface of the hemisphere must be the rate of emission R of the circular area.

Let the position of any point P on the hemisphere be defined by the azimuth angle ψ and the elevation angle ϕ as shown in figure 2. Increasing the elevation angle ϕ by the differential amount $d\phi$ causes the point P to describe upon the hemisphere the differential arc $r\,d\phi$. Increasing the azimuth angle ψ by the differential amount $d\psi$ causes the point P, which point is located at the normal distance $r \sin \phi$ from the Z-axis, to describe upon the hemisphere the differential arc $d\psi\, r \sin \phi$. Accordingly, a differential area dS of the hemisphere is given by

$$\begin{aligned} dS &= (r\,d\phi)(d\psi r \sin \phi) \\ &= r^2(\sin \phi)d\phi\, d\psi \end{aligned} \tag{6}$$

The product of the radiation flux f and the differential area dS is the quantity of radiant energy per unit of time passing through the differential area dS. The integral of $f\,dS$ over the entire hemisphere is the rate of emission R of the circular area; that is,

$$R = \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f\,dS$$

Upon substitution of equation (6), this equation becomes

$$R = r^2 \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f(\sin\phi)d\phi\,d\psi \tag{7}$$

Thus, the rate of emission R is related to the flux f by equation (7).

Equation for Total Hemispherical Emissivity in Terms of Radiant Flux

The ratio R_u/R_b occurring in the general emissivity equation (4) and in the restricted emissivity equation (5) may be expressed in terms of the flux f_u of the unknown surface and the flux f_b of the comparison black body by means of equation (7) as

$$\frac{R_u}{R_b} = \frac{r_u^2 \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f_u(\sin\phi)d\phi\,d\psi}{r_b^2 \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f_b(\sin\phi)d\phi\,d\psi} \tag{8}$$

In the experimental measurement of R_u/R_b by equation (8), r_u can readily be made equal to r_b. With this simplification, substitution of equation (8) into equation (5) yields the equation for measurement of the total hemispherical emissivity ϵ_u of an unknown surface in terms of the fluxes f_u and f_b as

$$\epsilon_u = \frac{\int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f_u(\sin\phi)d\phi\, d\psi}{\int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f_b(\sin\phi)d\phi\, d\psi} \tag{9}$$

when

$$T_b = T_u$$

$$A_b = A_u$$

$$r_b = r_u$$

Simplification Resulting From Conformance With Lambert Cosine Law by Reference Black Body

A black body emits the theoretical maximum amount of thermal radiation. It can do so only by emitting with maximum, and therefore equal, intensity at all angles to its surface. Accordingly, the black-body radiation flux f_b in equation (9) may be expressed as a function of the elevation angle ϕ as follows.

In figure 2, let the circular emitting surface be a black body having a diameter d which is small in comparison with the radius r of the hemisphere. When viewed from the point of intersection of the Z-axis with the surface of the hemisphere, that is, from the point where $\phi = 0$, the emitting surface is seen as a circle whose area is $\pi d^2/4$. When viewed from any point on the hemisphere other than $\phi = 0$, the emitting surface is seen as an ellipse whose major diameter is d and whose minor diameter is $d \cos\phi$. The area of such an ellipse is $(\pi d^2 \cos\phi)/4$. Let the flux at $\phi = 0$ be denoted by $f_{b,0}$, and that at $\phi \neq 0$ by f_b. For equal radiating ability of the circular black-body surface in all directions, the flux is proportional to the area viewed, or

$$\frac{f_b}{f_{b,0}} = \frac{\frac{\pi d^2 \cos\phi}{4}}{\frac{\pi d^2}{4}} = \cos\phi$$

so that

$$f_b = f_{b,0} \cos \phi \tag{10}$$

Equation (10) is recognized as being the Lambert cosine law for diffusely radiating surfaces.

Substitution of equation (10) into equation (9) permits integration of the denominator of equation (9), whereupon equation (9) reduces to

$$\epsilon_u = \frac{1}{\pi} \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} \frac{f_u}{f_{b,0}}(\sin \phi) d\phi \, d\psi \tag{11}$$

when

$$T_b = T_u$$

$$A_b = A_u$$

$$r_b = r_u$$

Thus, the flux emitted by the comparison black body need be measured only at $\phi = 0$. This simplification greatly facilitates the design of the comparison black body and reduces the number of measurements required upon it.

Special Case of Surfaces Which Emit Diffusely

Many surfaces are found experimentally to obey the Lambert cosine law of diffuse emission. For such surfaces, equation (11) may be simplified as follows.

Let the flux at $\phi = 0$ of the unknown surface be $f_{u,0}$, and that at any finite elevation angle be f_u. In analogy to equation (10), for diffuse emission,

$$f_u = f_{u,0} \cos \phi \tag{12}$$

Substituting equation (12) into equation (11) permits integration and gives

$$\epsilon_u = \frac{f_{u,0}}{f_{b,0}} \tag{13}$$

for

$$T_b = T_u$$

$$A_b = A_u$$

$$r_b = r_u$$

$$\epsilon_u = \text{Diffuse}$$

Thus, the total hemispherical emissivity of surfaces which emit diffusely in accordance with the Lambert cosine law may be simply measured by measuring the ratio of their normal total flux $f_{u,0}$ to that of a black body $f_{b,0}$.

That a surface of unknown emissivity does emit diffusely in accordance with the Lambert cosine law may be readily established experimentally by measuring f_u at various values of ϕ and observing that $f_u/f_{u,0} = \cos \phi$ in accordance with equation (12). This comparison may be readily done graphically because the locus of equation (12) plotted on the Cartesian coördinates X and Y is a circle of diameter $f_{u,0}$ whose center lies on the Y-axis at $y = f_{u,0}/2$. When the Lambert cosine law is not fulfilled, equation (11) must be used.

APPARATUS FOR MEASUREMENT OF TOTAL HEMISPHERICAL EMISSIVITY

Preface

In this section is presented a description of the apparatus constructed for measuring the total hemispherical emissivity of surfaces in accordance with the theory of the technique set forth in the preceding section. The apparatus is a compromise among several factors. It has not been designed with the objective of attaining the highest possible precision, but rather a precision adequate for most engineering purposes in order that it may possess the following features: It is designed to be readily adaptable to the measurement of the emissivity of a large variety of surfaces that can be produced upon, or mounted upon, various metals in order that the utility of these surfaces for the radiative cooling of aircraft may be explored. It is constructed insofar as possible of commercially available components in order that it be readily duplicable. Accordingly, the description of the apparatus is given in sufficient detail to provide not only understanding of the measurements obtained but also information sufficient for the apparatus to be duplicated in all essential features.

General Description of Apparatus

A general view of the complete apparatus, with identification of the principal components, is shown in figure 3. A schematic wiring diagram of the complete apparatus is given in figure 4. The complete apparatus consists of the following three groups of components: first, the test specimen with its associated holder, the electric power supply for heating the specimen by means of a heavy current through it, and a thermocouple together with a self-balancing potentiometer and temperature indicator for determining the temperature of the specimen; second, the reference black body with its associated electric furnace for heating it and a thermocouple for determining the temperature of the black body with the same self-balancing potentiometer and temperature indicator as used with the test specimen; third, the thermopile for comparing the intensity of radiation emitted by the test specimen with that emitted by the black body, the thermopile's associated water-cooled shield and aperture, and the precision potentiometer for measuring the potential developed by the thermopile. These three groups of apparatus are described in detail in the following sections.

Test Specimen and Associated Apparatus

The surface whose emissivity is to be measured is prepared upon the front face of a flat strip of metal and mounted in the specimen holder identified in figure 3 and shown in detail in figures 5 and 6 with a specimen installed. The specimen is heated to the desired temperature by running through it a suitable electric current obtained from the specimen heater power supply which is also shown in detail in figure 5. As indicated in the circuit diagram of figure 4, the heater power supply consists of a variable autotransformer (Superior Electric Co. (Bristol, Conn.) powerstat, model 1256L-25-B) feeding a stepdown transformer (Central Transformer Co. (Chicago 7, Ill.), model G1-117). The input of the autotransformer is 440 volts, 60-cycle, single-phase current, and its output is adjustable from zero to 440 volts at a maximum current of 28 amperes. The stepdown transformer has an output of 4 volts at 440 volts input and a maximum output current of 600 amperes. The output of the stepdown transformer is connected to the test specimen by means of cables and clamps as shown in figures 5 and 6. The specimen is electrically insulated from the jaws of the specimen holder. The jaws permit the specimen to expand freely in the longitudinal direction so that the specimen does not buckle under thermal expansion. The jaws are also rotatable about the longitudinal axis of the specimen so that the specimen may be alined relative to the optical axis of the thermopile. This arrangement permits use of specimens of various lengths, widths, and thicknesses which, together with the adjustable power supply, makes possible the heating of specimens of almost every type of metal to all temperatures up to their melting temperature.

The temperature of each specimen is measured by means of a thermocouple attached to the rear surface of the specimen opposite the small area on the front surface of the specimen that is viewed by the thermopile. In figure 7 are shown details of a typical thermocouple installation on a test specimen. The thermocouple is made of calibrated chromel and alumel wires of No. 30 gage (American wire gage) wire. In order to insure that the heat conducted away from the thermocouple junction by the thermocouple wires is negligible, so that accurate specimen temperature measurements are obtained, the smallest diameter thermocouple wires that can be used conveniently are employed, and the wires are led away from the thermocouple junction approximately parallel to the surface of the specimen in the longitudinal direction to minimize the thermal gradient in the wires. As shown in figure 7, the thermocouple junction is formed by electrically spotwelding the ends of the chromel and alumel wires to the test specimen. The junction points are located as accurately as possible on a line perpendicular to the longitudinal axis of the specimen. If the specimen were heated by a direct electric current, any misalinement of the junction points would impose upon the thermocouple junction an electrical potential because of the potential drop in the longitudinal direction along the specimen. In order to avoid this source of error in measurement

of the specimen temperature, alternating current was selected for heating the specimen. With alternating current any misalinement of the thermocouple-junction points imposes upon the direct-current output of the thermocouple an alternating-current component which is not sensed by the potentiometer employed for measurement of the thermocouple electromotive force.

As indicated in figure 4, the temperature measured by the thermocouple may be read with a commercial self-balancing potentiometer containing an automatic cold junction (Instrument Division, Minneapolis-Honeywell Regulator Co. (Philadelphia, Pa.) Brown potentiometer, pyrometer model no. 156X15P) shown in figure 3; or alternatively with a self-balancing, recording, and indicating potentiometer containing an automatic cold junction (Instrument Division, Minneapolis-Honeywell Regulator, Co. (Philadelphia, Pa.) Brown potentiometer, model no. 153X17V-X-9) also shown in figure 3. The recording potentiometer is employed primarily for monitoring the temperature of metal test specimens having oxidized surfaces prepared by electrically heating the specimen in air for long durations of time while installed in the specimem holder.

Reference Black Body and Associated Apparatus

The reference black body is constructed upon the theoretical principle frequently employed (ref. 7, pp. 24 to 26) that the radiation emitted from a small aperture in a large chamber whose interior surfaces are uniformly heated is black-body radiation and is independent of the emissivity of the interior surfaces of the chamber. High-precision reference black bodies have been constructed upon this principle (ref. 8) but are difficult to use. For the rapid exploratory work and measurements of interest in this investigation, an easily used reference black body was produced by placing the conical target shown in figure 8 within the commercial tubular gas-analysis furnace (Lindberg Engineering Co. (Chicago 12, Ill.) combustion-tube laboratory furnace, type CF-1) shown in figures 3 and 9.

The black-body target, shown in figure 8, is an Inconel hollow cone of 6 inches overall external length whose internal surface has a total apex angle of 8.6° and a base diameter of 1 inch. It has been heavily oxidized by heating to high temperature in air for a long duration to give it a stable surface of high emissivity. A chromel-alumel thermocouple of No. 30 gage wire (American wire gage) is electrically spotwelded to the exterior surface of the target so that its temperature may be measured by using the same self-balancing potentiometers as are employed with the test specimen, as indicated in figure 4. The electric furnace, shown in figures 3 and 9, into which the target fits is essentially a ceramic tube 1.25 inches in internal diameter and 17 inches long that is surrounded and heated by calrod electric heating elements deriving power from a variable transformer of 1,500 watts capacity operating on 120 volts, 60-cycle,

single-phase current, as shown in the wiring diagram of figure 4. The target is placed near the center of the ceramic tube, and the interior surface of the conical target is viewed by the thermopile, as shown in figure 9, through a 3/4-inch-diameter aperture in a 1/4-inch-thick asbestos cover plate placed over the end of the ceramic tube. By this arrangement the interior surface of the conical target is in effect a chamber whose walls are at uniform temperature, which chamber is in turn within a larger chamber of approximately uniform and equal wall temperature formed by the ceramic tube, thus approximating the theoretical chamber that emits radiation as a black body.

Thermopile and Associated Apparatus

The thermopile, water-cooled shield, and test specimen, shown in figure 6, together form the optical system shown schematically in figure 10(a), in which the vertical scale is five times the horizontal scale for clarity. The thermopile, optical stop, calcium fluoride lens, and housing in which they are mounted, as indicated in figure 10(a), are components from a commercial pyrometer (Industrial Division, Minneapolis-Honeywell Regulator Co. (Philadelphia 44, Pa.) Brown radiamatic pyrometer, model RL-1). These parts, together with the water-cooled shield which also forms an optical stop, are rigidly mounted relative to each other on a base plate so that they may as a unit be attached to a pivoted arm on the specimen holder as shown in figure 6 for measuring the radiation from the test specimen, or as a unit be attached to the black-body furnace as shown in figure 9 for measuring the radiation emitted by the black-body target.

A calcium fluoride lens is employed in the optical system of the radiation-sensing thermopile, as indicated in figure 10(a). The transmittance of calcium fluoride as a function of wavelength, as given in reference 9, is shown in figure 11(a). Beneath it is plotted in figure 11(b) the spectral intensity of a black body as a function of wavelength for five different temperatures. By comparison of figures 11(a) and 11(b), it is seen that the calcium fluoride lens permits the optical system to be highly transparent to radiations of the wavelengths emitted over the range of temperatures of interest for the cooling of aircraft. The lens is located so that the radiating surface and the optical stop are at its conjugate foci, as indicated by the extreme ray paths shown in figure 10(a). When the radiating surface is normal to the optical axis, only those rays emanating from a 0.62-inch-diameter area on the radiating surface are permitted by the aperture of the water-cooled shield and the optical stop to pass through the aperture of the optical stop and fall upon the thermopile. The optical system thus restricts the radiation incident upon the thermopile to rays that deviate only by small angles from the optical axis, so that measurements may be made of the variation of intensity of radiation with the elevation angle ϕ

between the optical axis and the radiating surface. For such measurements, the pivoted arm shown in figure 5, upon which the system mounts as shown in figure 6, is pivoted about an axis coplanar with the test surface of the specimen. The water-cooled shield prevents unwanted radiation from falling upon and heating the housing containing the thermopile. The shield is equipped with a shutter as shown in figure 6 so that radiation can be permitted to pass through its aperture only for the brief time intervals required for obtaining measurements.

The thermopile consists of 10 hot- and cold-junction pairs of chromel-constantan arranged radially in a plane parallel to and about 0.032 inch behind the aperture of the optical stop. Figure 10(b) is an enlarged view of the thermopile hot junctions showing their orientation relative to the aperture in the optical stop as seen when viewed along the optical axis toward the test specimen. Each hot junction is flattened to increase its area exposed to radiation and blackened to maximize its absorptivity of radiation. The entire interior of the thermopile housing is also optically black to prevent reflections of radiation. The cold junctions of the thermopile are protected from radiation by being behind the optical stop as shown in figure 10(a) and are in thermal contact with the housing so that their temperature is that of the housing. As indicated in figures 4 and 10(a), temperature-compensating resistors in thermal contact with the housing are connected in series and in parallel with the thermopile so that its output potential is very nearly independent of the temperature of its cold junctions, and hence of the housing, up to housing temperatures of 250° F. The protection afforded by the water-cooled shield was found to prevent the housing temperature from rising more than a few degrees above room temperature.

The potential developed by the thermopile is measured with the conventional precision manual bucking potentiometer (Rubicon Co.(Ridge Ave. at 35th St., Philadelphia 32, Pa.), Rubicon portable precision potentiometer, model 2703) shown in figures 3 and 9 and in the wiring diagram of figure 4.

CALIBRATION OF APPARATUS

Need for Calibration

For determination of the total hemispherical emissivity of surfaces that emit diffusely in accordance with the Lambert cosine law, the apparatus must measure the flux ratio $f_{u,0}/f_{b,0}$ as shown by equation (13); and, for surfaces that emit in any other manner, it must measure the flux ratio $f_u/f_{b,0}$ as shown by equation (11). Although the need for

only flux ratios materially lessens the requirements upon the instrumentation in that only relative rather than absolute values of the fluxes need be measured by it, it is nevertheless necessary to calibrate the response of the apparatus to fluxes of various relative intensities, for it is not valid to assume that the response is directly proportional to the flux. Thus, the response of the apparatus need be calibrated only in terms of an arbitrary relative scale of flux intensity.

Method of Calibration

The thermopile and its optical system constitute the radiation-flux sensing components of the apparatus. Their response is the electrical potential developed by the thermopile. The required calibration must therefore be a graph of potential developed by the thermopile against relative flux intensity, so that when the potentials resulting from exposing the apparatus to two fluxes of unknown magnitudes are measured, the ratio of the fluxes may be determined for use in equation (11) or (13). Such a calibration may readily be made with the reference black body.

For a black body the total hemispherical emissivity is unity, so that its rate of emission R_b is, in accordance with equation (2),

$$R_b = \sigma T_b^4 A_b \tag{14}$$

Since a black body obeys the Lambert cosine law as expressed by equation (10), its rate of emission in terms of its normal flux $f_{b,0}$ is given by equation (7) as

$$R_b = r_b^2 \int_{\phi=0}^{\phi=\frac{\pi}{2}} \int_{\psi=0}^{\psi=2\pi} f_{b,0} \cos \phi \sin \phi \, d\phi \, d\psi$$

which integrates to

$$R_b = \pi r_b^2 f_{b,0} \tag{15}$$

Equating equations (14) and (15) gives

$$f_{b,0} = \frac{\sigma T_b^4 A_b}{\pi r_b^2} = K T_b^4 \tag{16}$$

Because the dimensions of the thermopile optical system are held constant, A_b and r_b are constants, which, together with the constants σ and π, comprise the constant K in equation (16). Thus, the flux from the black body incident upon the thermopile and its optical system is proportional to the fourth power of the absolute temperature of the black body.

Although the absolute value of K, and hence of the flux, may be determined from the values of the constants comprising K, such need not be done because only relative values of flux are required. Relative flux values corresponding to black-body temperatures may be determined by equation (16) by arbitrarily choosing a convenient numerical value for K. Since there is a thermopile potential corresponding to each value of black-body temperature, there is also a relative flux value corresponding to each value of thermopile potential. Therefore, the required calibration of thermopile potential as a function of relative flux intensity may be determined by means of the black body.

Calibration

The calibration of the radiation-flux measuring system, consisting of the thermopile and its optical system, is given in figure 12. Three calibrations of thermopile potential as a function of the black-body temperature are shown to indicate the degree of consistency and stability of the system. The first calibration was made before the emissivity measurements herein reported were begun, the second approximately midway through the course of measurements, and the third after completion of the measurements. There being no distinguishable difference between the three calibrations, the single curve shown in figure 12 was taken as being the calibration and was used in reduction of the emissivity measurements. In order that the scale of relative flux intensity consist of numbers greater than unity, the black-body flux intensity at 1,000° R was chosen as unit flux intensity for calculation of the relative-flux-intensity scale given in figure 12.

INVESTIGATION OF TOTAL HEMISPHERICAL EMISSIVITY OF INCONEL

Preface

The first measurements of emissivity made with the apparatus described herein were performed upon Inconel because of its utility as a material of construction of aerodynamic-heat-transfer research models as described in reference 10 and because of its general utility as a

heat-resistant material in many diverse fields, which creates need for knowledge of its emissivity. The nominal chemical composition of wrought Inconel, as given in reference 11, is given by the following table (all values are given in percent):

Nickel	77.0
Chromium	15.0
Iron	7.0
Manganese	0.25
Copper	0.2
Silicon	0.25
Carbon	0.08
Sulfur	0.007

Preparation of Test Specimens

When Inconel is heated in air to high temperatures, yet is below that temperature at which it suffers loss of mechanical properties to the extent that it cannot be used, it is observed to undergo a discoloration of its surface which alters its emissivity. Although the chemistry of this surface alteration was not investigated, it presumably is one of oxidation and, accordingly, is termed an oxidized surface herein. A preliminary investigation revealed that when samples of Inconel sheet are heated in air without prior meticulous cleansing, the oxidation is erratic. Sometimes there is formed a greenish-gray surface that is powdery, loosely adherent, and generally unsuitable as a surface having stable emissivity characteristics for the radiative cooling of aircraft. At other times there is formed a bluish-black surface that is smooth, thin, strongly adherent, resistant to mild abrasion, capable of withstanding rapid heating and cooling without cracking or spalling, and generally suitable as a surface for use in the radiative cooling of aircraft. The following procedure for consistently producing this bluish-black oxidized surface was developed and used in preparing the test specimens.

By trial, it was determined that Inconel specimens 9 inches long, $1\frac{1}{2}$ inches wide, and 0.030 inch thick could readily be heated to near their melting temperature in the specimen holder by the specimen heater power supply. Accordingly, specimens of this size were prepared from sheet Inconel and their surfaces thoroughly cleansed of any trace of mill scale and other contamination by immersion in an etching solution, at room temperature, composed of 1 gallon of commercial nitric acid of 70 percent HNO_3, $1\frac{1}{4}$ pints of commercial hydrofluoric acid of 60 percent HF, and 1 gallon of water. After removal and rinsing with water, the specimens were polished to give them a smooth surface. They were then again immersed in the etching solution to remove all contamination resulting

from the polishing, and thereafter precautions were taken to prevent contamination. Upon removal from the etching solution they were scrubbed first with methyl alcohol and then with deionized distilled water by using absorbent cotton swabs and handling the specimens only with clean cotton gloves. Following air drying, the specimens were placed upon a cleansed Inconel rack and inserted in a clean electric furnace preheated to between 1,950° F and 2,000° F and having an air atmosphere. The degree of oxidation of the specimen surfaces being dependent upon the length of time in the furnace, specimens having various degrees of oxidation were prepared by withdrawing specimens from the furnace after time intervals ranging from 3 to 13 minutes. After oxidation, the thermocouple used for measurement of specimen temperature was installed on each specimen.

Tests of Stability of Emissivity of Oxidized Inconel

Preliminary measurements of lightly oxidized Inconel specimens disclosed that their emissivity increased with time when they were held at an elevated temperature in air, indicating progressive oxidation. Accordingly, the length of time that Inconel must be oxidized in the furnace by the procedure employed in preparing the test specimens in order to establish a stable oxidized surface was investigated. The total normal emissivity, that is, the emissivity at $\phi = 0$, was measured at a specimen temperature of 650° F. The specimen was then heated to 2,000° F and held at this temperature in air for 30 minutes. The specimen was then cooled to 650° F and its total normal emissivity measured a second time. The first measurement of total normal emissivity divided by the second measurement was taken as an index of the stability of the oxidized surface.

In figure 13 is plotted as the ordinate the measured index of stability of the oxidized Inconel surface and as the abscissa the time in minutes that the test specimens were held in the electric furnace in their preparation. It is seen that specimens which had been oxidized in the furnace for 9 minutes or longer exhibited no change in their total normal emissivity measured at 650° F after being held at 2,000° F for 30 minutes in air.

The following hypothesis is suggested as explaining the observed emissivity stability behavior of Inconel shown in figure 13. The increase in the stability index with furnace oxidation time up to 9 minutes indicates that specimens oxidized for less than 9 minutes in the furnace experienced an increase in emissivity upon being held at 2,000° F for 30 minutes in air. This increase indicates that the emissivity of unoxidized Inconel is less than that of oxidized Inconel at the test temperature of 650° F. Since emissivity is a property of the surface, it is to be expected that, as the unoxidized surface is replaced by an oxidized surface of higher emissivity, the emissivity will increase until the unoxidized metal no longer shows through the oxide coating, whereupon no

further change in emissivity of the surface is to be expected. In the light of this hypothesis, oxidation in the furnace for 9 minutes or more produced an oxide coating of sufficient thickness to replace completely the lower emissivity of the unoxidized metal with that of the oxide.

Accordingly, all further tests were performed upon specimens that had been oxidized by heating at 1,950° F to 2,000° F in air for 9 minutes or more. It was observed visually that such stabilized specimens appeared not to experience continued growth in the thickness of their oxide coating despite repeated and prolonged heating, suggesting that the coating protected the metal from further oxidation. However, weighing of a specimen before and after being maintained at an elevated temperature in air would be required to verify this observation precisely.

Tests of Conformity of Emission of Stably Oxidized Inconel With Lambert Cosine Law

In order to determine whether or not stably oxidized Inconel emits thermal radiation diffusely in accordance with the Lambert cosine law, measurements were made of the intensity of radiation at various elevation angles ϕ to the surface of two test specimens oxidized for 9 and 13 minutes, respectively, over a range of specimen temperatures from 800° F to 1,800° F.

Because the optical system of the radiation-sensing thermopile accepts emission from a circular area of the specimen when viewing the specimen at $\phi = 0$, it views a larger elliptic area when $\phi \neq 0$. Since equations (11) and (13) are based upon the thermopile receiving radiation from a constant area of the emitting surface, the measurements made at $\phi \neq 0$ were corrected to a constant area as follows: As in the derivation of equation (10), the area A_ϕ viewed when $\phi \neq 0$ divided by the area A_0 viewed at $\phi = 0$ is

$$\frac{A_\phi}{A_0} = \frac{1}{\cos \phi}$$

Since the radiation received by the thermopile is proportional to the area viewed, measurements of the relative flux intensity at $\phi \neq 0$ were divided by $1/\cos \phi$ to correct them to an area equal to that viewed by the thermopile at $\phi = 0$.

In figure 14 is plotted as a function of ϕ the ratio of the relative flux intensity measured at several elevation angles ϕ to that

at $\phi = 0$. In order to test conformity with the Lambert cosine law, there is plotted as the circle in figure 14 the Lambert cosine law as expressed by equation (12). The experimental points shown in the right half of figure 14 were measured upon a test specimen oxidized for 9 minutes, and those on the left upon a specimen oxidized for 13 minutes. For both specimens, experimental points are shown for measurements made at specimen temperatures of 800° F, 1,000° F, 1,200° F, 1,400° F, 1,600° F, and 1,800° F. Both the 9- and 13-minute oxidized specimens are seen to emit in conformity with the Lambert cosine law of diffuse emission at all temperatures investigated.

Measurements of Total Hemispherical Emissivity of Stably Oxidized Inconel

Stably oxidized Inconel having been found to emit diffusely in accord with the Lambert cosine law, its total hemispherical emissivity can be readily measured by using equation (13). The measurements so obtained over the temperature range from 600° F to 1,800° F are shown in figure 15 for two specimens oxidized in air at 1,950° F to 2,000° F, one for a duration of 9 minutes and the other for 13 minutes. No measurable difference is observed between the specimens oxidized 9 and 13 minutes, confirming the stability measurements of figure 13. The total hemispherical emissivity of the stably oxidized Inconel is shown in figure 15 to increase linearly with temperature from a value of 0.69 at 600° F to 0.82 at 1,800° F. Stably oxidized Inconel is thus found to possess a moderately high total hemispherical emissivity that is a definite function of temperature.

The small scatter of the experimental points and the close agreement between the two specimens indicate random errors of 1 to 2 percent. The possibility exists of systematic errors which might cause the general level of the measurements to be in error. In this regard, the method here employed of comparison with a reference black body could give rise to systematic errors if the reference body were not truly a black body. This is readily seen from the derivation of equation (4) wherein the emissivity of the reference black body ϵ_b is assumed to be unity. If this assumption is not made, ϵ_b appears as a factor in the right-hand side of equation (4) and subsequent equations derived from it. Therefore, if ϵ_b is less than unity, the values of total hemispherical emissivity shown in figure 15 are too large, and the correct values are obtained by multiplying by the value of ϵ_b. Since the reference black body was designed on the basis of theory, as described previously, it is highly unlikely that ϵ_b could in any event be less than 0.95 since values this high are readily attained on oxidized cast iron and rough steel plates.

Thus, due to systematic error, the values of total hemispherical emissivity shown in figure 15 cannot be too low, and it is highly unlikely that they could be too high by more than 5 percent.

INVESTIGATION OF TOTAL HEMISPHERICAL EMISSIVITY OF INCONEL X

Preface

The total hemispherical emissivity of Inconel X was investigated because Inconel X possesses superior strength properties at elevated temperatures as compared with Inconel while retaining many other desirable properties of Inconel. Inconel X is thus interesting as a material of construction of high-supersonic- and hypersonic-speed aircraft subject to aerodynamic heating which may utilize radiative cooling to maintain structurally tolerable temperatures. The high-temperature properties of Inconel X may also result in its use in other fields with resultant need for information on its emissivity characteristics. The composition of Inconel X as given in reference 12 is given by the following table (all values are given in percent):

Nickel	70.00 minimum
Chromium	14.00 to 16.00
Titanium	2.25 to 2.75
Columbium	0.7 to 1.20
Aluminum	0.4 to 1.00
Iron	5.00 to 9.00
Manganese	0.30 to 1.00
Silicon	0.50 maximum
Copper	0.20 maximum
Carbon	0.08 maximum
Sulfur	0.01 maximum

Preparation of Test Specimens

By preliminary trials it was determined that Inconel X specimens 9 inches long, 1.5 inches wide, and 0.030 inch thick could readily be heated to near their melting temperature in the specimen holder by the specimen heater power supply. Accordingly, specimens of this size were cut from sheet Inconel X and cleansed and polished by using the procedure employed with Inconel described previously. The thermocouple used for measurement of specimen temperature was then installed.

Tests of Stability of Emissivity of Oxidized Inconel X

The stability of the emissivity and the oxidation characteristics of Inconel X were investigated by placing a clean, bright specimen in the specimen holder and subjecting it to the temperature time history shown in figure 16(a) while simultaneously measuring its total normal emissivity which is shown in figure 16(b). As indicated in figure 16(a), the specimen temperature was quickly raised from room temperature at time zero to 900° F, and then in steps of 100° F up to 1,500° F, at which point the temperature was held constant for an hour. The total normal emissivity, as shown in figure 16(b), increased with temperature from a low value characteristic of most bright, white metals; but upon cessation of the temperature increase at 1,500° F, the total normal emissivity continued to rise with time at a decreasing rate so that it tended to approach an equilibrium value. This behavior clearly indicates that the surface of the specimen underwent chemical reaction with the air at elevated temperatures, which reaction is herein termed oxidation, and caused the observed changes in emissivity. The drifting of the emissivity after cessation of temperature change shows clearly that the emissivity is not only a function of temperature, but also of time at temperature. At 75 minutes after start of the test, the temperature of the specimen was again quickly increased from 1,500° F to 1,800° F as shown in figure 16(a), and again the total normal emissivity increased and with the passage of time approached an equilibrium value as shown in figure 16(b). At 136 minutes, the specimen temperature was again increased from 1,800° F to 2,000° F, and again the total normal emissivity increased and approached with the passage of time a steady value. Inspection of the specimen after this test showed that it had developed upon its surface a smooth, thin, dark gray, oxide coating which was strongly adherent and resistant to mild abrasion. Subsequent rapid heating and cooling have shown that the coating is highly resistant to flaking off under rapid changes of temperature.

From the measurements shown in figure 16 it is apparent that when Inconel X is heated to high temperatures in quiescent air its surface undergoes oxidation which increases its total normal emissivity. With the passage of time at elevated temperature, the emissivity approaches a stable value which is characteristic of the temperature. Up to 2,000° F, the limit of the test, the stable emissivity value increases with temperature, the increase becoming less the higher the temperature.

In view of these results, and because for the radiative cooling of aircraft the highest possible total hemispherical emissivity is desired, the temperature of 2,000° F was selected for oxidizing the surface of the Inconel X test specimens whose total hemispherical emissivity would be measured. In order to determine the length of time that the specimens would have to be held at 2,000° F in quiescent air to develop an oxide coating having a stable value of emissivity, a clean unoxidized

specimen was quickly heated in the specimen holder to 2,000° F and measurements were made of the variation of its total normal emissivity with time. The results are shown in figure 17, from which it is seen that a stable value of the total normal emissivity is attained after 30 minutes of oxidation. Accordingly, all further tests were performed upon specimens oxidized in air at 2,000° F for 30 minutes or longer.

Tests of Conformity of Emission of Stably Oxidized Inconel X With Lambert Cosine Law

In order to determine whether or not stably oxidized Inconel X emits thermal radiation in conformity with the Lambert cosine law of diffuse emission, measurements were made of the intensity of radiation at various elevation angles ϕ to the surface of a specimen oxidized in air at 2,000° F for 30 minutes. The measurements were made at specimen temperatures of 600° F, 1,000° F, 1,400° F, and 1,800° F, and corrected for the increase in area of the specimen viewed at $\phi \neq 0$, as described previously. In figure 18 the measurements are shown, and for comparison the Lambert cosine law is plotted as the circle. The measurements are seen to be in close agreement with the Lambert cosine law, from which it is concluded that Inconel X, stably oxidized by heating in quiescent air to 2,000° F for 30 minutes or longer, emits diffusely.

Measurements of Total Hemispherical Emissivity of Stably Oxidized Inconel X

Stably oxidized Inconel X having been found to emit diffusely in accord with the Lambert cosine law, measurements of its total hemispherical emissivity were conveniently made by using equation (13). Measurements so obtained at temperatures from 600° F to 2,000° F are shown in figure 19 for two specimens - one being oxidized in air for 30 minutes at 2,000° F and the other being the specimen that was subjected to oxidation at successively higher temperatures up to 2,000° F, and whose time history is given in figure 16.

Figure 19 shows that the total hemispherical emissivity of Inconel X stably oxidized in air at 2,000° F for 30 minutes or longer varies almost linearly with temperature from a value of 0.895 at 600° F to 0.925 at 2,000° F and thus has over this temperature range a high emissivity well suited for radiative cooling of aircraft. The close agreement between the measurements for the specimen oxidized a long time and that oxidized for the minimum time of 30 minutes required for attainment of stability indicates not only that full stability had been attained by the 30-minute

oxidized specimen, but also that the emissivity is dictated by the highest temperature at which the oxidation is performed irrespective of oxidation at lower temperatures.

As in the case of Inconel, the experimental points for Inconel X shown in figure 16 indicate a random error of 1 to 2 percent, and the systematic error cannot result in values that are too low but may result in values that are too high by an amount that is highly unlikely to be more than 5 percent. By constructing a series of progressively more refined reference black bodies and comparing their emissions, it is theoretically possible to deduce the amount, if any, by which the emissivity ϵ_b of the reference black body herein used departs from its intended value of unity.

CONCLUDING REMARKS

In the investigation reported herein, cooling by means of radiation is theoretically shown to be a promising and powerful means of keeping the temperature of high supersonic and hypersonic aircraft within structurally tolerable values, particularly at high altitudes. Exploitation of radiative cooling requires the development of suitable surfaces having high values of total hemispherical emissivity. It is shown theoretically that the characteristics of the total hemispherical emissivity of surfaces may be readily investigated to high temperatures by comparison with a reference black body.

Relatively simple and easily duplicable apparatus constructed principally from commerically available parts is described by means of which measurements of the total hemispherical emissivity and other emissive characteristics of a large variety of surfaces may be readily investigated. A simple procedure for calibration of the radiation-sensing portion of the apparatus is described and illustrated.

Inconel, when heated in air to temperatures between 1,950° F and 2,000° F for 9 or more minutes, is found to develop a thin oxide coating having stable emissivity characteristics at temperatures up to 2,000° F. This coating does not appear to grow with time at elevated temperature, is strongly adherent, resistant to mild abrasion, resistant to flaking off under rapidly changing temperature, and is approximately as smooth as was the clean metal before oxidation. The coating is found to emit diffusely in accord with the Lambert cosine law at temperatures from 800° F to 1,800° F. It is found to possess a total hemispherical emissivity which varies linearly with temperature from a value of 0.69 at 600° F to 0.82 at 1,800° F. The measurements of total hemispherical emissivity are shown to have a random error of 1 to 2 percent, and, based on the black body used, a systematic error may exist such that

the measurements cannot be low but may be too high by an amount that is unlikely to exceed 5 percent.

Inconel X, when heated in air at temperatures up to 2,000° F for 30 minutes or more, is found to develop a thin oxide coating having stable emissivity characteristics to 2,000° F. This coating does not appear to grow with time at elevated temperatures, is strongly adherent, resistant to mild abrasion, resistant to flaking off under rapidly changing temperatures, and is approximately as smooth as was the clean metal before oxidation. The coating is found to emit diffusely in accord with the Lambert cosine law at temperatures from 600° F to 1,800° F. It is found to possess a total hemispherical emissivity which varies almost linearly with temperature from a value of 0.895 at 600° F to 0.925 at 2,000° F. The measurements of total hemispherical emissivity are shown to have a random error of 1 to 2 percent, and, based on the black body used, a systematic error may exist such that the measurements cannot be low but may be too high by an amount that is unlikely to exceed 5 percent.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., July 22, 1957.

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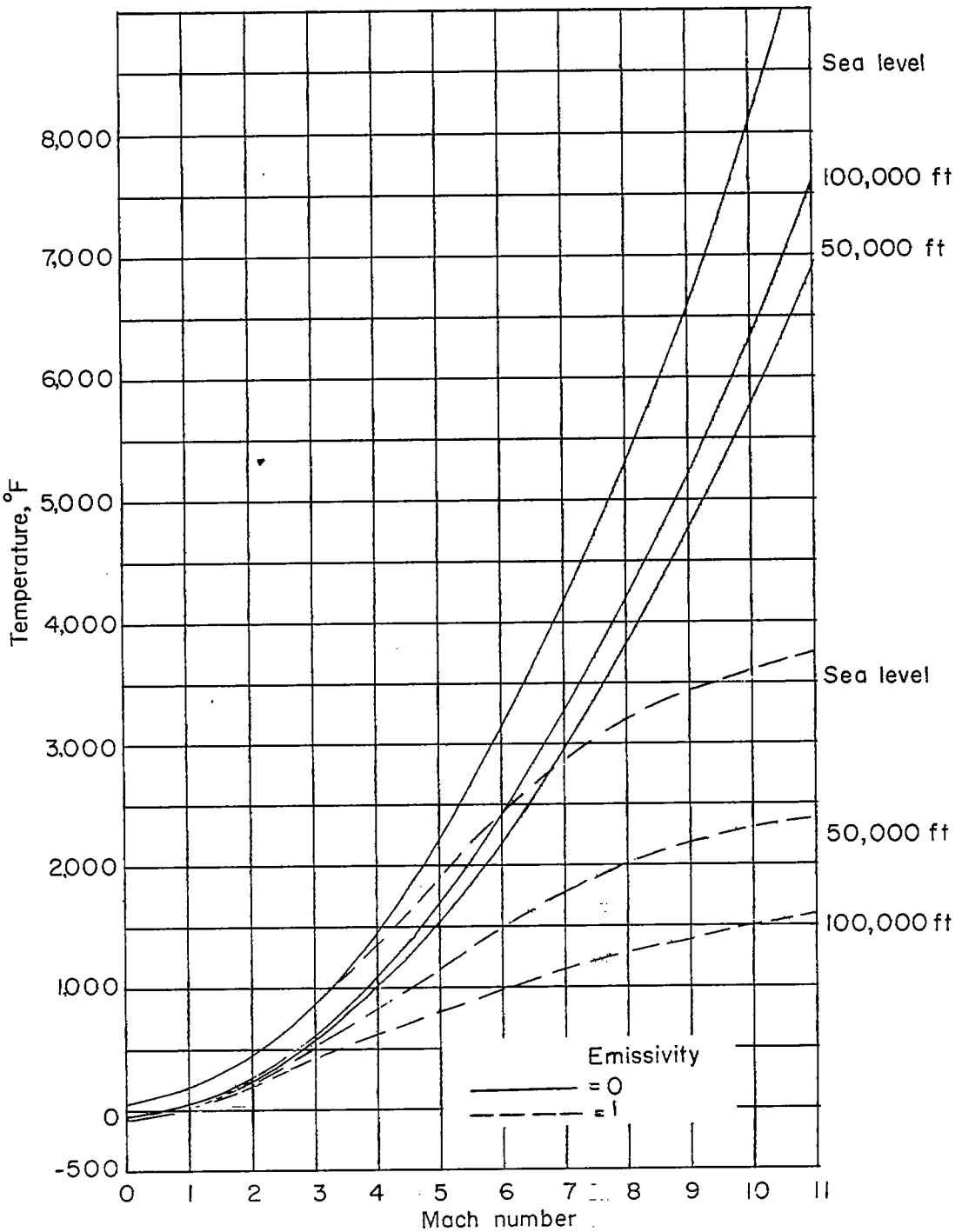

Figure 1.- Aircraft equilibrium skin temperatures at 2 feet from leading edge for turbulent boundary layer.

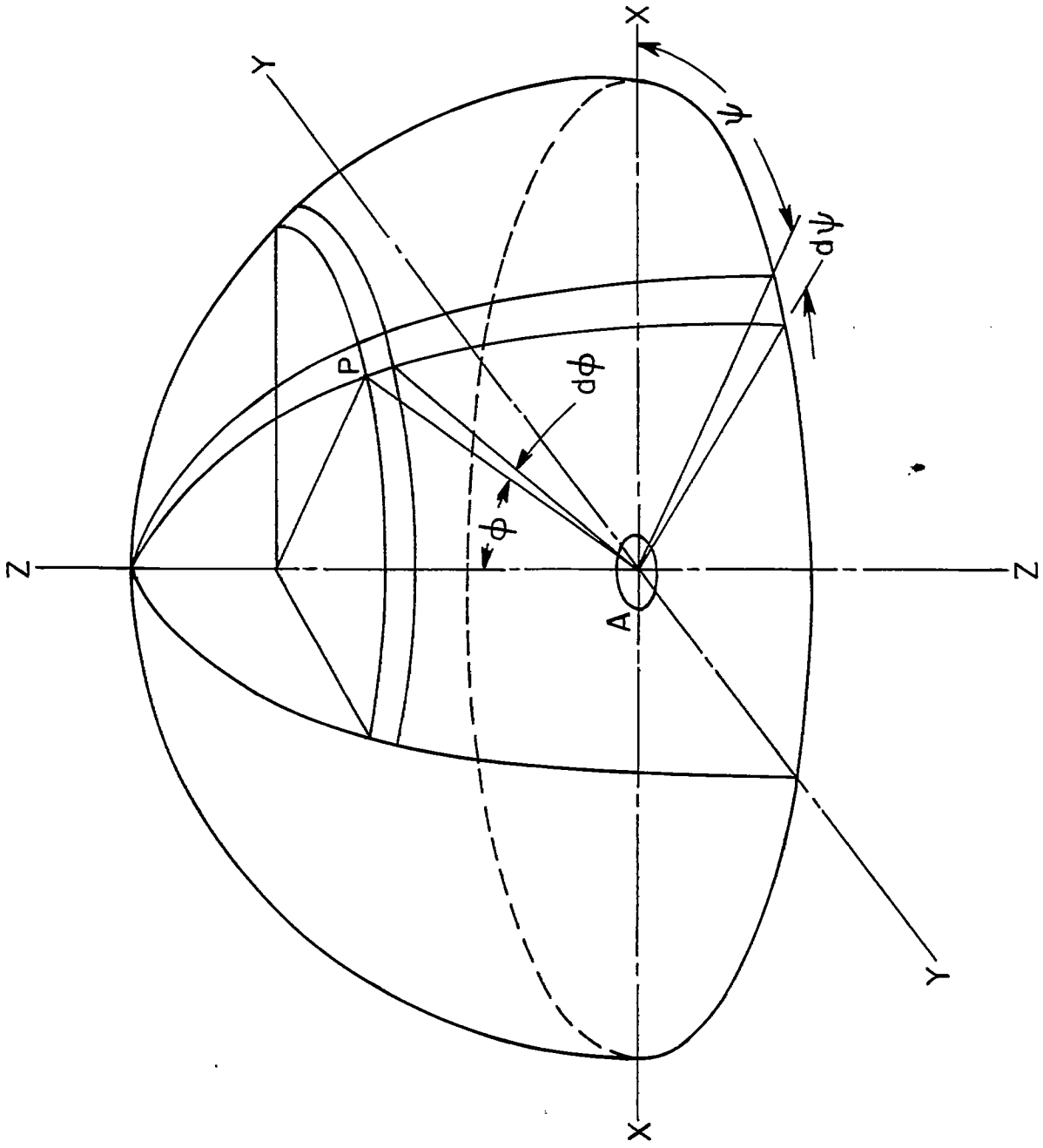

Figure 2.- Quantities involved in relation between rate of emission and radiant flux.

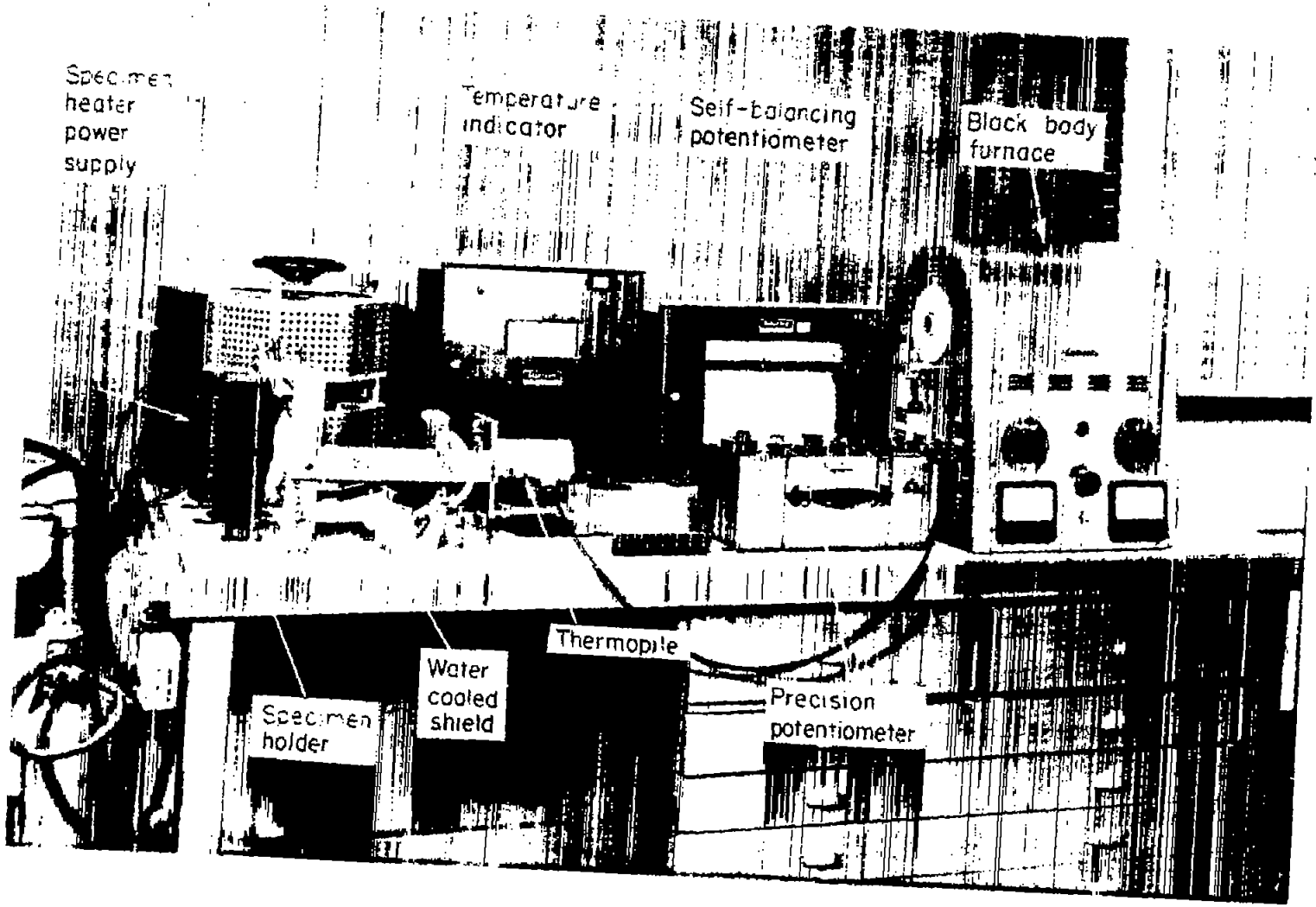

Figure 3.- General view of emissivity-measuring apparatus with identification of principal components.

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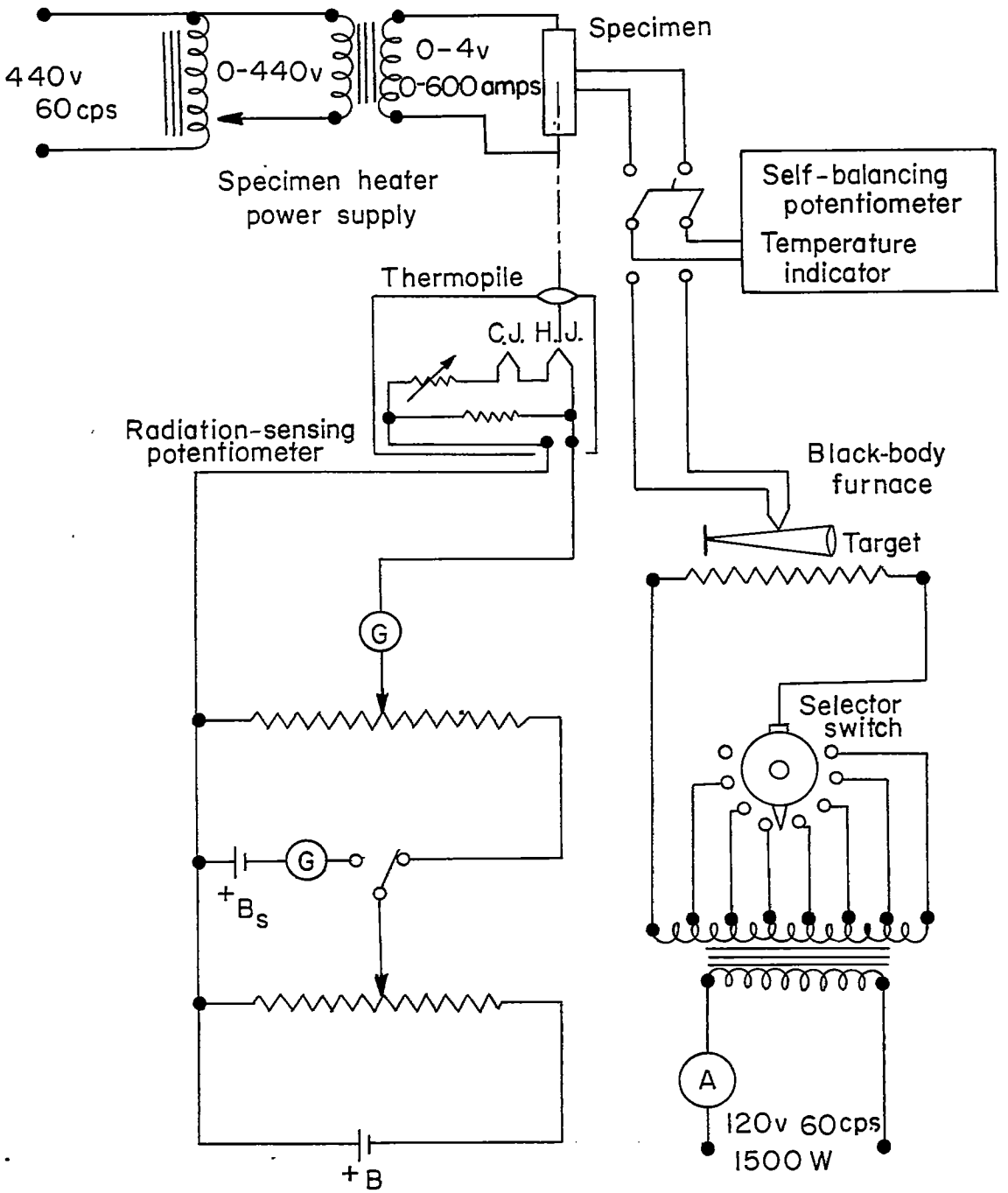

Figure 4.- Schematic drawing of electrical circuit of test setup.

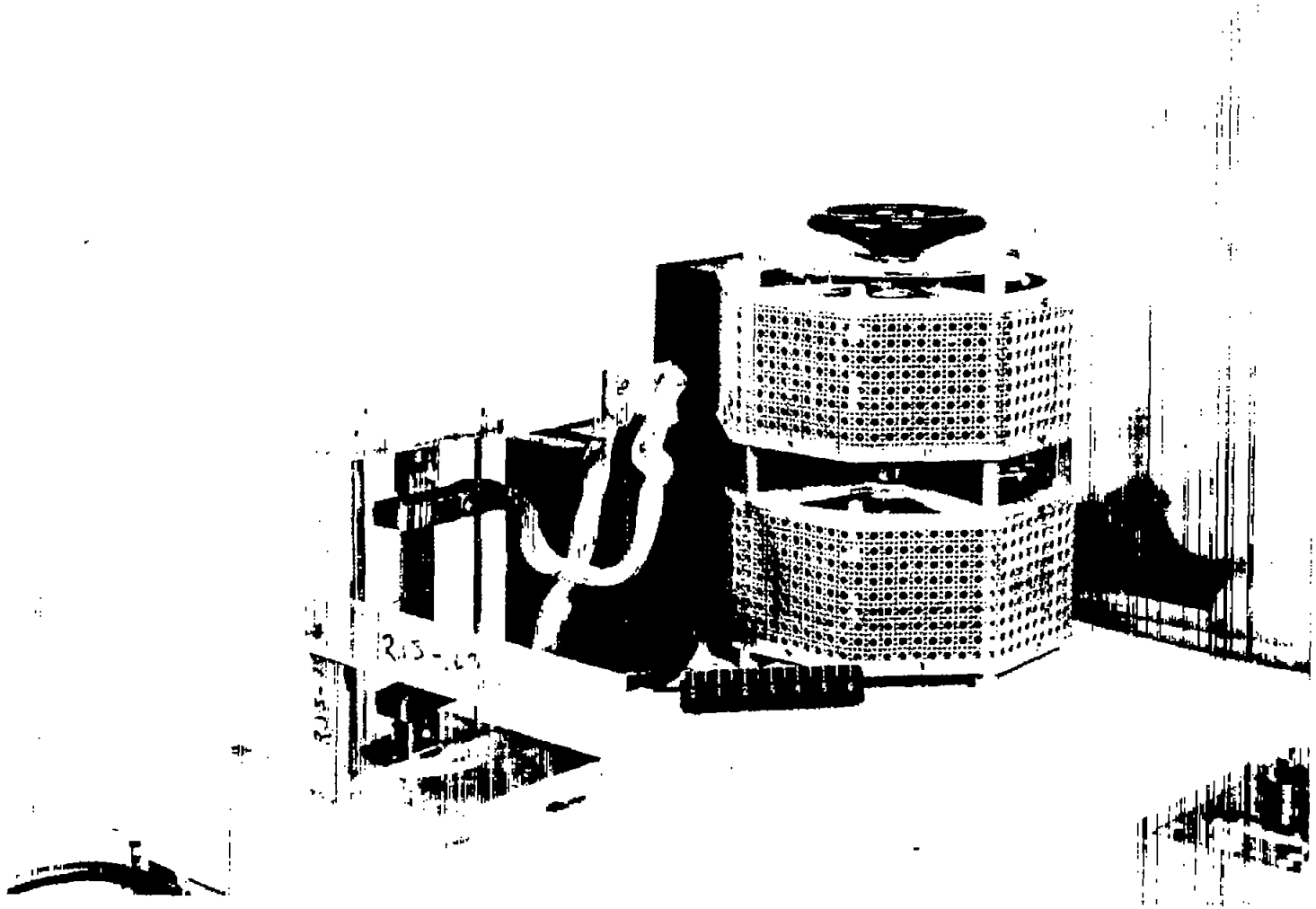

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Figure 5.- Test specimen holder with specimen installed and electric power supply for heating specimen.

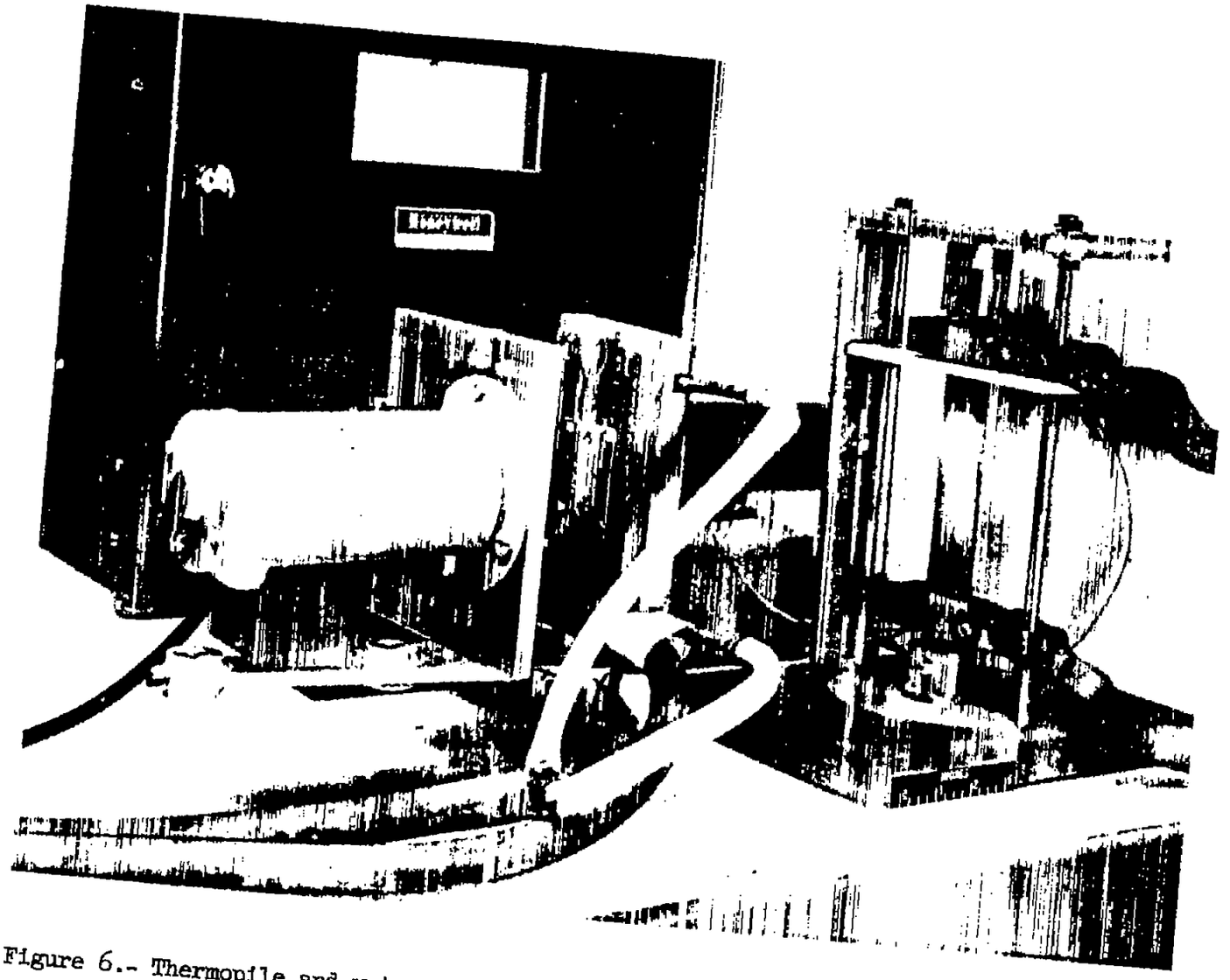
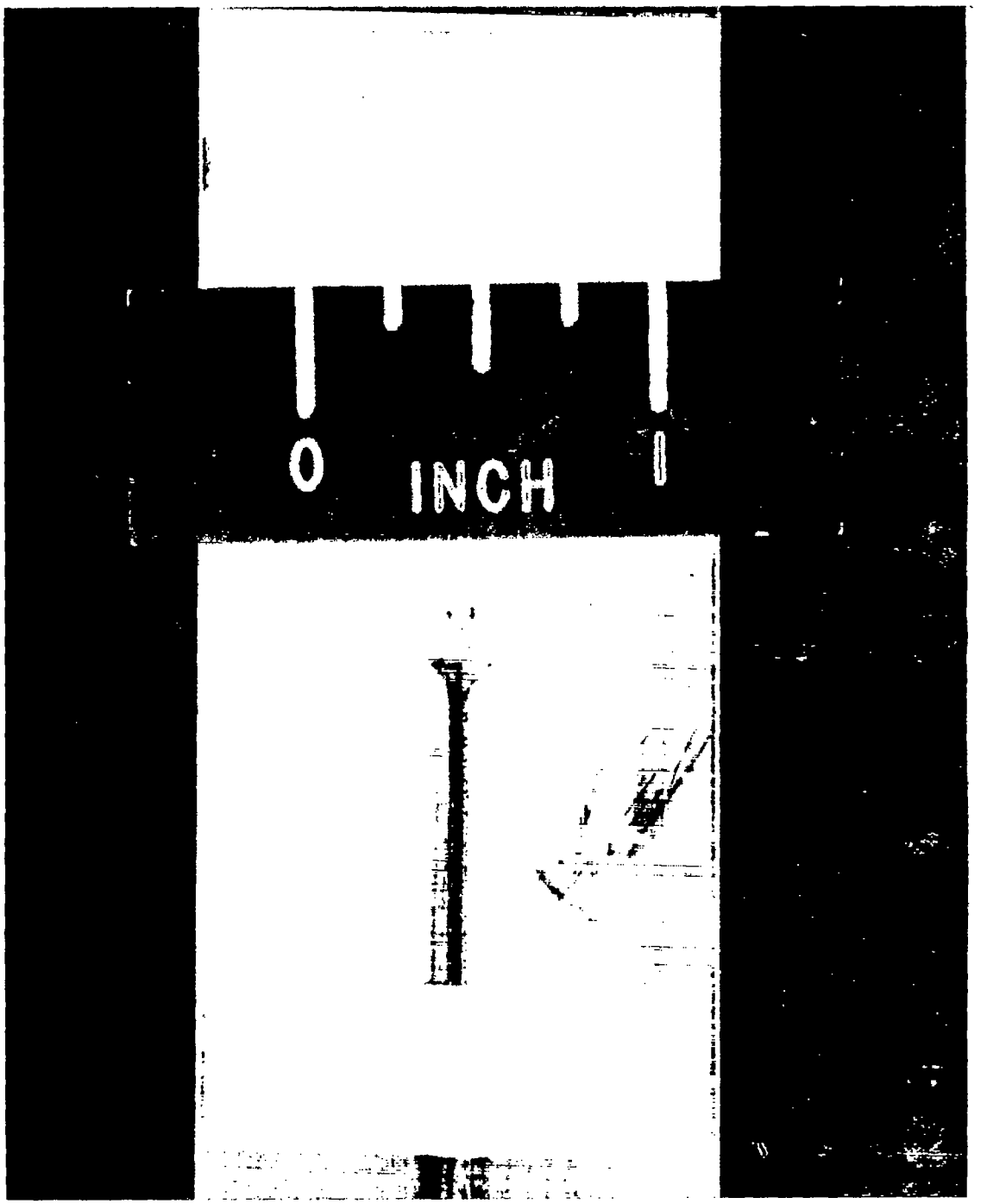


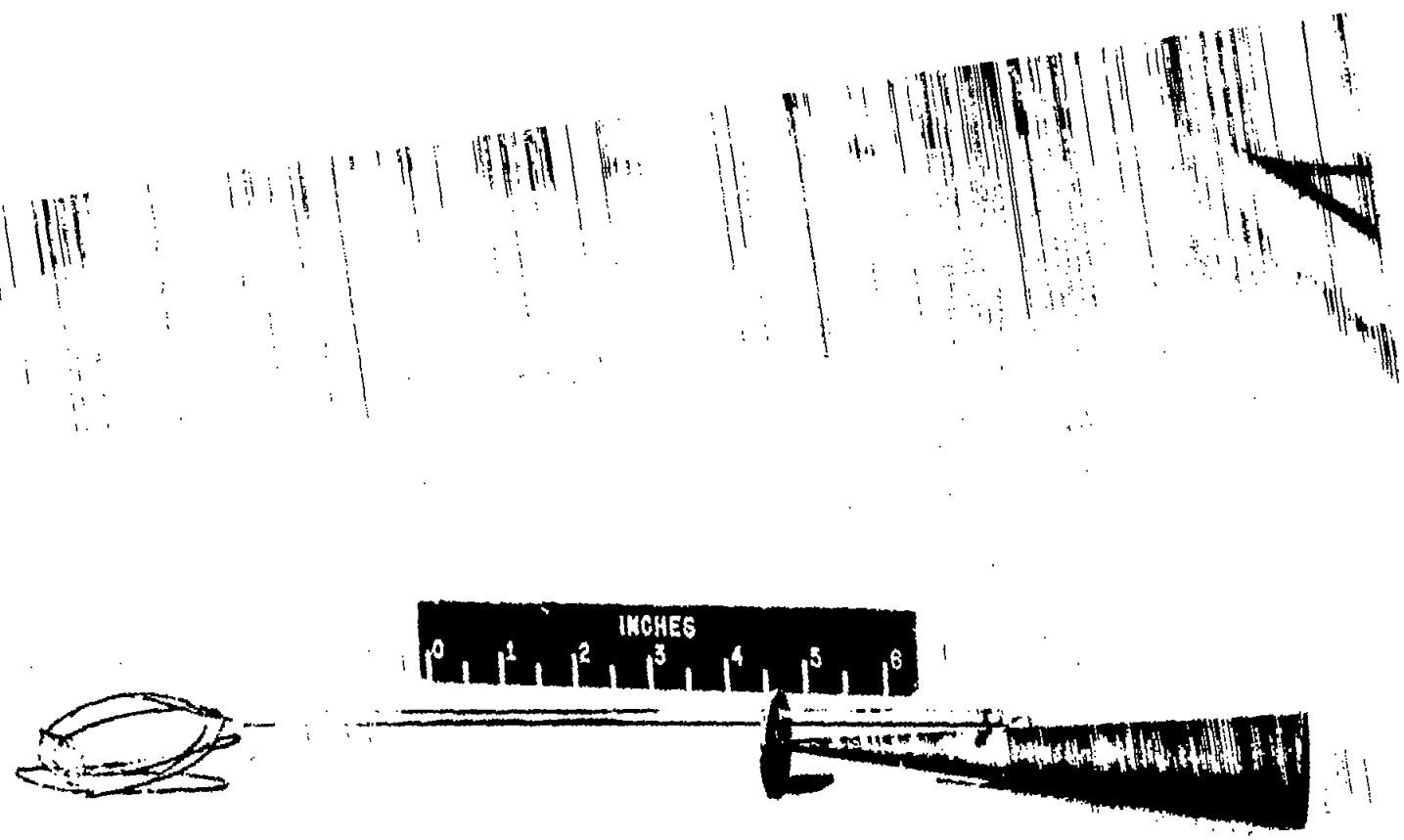
Figure 6.- Thermopile and water-cooled shield mounted on pivoted arm of test specimen holder with test specimen installed.

L-97037



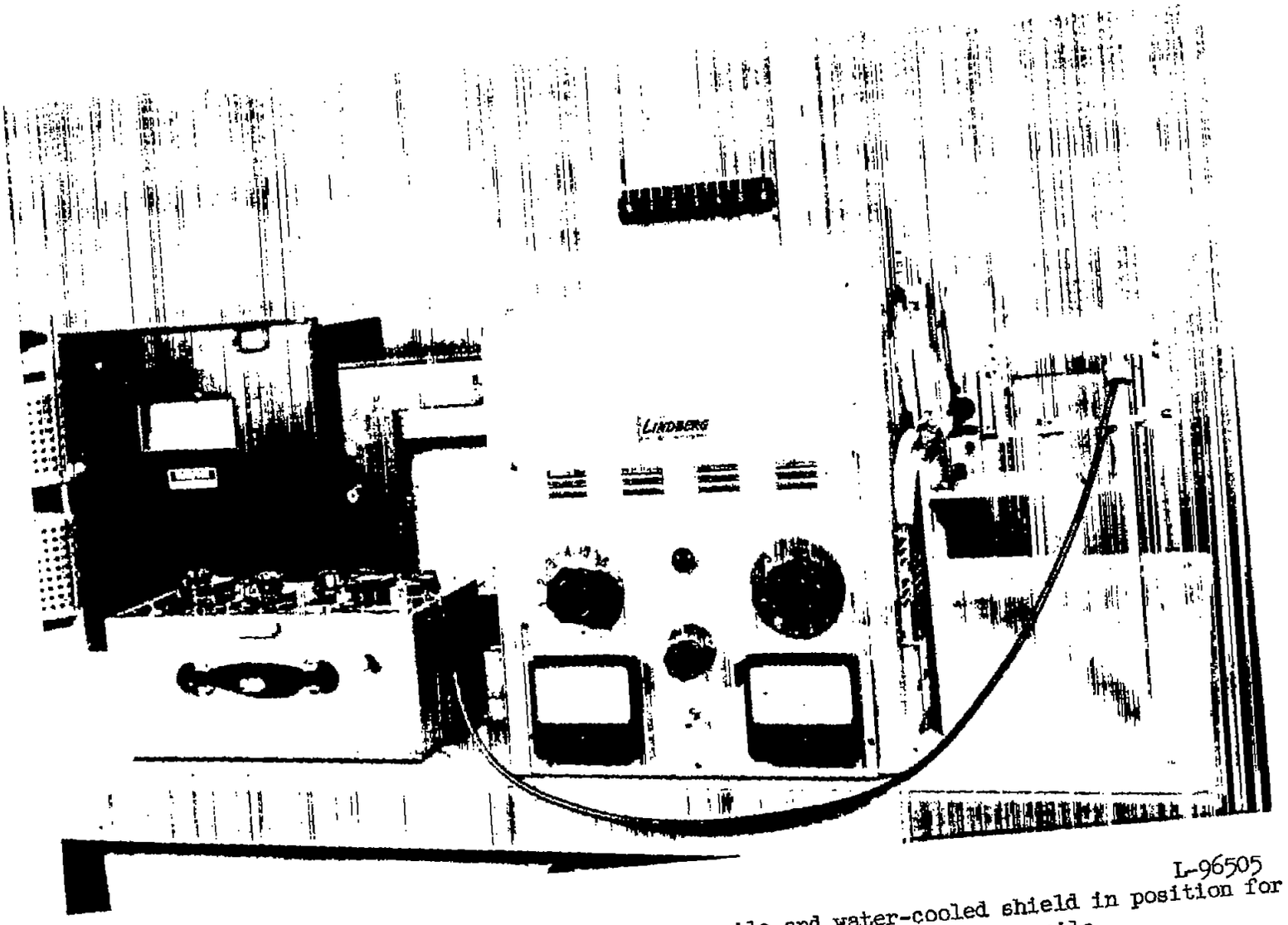
L-57-2472

Figure 7.- Typical thermocouple installation on a test specimen.



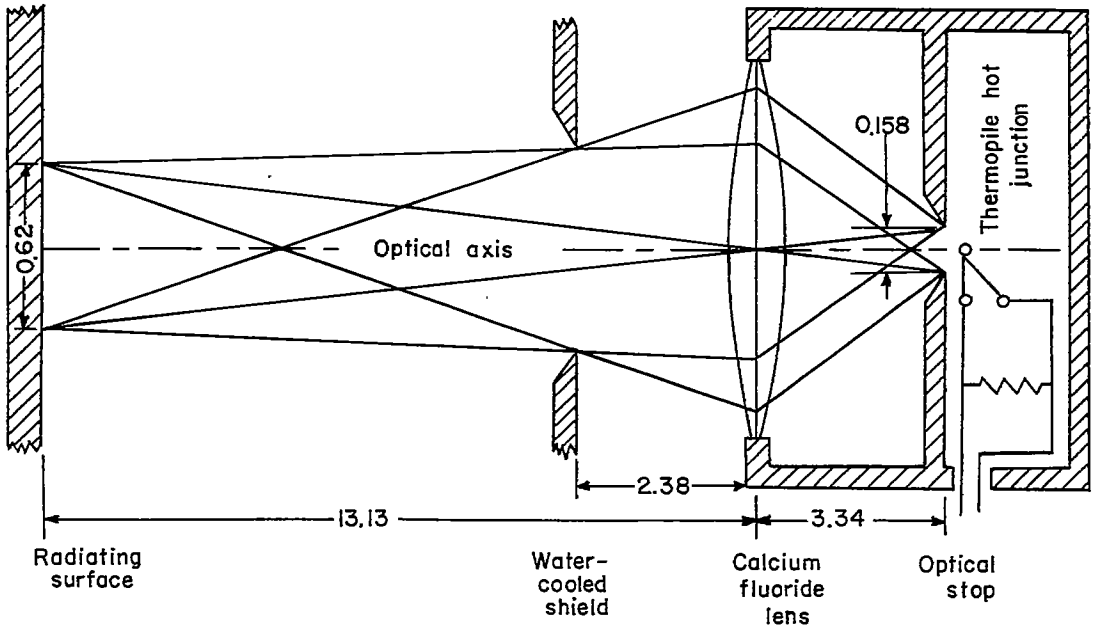
L-96506

Figure 8.- Reference-black-body conical target with thermocouple.

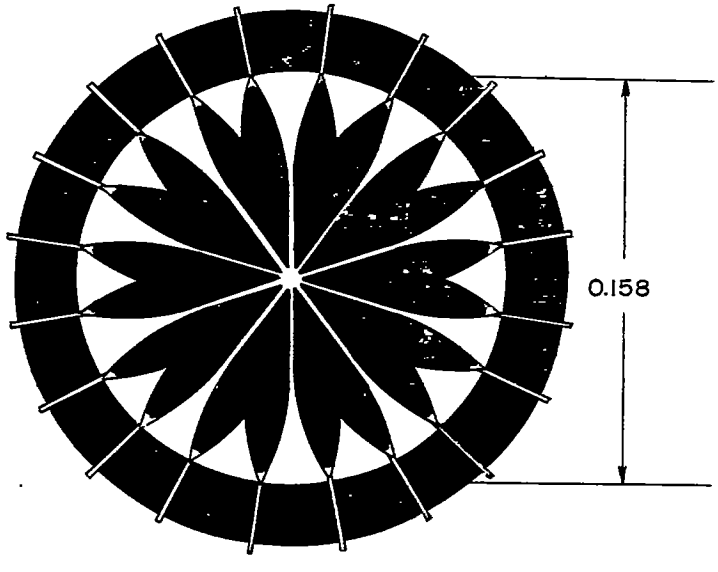


L-96505

Figure 9.- Reference-black-body furnace with thermopile and water-cooled shield in position for viewing black body and precision potentiometer used with thermopile.

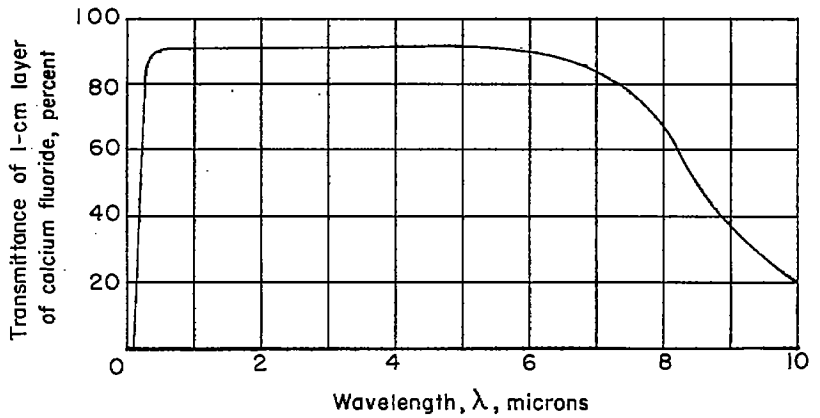


(a) Schematic arrangement of system. (Vertical scale is five times horizontal scale.)

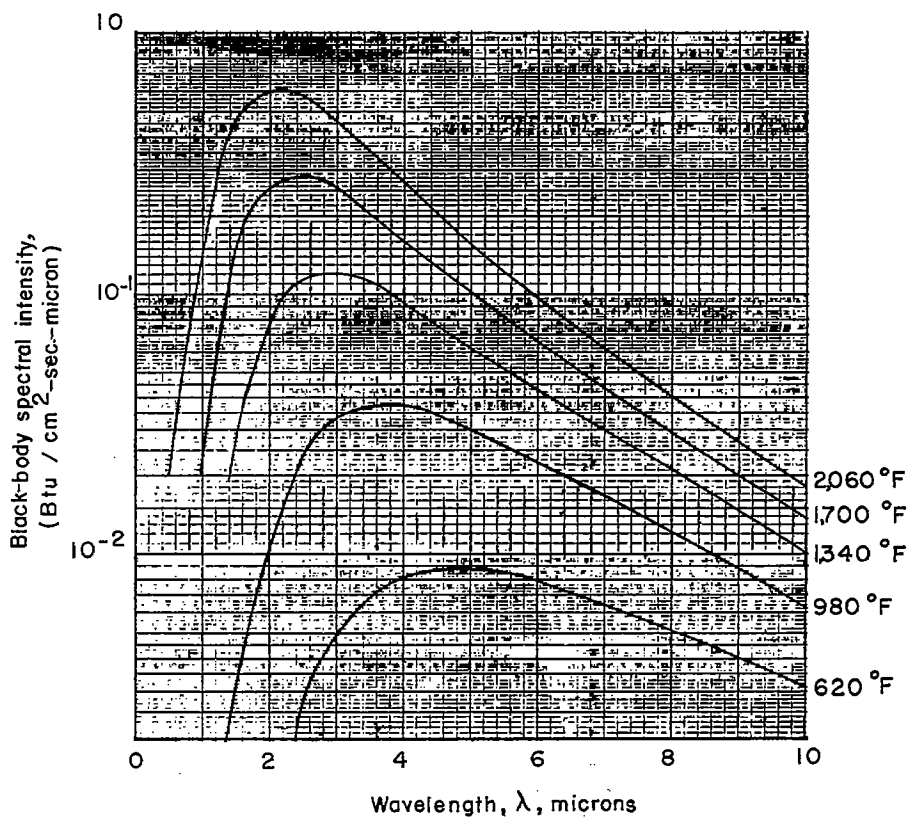


(b) Enlarged view of thermocouple hot junctions.

Figure 10.- Optical system. All dimensions are in inches.



(a) Transmittance of calcium fluoride.



(b) Spectral intensity of black body.

Figure 11.- Transmittance of calcium fluoride and spectral intensity of black body as functions of wavelength.

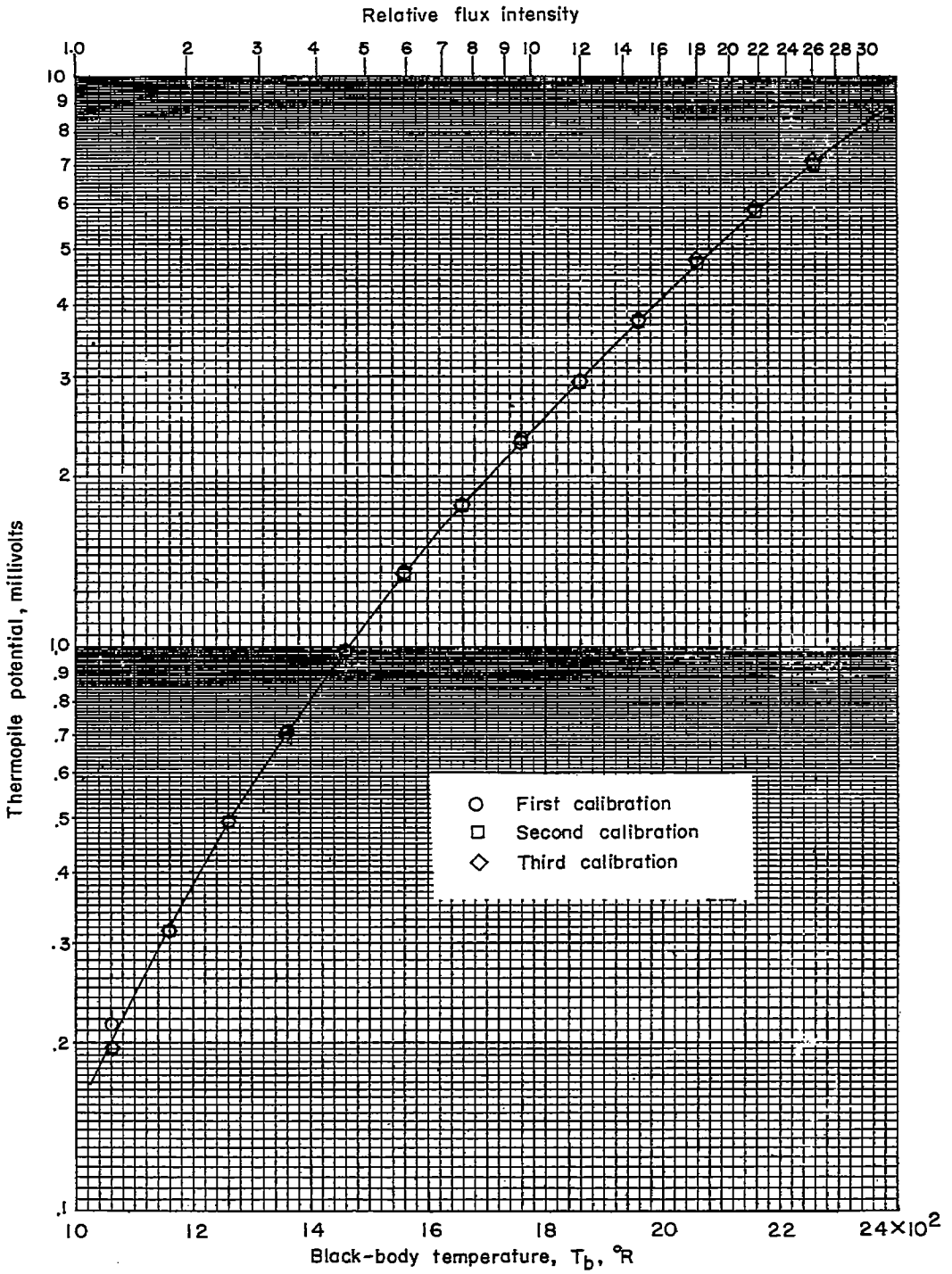


Figure 12.- Calibration of the thermopile radiation-flux measuring system.

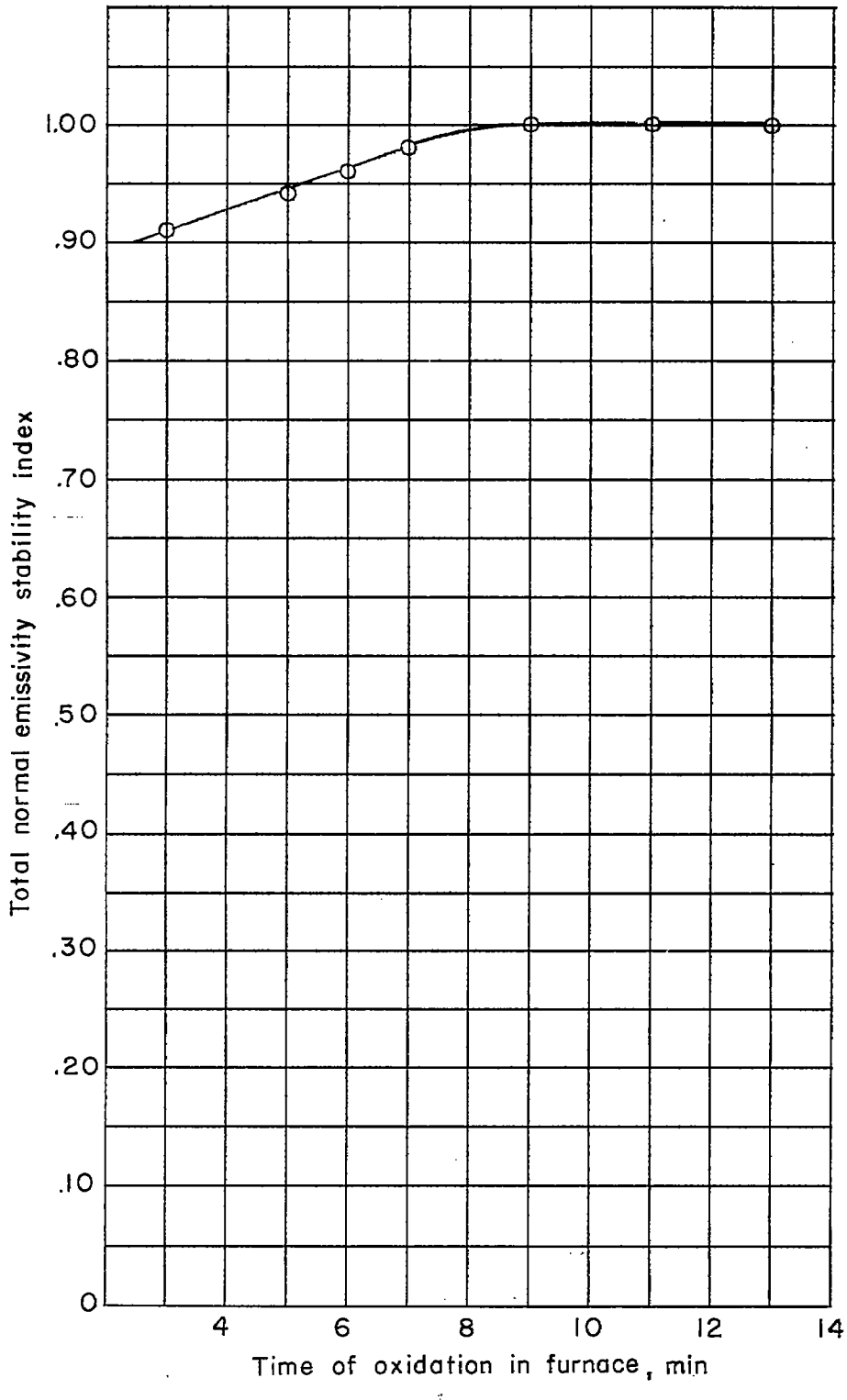


Figure 13.- Measurements of stability of total normal emissivity of oxidized Inconel as a function of duration of oxidation time.

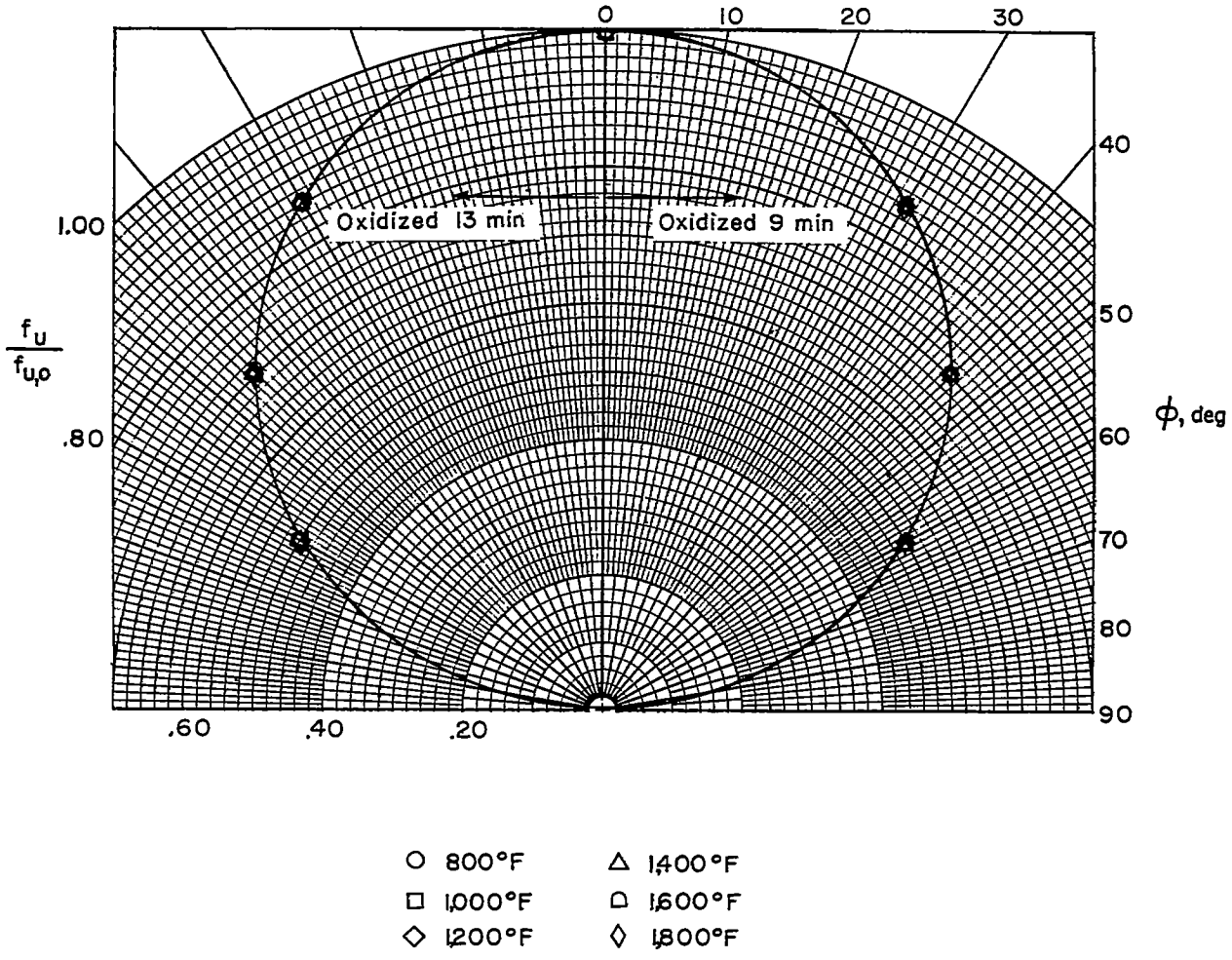


Figure 14.- Comparison of emission of Inconel oxidized 9 and 13 minutes with Lambert cosine law of diffuse emission at temperatures from 800° F to 1,800° F.

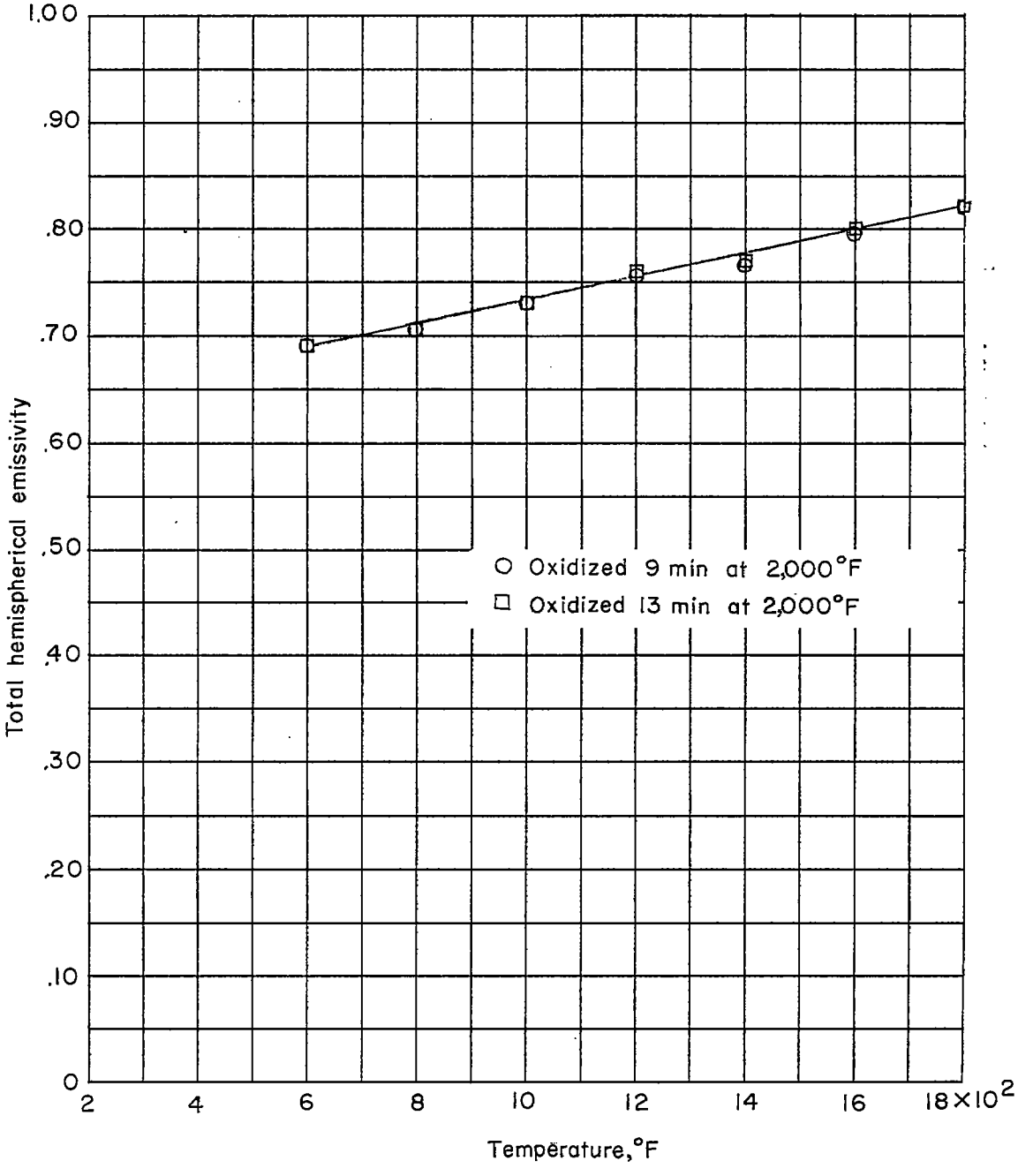
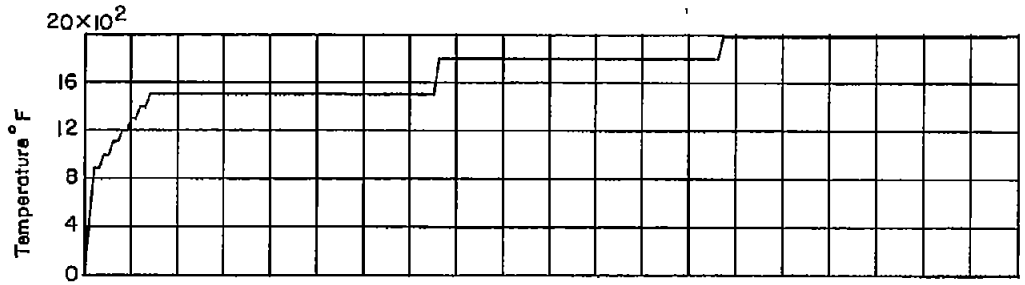
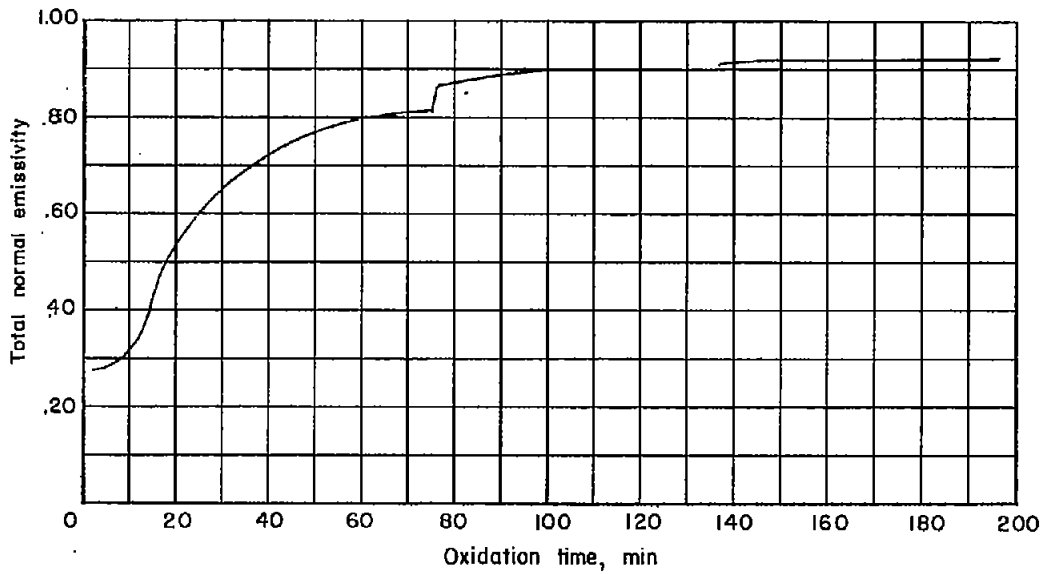


Figure 15.- Measurements of total hemispherical emissivity of stably oxidized Inconel as function of temperature.



(a) Time history of specimen temperature.



(b) Time history of total normal emissivity of specimen.

Figure 16.- Exploration of the stability of the total normal emissivity of Inconel X heated in quiescent air.

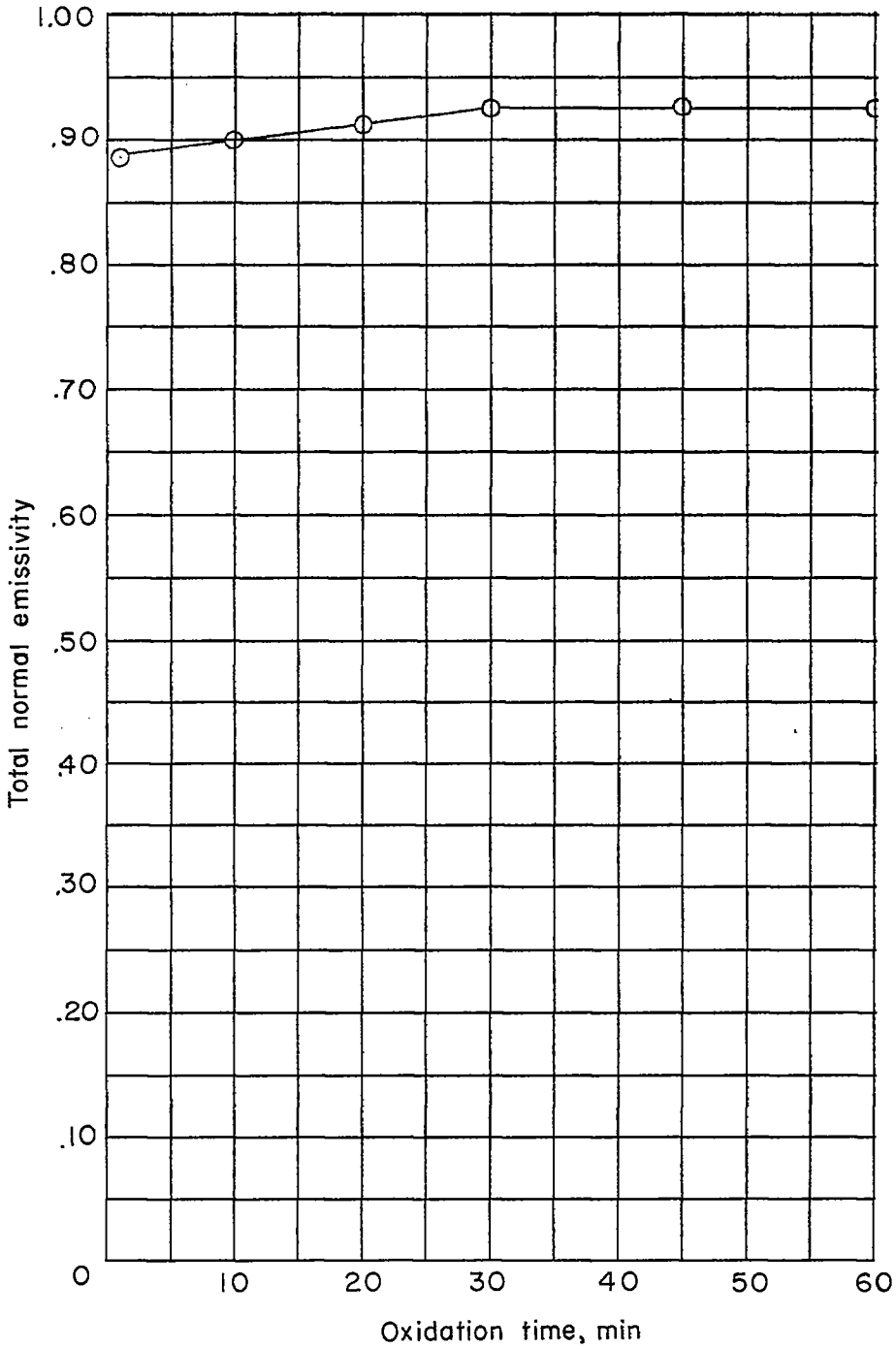


Figure 17.- Variation of total normal emissivity of Inconel X with time of oxidation at 2,000° F in quiescent air.

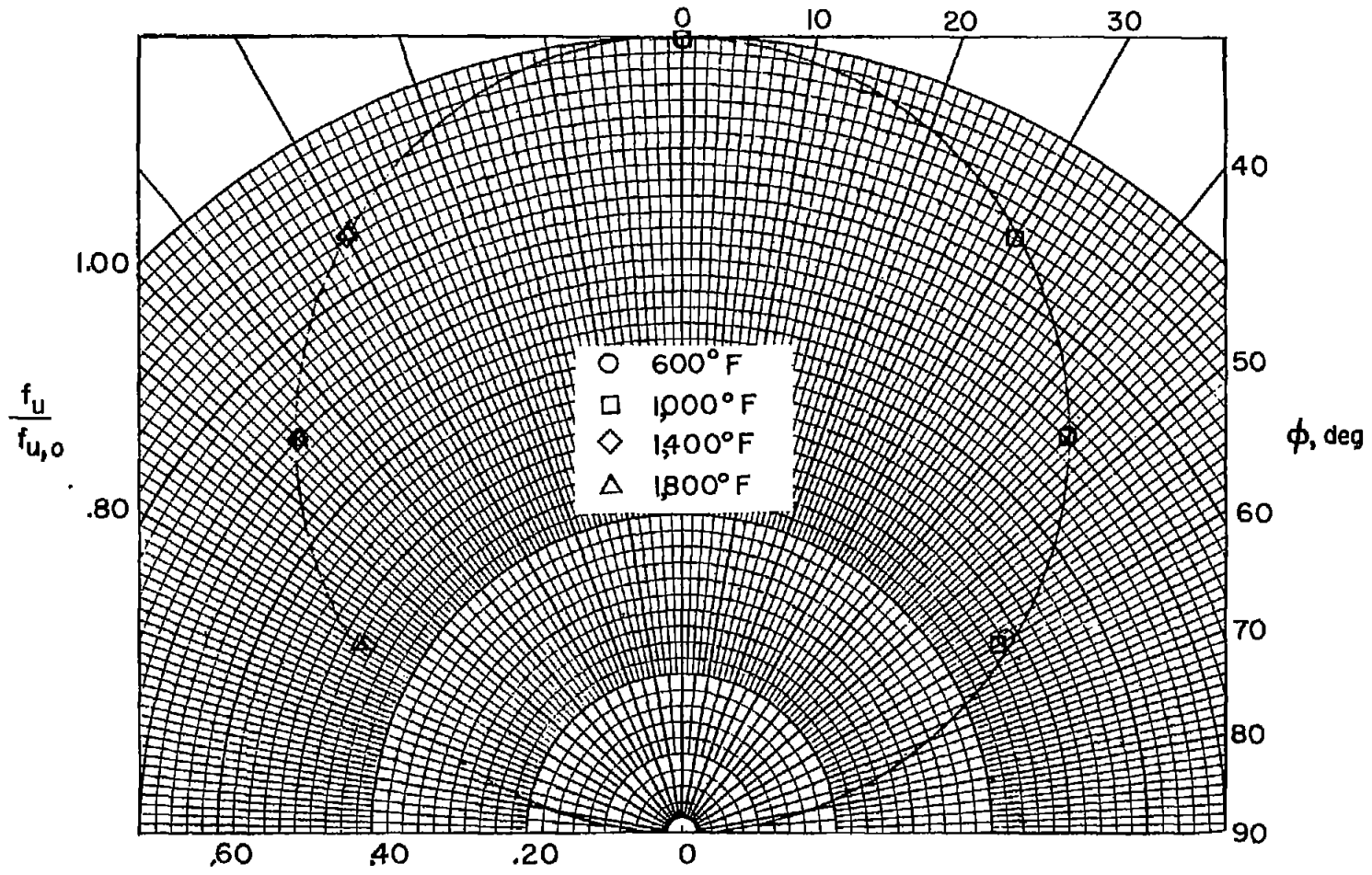


Figure 18.- Comparison of emission of Inconel X oxidized 30 minutes at 2,000° F with Lambert cosine law of diffuse emission at temperatures from 600° F to 1,800° F.

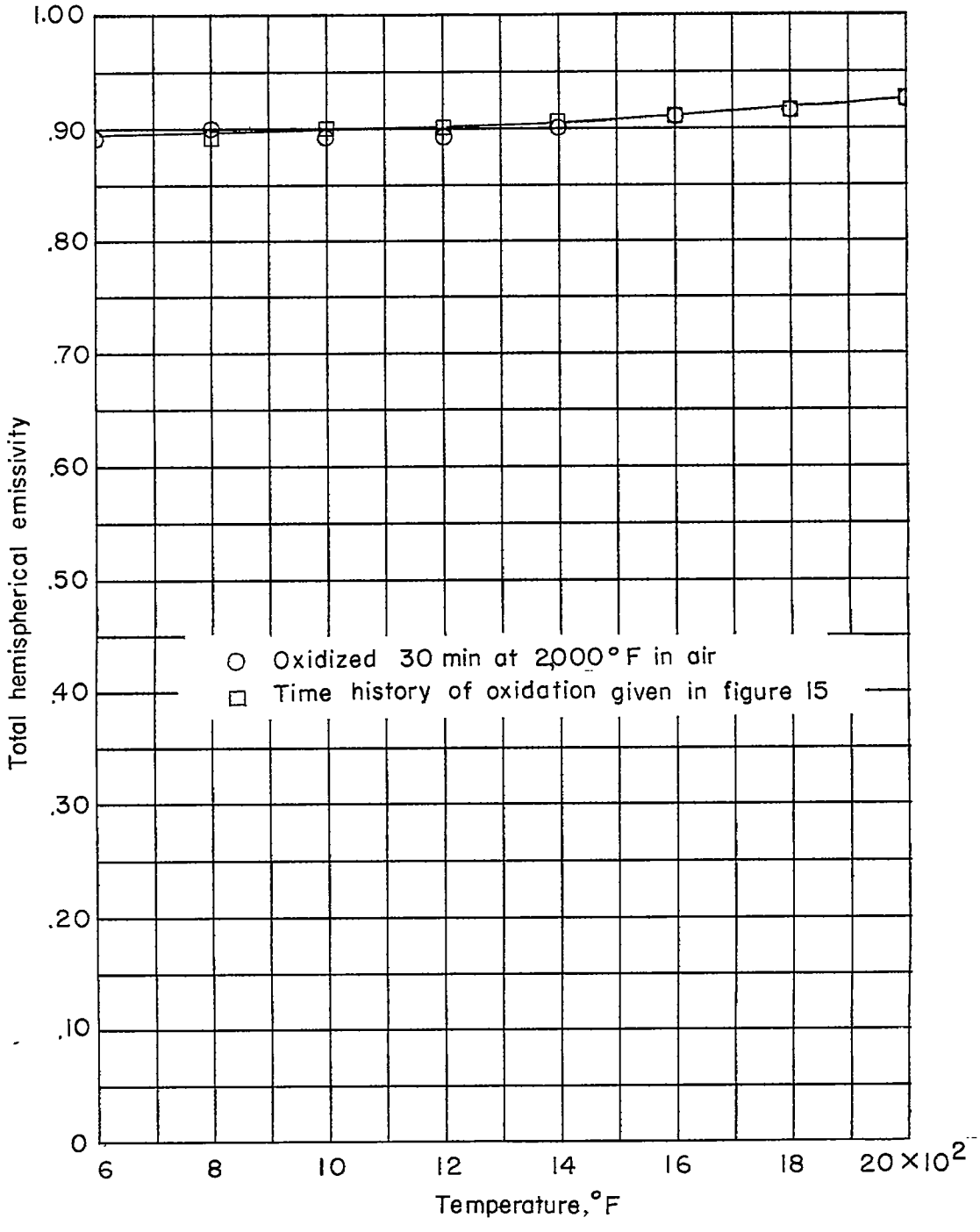


Figure 19.- Measurements of total hemispherical emissivity of stably oxidized Inconel X as function of temperature.