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WADC-TR-59-510
PART IV

STANDARDIZATION OF THERMAL EMITTANCE MEASUREMENTS

PART IV. NORMAL SPECTRAL EMITTANCE, 800-1400°K

TECHNICAL REPORT No. WADC-TR-59-510, PART IV

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AF MATERIALS LABORATORY
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National Bureau of Standards, Washington, D. C.;
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FOREWORD

This report was prepared by the National Bureau of Standards under USAF Contracts No. AF (33-616)-58-20, Amendment 1 to that contract, No. AF (33-616)-61-02, and Amendments 1, 2, 3 to that contract. The work was initiated under Project No. 7360, "Materials Analysis and Evaluation Techniques", Task No. 73603 "Thermodynamics and Heat Transfer." The contracts were administered under the direction of the Materials Laboratory, Directorate of Laboratories, Wright Air Development Center, with Capt. F. V. Zaleski acting as project engineer, and later under the direction of Materials Central, Directorate of Advanced Systems Technology, Wright Air Development Division, with Mr. R. A. Winn acting as project engineer, and still later under the direction of the Directorate of Materials and Processes, Deputy for Technology, Aeronautical Systems Division, again with Mr. R. A. Winn as project engineer.

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ABSTRACT

Equipment and procedures were developed to measure normal spectral emittance of specimens that can be heated by passing a current through them, at temperatures in the range of 800 to 1400°K, and over the wavelength range of 1 to 15 microns.

A data-processing attachment for the normal spectral emittance equipment was designed to (1) automatically correct the measured emittance for "100% line" and "zero line" errors on the basis of previously-recorded calibration tests; (2) record the corrected spectral emittance values and wavelengths at preselected wavelength intervals on punched paper tape in form suitable for direct entry into an electronic digital computer; and (3) to compute during a spectral emittance test on a specimen the total normal emittance, or absorptance for radiant energy of any known spectral distribution of flux, of the specimen.

Working standards of normal spectral emittance having low, intermediate and high emittance values, respectively, were prepared and calibrated for use in other laboratories to check the operation of equipment and procedures used for measuring normal spectral emittance.

This report has been reviewed and is approved.

Jules I. Wittebort

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I. OBJECTIVES

The broad objective of this project is to develop standard procedures, and to select or design suitable equipment, for the measurement of spectral emittance and/or spectral reflectance of materials, particularly those used in aircraft, missiles and space vehicles, at temperatures from below room temperature to near the melting point of refractory materials of interest, and over the wavelength range from the visible range into the infrared to 15 microns and beyond. The specific objectives include (1) the selection of suitable materials and the preparation and calibration of specimens as working standards of normal spectral emittance, to be used for calibration of spectral emittance equipment in other laboratories, and (2) the design or selection of suitable data-processing equipment (a) to automatically correct the emittance data for calibration errors of equipment, (b) to record the corrected data in form suitable for direct entry into an electronic digital computer, and (3) to compute, concurrently with a spectral emittance measurement, a single value of total emittance, solar absorptance or absorptance for radiant energy having any other known spectral distribution of flux.

II. DEFINITIONS

Several important items of nomenclature in the field of electromagnetic radiation have not been firmly established. Different meanings are ascribed to the same words by different individuals, and some of the conflicting definitions have been adopted by different technical and scientific organizations of national scope. The terminology used in this investigation follows that advocated by Jones [1] 1/, Worthing [2] and others, including American Standards Association [3], in that the word-ending "ivity" is reserved for the properties of materials, and "ance" for the properties of specimens. The word-ending "ion", as in reflection, absorption and transmission, is applied to acts or processes; radiation is a process, and sometimes denotes that which has been radiated.

All bodies are constantly emitting electromagnetic energy as a result of the thermal vibration of the particles, atoms and molecules comprising the body; this process is known as <u>thermal emission</u>, and the rate of such emission per unit area is often referred to as <u>thermal emissive power</u>.2/

1/ Bracketed numbers are references. See Section XIII of this report.

2/ Also sometimes called <u>radiant emittance</u>.

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Radiant flux is the rate of flow of radiant energy.

Emittance is a property of a specimen; it is the ratio of the emitted radiant flux per unit area to that of a blackbody radiator at the same temperature and under the same conditions.

A blackbody absorbs all radiant energy incident upon it and at any given temperature has the maximum possible emissive power for the temperature. An ideal blackbody is a complete enclosure with opaque walls at a uniform temperature. The amount, and also the geometric and spectral (or wavelength) distribution of radiant flux per unit area, from a blackbody at a given temperature can be computed from the Stefan-Boltzmann relationship, Lambert's cosine law and the Planck radiation law, respectively. Laboratory blackbody furnaces which radiate energy are only approximate blackbodies, because the opening through which the radiant energy is emitted constitutes a deviation from the ideal. The extent to which they deviate from the ideal depends upon such factors as the relative size of the opening, the emittance of the inside surface, and the thermal gradients that may be present in the cavity walls. The rate of thermal emission of any real specimen is less than that of a blackbody at the same temperature.

Emissivity is a special case of emittance; it is a fundamental property of a material, and is measured as the emittance of a specimen of the material which has an optically smooth surface[1/], and is sufficiently thick to be completely opaque (non transmitting).

Reflection is the process by which radiant flux incident upon a surface is reflected.

Reflectance is a property of a specimen; it is the ratio of reflected radiant flux to incident radiant flux.

Reflectivity is a special case of reflectance; it is a fundamental property of a material, and is measured as the reflectance of a specimen of the material that has an optically smooth surface[1/], and is sufficiently thick to be completely opaque.

Transmission is the process whereby radiant flux is transmitted through a body.

Transmittance is a property of a specimen; it is the ratio of transmitted radiant flux to incident radiant flux.

Absorption is the process by which radiant energy is absorbed and converted into other forms of energy.

1/ Any surface contamination may alter the thermal radiation properties, hence a contamination-free surface is also essential.

Absorptance is a property of a specimen; it is the ratio of absorbed radiant flux to incident radiant flux.

Absorptivity is a special case of absorptance; it is a fundamental property of a material and is measured as the absorptance of a specimen of the material that has an optically smooth surface[1] and is sufficiently thick to be completely opaque.

Absorption Coefficient is a fundamental property of a material; it is a quantitative expression of the rate of decrease of radiant flux density in the direction of propagation of radiant energy through a material due to absorption. Expressed mathematically

$$I = I_o e^{-ax} \tag{1}$$

in which "I" is the flux density after passing through a thickness "x" of a non-scattering material, "I_o" is the flux density at zero thickness, just after penetration of the surface (thus not including the reflected portions of the incident radiation) "a" is the absorption coefficient, and "e" is the base of natural logarithms.

In a light-scattering material, some of the reduction in unidirectional flux density results from internal scattering. Equation (1) is also used to express the rate of decrease in flux density due to scattering; in this case the letter "a" symbolizes the scattering coefficient. In light-scattering materials the reduction in flux density is due to both absorption and scattering, in which case the letter "a" represents the extinction coefficient.

A specimen is opaque when none of the radiant energy incident upon it is transmitted through it. All materials theoretically require infinite thickness to become opaque, as illustrated by equation (1). In practice, a specimen is considered to be opaque when the transmitted radiant flux is too small to be detected, a condition which occurs at a very small thickness for some materials, and at great thicknesses for others. The thickness required for a specimen to be opaque also varies with the wavelength of the incident flux, for any one material.

All of the properties that are defined above vary with the spectral (or wavelength) distribution of the radiant flux. All are temperature dependent, some strongly so, and others only moderately. All of the properties except the coefficients are influenced by the angular distribution of flux in the radiant energy. All of the properties that pertain to specimens are influenced by the surface texture of the specimen, and by the thickness, unless the specimen is opaque.

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[1] See footnote 1 on page 2.

Since the emission, reflection and absorption characteristics of a specimen are influenced by the direction of propagation, relative to the surface, of the emitted, incident, or reflected energy, and by the spectral distribution of radiant flux, most of the terms defined above must be qualified in order to convey precise meanings. For reflection, the direction of propagation of both the incident and reflected radiation must be specified. Specular, referring to reflection, means in the direction of mirror reflection. Diffuse, referring to reflection, means in all possible directions. Emission in all possible directions is referred to as hemispherical. When limited directions of propagation are involved, the word directional may be used. Normal is a special case of directional, and means a direction normal to the surface. For other directions, the angle of deviation from the normal is stated. The terms normal and directional apply strictly to beams of parallel radiation, but are also used for beams contained within a small solid angle, in which case the direction of propagation is taken as that of the axial ray. Since all laboratory sources, specimens and receptors are of finite size, significant deviations from parallelism exist in all laboratory instruments. Hence the source and field apertures should be specified to define the extent of such deviations from parallelism.

Radiant energy having a stated wavelength, or more precisely, that is within a narrow wavelength interval centered on a specified wavelength, is referred to as spectral. Spectral emittance at a stated temperature is frequently plotted as a function of wavelength to produce a spectral emittance curve. The word total as used to modify terms describing thermal emission characteristics, means that the modified term pertains to the integral of rates of spectral emission at all wavelengths.

Some examples of the qualified expressions that are required to convey precise meanings are: "total hemispherical emittance at 500°K", "normal spectral emittance at 1400°K in the wavelength interval 1 to 15 microns", and "spectral diffuse reflectance for normal illumination over the wavelength interval 0.3 to 3.0 microns."

III. FUNDAMENTAL CONSIDERATIONS

Thermal emission is frequently referred to as a surface phenomenon. Actually all of the radiant energy that is emitted originates within the body of the specimen (solid, liquid or gas). The function of the surface, or interface, in this respect is to fix the fraction of the radiant energy incident upon it from inside the specimen that is internally reflected, the remainder being refracted and allowed to radiate from the specimen. The same function is performed with respect to radiant energy incident on the interface from outside the specimen. The fraction of incident radiant energy that passes through the interface (the remainder being reflected) is determined by (a) its wavelength, (b) the angle of incidence (internal or external), and (c) the indices of refraction of the two materials (such as glass and air) that share the interface. For a material such as metal, that has a high extinction coefficient, radiant energy that reaches the surface from the interior must be emitted by particles very close to the surface. As the extinction coefficient (see equation 1) of the specimen decreases, there is a corresponding increase in the depth within the specimen from which a significant fraction of the internally emitted energy reaches the surface by radiation through the material of the specimen without being absorbed. For some materials, and within some wavelength intervals, the maximum such depth may be quite large, as for example in the case of optical glass and visible light. Gardon [4] presents a detailed mathematical treatment of emission by optically homogeneous materials having relatively low absorption coefficients. In dealing with ceramic materials the fact that all emitted radiant energy originates internally cannot be safely ignored.

The emittance of a specimen that consists of a partially transmitting coating on a substrate is influenced by the emittance and reflectance of the substrate. If the coating is completely opaque, it controls the emittance of the specimen. Emittance, reflectance, and transmittance, under equilibrium conditions, when all heat transfer is by radiation, and when other conditions, specified below, are fulfilled, are related by the following equations:

$$E + R + T = 1 \tag{2}$$

$$E_{\infty} + R_{\infty} = 1 \tag{3}$$

$$E = A \tag{4}$$

$$E_{\infty} = A_{\infty} \tag{5}$$

in which:
E = emittance
E_{∞} = emissivity
R = reflectance
R_{∞} = reflectivity
T = transmittance
A = absorptance
A_{∞} = absorptivity

These equations are valid for the entire span of the spectrum considered as a whole, and likewise for any given wavelength interval within the spectrum, provided that consistent and pertinent geometric and spectral conditions of illumination and viewing are used. If hemispherical emissivity is specified, the corresponding reflectivity is the value that applies to diffuse illumination and hemispherical viewing, a condition not readily achieved experimentally. Likewise, for hemispherical emittance the corresponding transmittance value is for conditions of uniformly diffused illumination and hemispherical viewing. For normal emittance the corresponding reflectance and transmittance values are for uniformly diffused illumination and normal viewing, or the optical equivalent, normal illumination and hemispherical viewing.

In addition to these considerations involving the angular distribution of radiant flux, there are certain aspects of the spectral distribution that must not be overlooked in applying equations (2) to (5). Since by definition emittance is the ratio of radiant flux from the specimen to that from a comparable blackbody, it follows that one of the conditions for validity of these equations which pertain to equilibrium conditions (equal rates of absorption and emission), is that the radiant energy impinging upon the specimen must have the characteristics of blackbody radiation at the temperature of the specimen. If total emittance is under consideration the whole spectrum is involved. If spectral emittance within any specified wavelength increment is under consideration, then the radiant energy impinging upon the specimen must have, within the same limits of wavelength, the characteristics of blackbody radiation at the temperature of the specimen. For extremely narrow wavelength intervals the spectral distribution of flux from any source that would be used is sufficiently close to blackbody distribution (just as a sufficiently short segment of a circle approximates a straight line).[1/]

Furthermore, in considering applicable spectral conditions for equations (2) to (5) a clear distinction must be made between emittance (or emissivity), on the one hand, and the rate of emission of radiant energy, on the other. For the latter case the counterpart of equation (2) is

$$\epsilon + \rho + \tau = \omega \qquad (6)$$

in which:

ϵ = rate of emission of radiant energy by the specimen

ρ = rate at which radiant energy is reflected from the specimen

τ = rate at which radiant energy is transmitted through the specimen

ω = rate at which radiant energy, of any wavelength distribution, is impinging upon the specimen.

[1/] At first glance these conditions for validity of the equations might appear to preclude their use in the computation of emittance from reflectance data obtained with incident flux at a higher level than could be produced by a blackbody of the same size and temperature as the specimen. Fortunately, however, even though the reflectance of the specimen be measured for incident radiant flux much greater than that required to maintain the desired temperature of the specimen under equilibrium conditions, with radiative transfer alone, properly measured reflectance values are valid for substitution in equation (2); the test temperature is maintained in this case by dissipating part of the energy absorbed in the specimen by means of refrigeration; often conduction and convection losses are sufficient without special apparatus, when the specimen is at room temperature. The use in equation (2) of reflectance values determined under these conditions is permissible because the spectral reflectance of the specimen is a function of its temperature regardless of how this temperature is maintained. Equation (2), as stated in the text, is applicable to either total emittance or spectral emittance when corresponding values of R and T are used. Thus a spectral reflectance curve for an opaque specimen yields a spectral emittance curve, since $T = 0$, $E = 1-R$, and $E_\lambda = 1-R_\lambda$. The conversion of spectral to total emittance is described in the immediately following pages.

Equation (6), in which the rate of flow of energy is being considered rather than the relative rate as compared to that of a blackbody as in equations (2) to (5), is not necessarily valid for limited portions of the spectrum. Thus a specimen in thermal equilibrium that is heated solely by solar radiation will be emitting energy with a spectral distribution of flux that is characteristic of the specimen at the equilibrium temperature, which may reach a peak at, say, 10 microns. Hence it would be fallacious to assume that equation (6), or the analogous counterparts of equations (3), (4), and (5), rewritten to apply to rates of flow of energy, would always be applicable to wavelength intervals of limited width.

IV. COMPONENT PARTS OF THE INVESTIGATION AND ORDER OF PRIORITIES

The objectives outlined in Section I of this report cover such a wide range of wavelengths and temperatures, that significant progress on all phases could not be made in the time and with the facilities available, and work on the remaining phases is being continued. The temperature range of interest can be divided into four smaller ranges, as follows: (1) below room temperature, (2) room temperature to 800°K, (3) 800° to 1400°K and (4) above 1400°K. In general, different equipment or techniques are required for each of these temperature ranges. The wavelength range of interest was also, for convenience, divided into three smaller ranges, as follows: (1) from about 0.3 micron to about 1.5 microns; (2) from about 1.5 microns to 15 microns; and (3) from 15 to 35 microns. Again different items of equipment, such as prisms and detectors, are needed in the different wavelength ranges. A third subdivision can be made on the basis of the type of specimen to be evaluated, as follows: (1) metals and other materials that can be heated by passing a current through them, and (2) dielectric materials, such as ceramics, that cannot conveniently be heated by passing a current through them.

Top priority was given to the development of instrumentation and procedures for the measurement of normal spectral emittance of specimens that can be heated by passing a current through them, at temperatures in the range of 800° to 1400°K, and over the wavelength range of 1.5 to 15 microns. The selection was made on the basis of the greatest current interest of the Air Force.

The selection and calibration of physical working standards of normal spectral emittance were undertaken after equipment and procedures for their measurement had been developed.

The design and construction of automatic data-processing equipment also followed the design and construction of the measuring equipment.

V. CONSIDERATIONS IN SELECTION OF EQUIPMENT AND PROCEDURES

In general, accurate absolute measurements of radiant energy are not easy to make. Comparative measurements of radiant energy can be made much more readily. For this reason it appears logical to base emittance determinations on direct comparison of the radiant flux from a specimen at a given temperature to that from a comparison standard.

Since any comparison standard, other than a blackbody furnace, that is used for emittance determinations must be calibrated against a blackbody furnace at each temperature of test, and even then may change with continued use, it is desirable to use a blackbody furnace as the comparison standard.

The total emissive power of a blackbody varies as the fourth power of its absolute temperature. Thus even a small error in temperature measurement can lead to a large error in an emittance measurement. The emittance of a given material, however, and particularly spectral emittance, usually varies only slightly with small changes in temperature. The critical requirements with respect to temperature control in the determination of emittance are (a) that the thermal gradients over the surface of the specimen and comparison standard be minimized, and (b) that the specimen and standard be kept at the same temperature within acceptable tolerance. Very small temperature differences can be measured accurately by means of a differential thermocouple, while if the two temperatures are measured separately and the difference computed, the error in the difference may be much larger. Thus it is desirable to use a differential thermocouple with suitable instrumentation to maintain the specimen and the comparison standard at the same temperature.

The spectral emittance curve of a solid material heated to a temperature below its melting point does not show the sharp peaks and valleys that are characteristic of the emission and absorption curves of solutions and gaseous materials. Hence prism monochromators with relatively wide slits are suitable for use in spectral emittance determinations, in spite of their rather poor wavelength resolution, because they pass relatively large amounts of radiant flux for measurement over a wide spectral range. The use of a variable-width slit is desirable so that in wavelength regions of low radiant flux the amount passed can be increased by broadening the wavelength band accepted for measurement. Thus the available radiant flux in the comparison beam can be maintained at a level commensurate with the sensitivity of the detector.

VI. DEVELOPMENT OF EQUIPMENT FOR NORMAL SPECTRAL EMITTANCE MEASUREMENTS

The general plan that was followed in developing equipment for determination of normal spectral emittance was to use a double-beam ratio-recording infrared spectrometer with a laboratory blackbody furnace and a heated specimen mounted normal to the direction of viewing as the respective sources for the two beams. With this arrangement the instrument will record directly the normal spectral emittance of the specimen, if the following conditions are met within acceptable tolerances: 1) The temperature of the specimen must be the same as that of the blackbody furnace; 2) the optical path length in the two beams must be equal or, preferably, the instrument must operate in a non-absorbing atmosphere or a vacuum, in order to eliminate the effects of differential atmospheric absorption in the two beams; 3) front-surface mirror optics must be used throughout, except for the prism, and equivalent optical elements must be used in the two beams in order to reduce and balance attenuation of the beams by absorption in the optical elements; 4) the source and field apertures of the two beams must be equal in order to ensure that radiant flux in the two beams compared by the apparatus will pertain to equal areas of the sources and equal solid angles of emission, and 5) the response of the detector-amplifier system must vary linearly with the incident radiant flux.

Early in the investigation it became apparent that the conditions specified under 2, 3 and 4 above were not being met within sufficiently close tolerances to permit direct recording of normal spectral emittance to the desired accuracy. To enable corrections to be made for the errors thus introduced a second, or reference, laboratory blackbody furnace, identical to the first, or comparison blackbody furnace was used.

A. Description of Spectrometer

The Perkin-Elmer Model 13 spectrometer used for the measurements is equipped with a wavelength drive that provides automatic scanning of the spectrum of radiant flux, and a slit servomechanism that automatically opens and closes the slits to minimize the variations of radiant flux in the comparison beam. Three prisms were available, 1) fused silica, to cover the spectral range of 0.25 to 3.5 microns, 2) sodium chloride to cover the spectral range 0.7 to 15 microns, and 3) cesium bromide, to cover the spectral range of 15 to 38 microns. Several photomultiplier detectors were available for use in the spectral range of 0.25 to 1.0 micron, a lead sulfide detector for use in the spectral range 1.0 to 2.0 microns, a vacuum thermocouple with sodium chloride window for use in the spectral range 1 to 15 microns, and a vacuum thermocouple with cesium bromide window for use in the spectral range 1 to 40 microns.

The source optics of the instrument were modified by incorporation of an external optical system, which is the standard Perkin-Elmer transfer optical system, used with the hohlraum reflectometer. Two 90° folds in a vertical plane were introduced in the specimen beam, to raise the axial ray of the beam 9 inches above the optical plane of the spectrometer. The comparison blackbody furnace was mounted in a fixed position to act as the source for the comparison beam, and the specimen furnace and reference blackbody furnace were mounted side by side on a movable plate attached to a slide in positions such that they could be brought alternately into position to serve as source for the specimen beam, by sliding the plate against fixed stops on the slide. A sketch of the complete optical path is shown in figure 1, and a photograph of the external optical system with furnaces in place and cover removed is shown in figure 2.

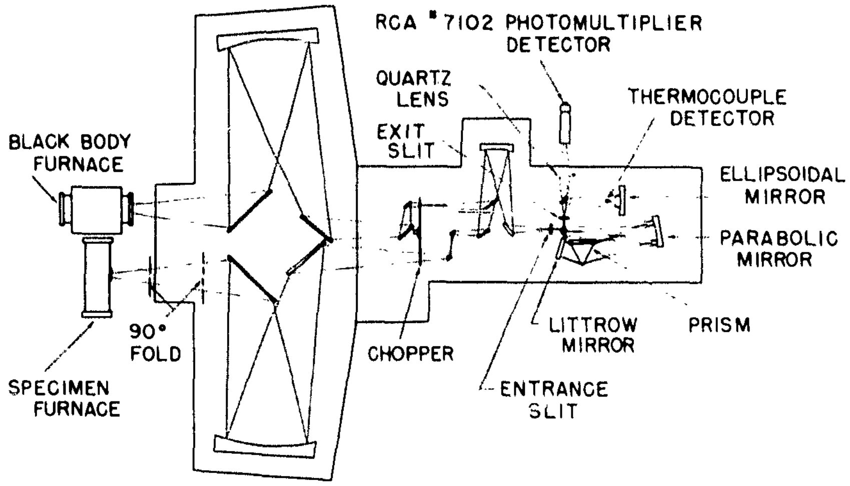

Fig. 1 Sketch of the optical path in the modified spectroradiometer.

It was found by experience that when the two blackbody furnaces were used as sources for the respective beams of the spectrometer, deviations of the recorded "100% curve" occurred at the wavelength intervals within which there is significant absorption of radiant energy by water vapor and carbon dioxide in the atmosphere. Such absorption should be identical in both beams if the spectral distribution of flux and path lengths are identical. However, the two beams are separated in time, passing through the monochromator alternately at a frequency of 13 cycles per second. Since the spectrum is being traversed continuously, one energy pulse is displaced relative to the other on the wavelength scale, by a very small amount. The effect of this displacement is negligible over most of the range, where the slope of the energy-wavelength curve is not large. But at the wavelengths near those of maximum absorption, the energy-wavelength curves become very steep, and the slight spectral displacement of the successive energy pulses can produce significant deviations in the ratios which are continuously recorded by the instrument.

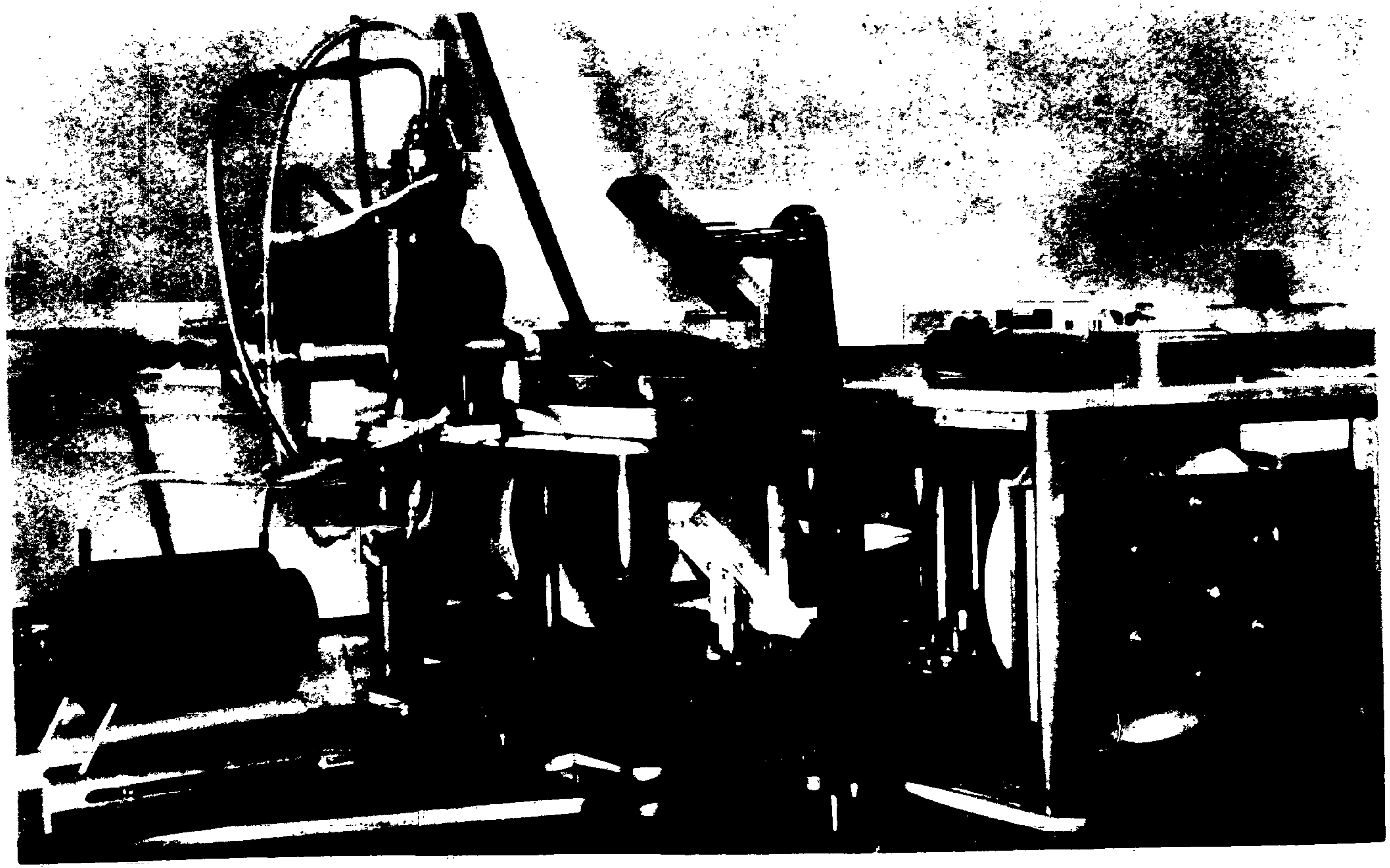

Fig. 2 A photograph of the external optical system of the spectroradiometer. The comparison blackbody furnace remains in position to act as source for the comparison beam, and the specimen enclosure is in position to act as source for the specimen beam, but can be replaced by the reference blackbody furnace by shifting the movable table on the slide.

In order to reduce the effects of absorption by atmospheric water vapor and carbon dioxide, the entire external optical system of the normal spectral emittance equipment, including the blackbody furnaces and specimen furnace, was enclosed in a lucite box. Gas-tight connecting passages were designed to join 1) the lucite box enclosing the external optics, 2) the metal cover for the chopper assembly, 3) the metal cover for the combining optics, and 4) the metal cover for the monochromator. Thus the entire length of both optical paths in the instrument was enclosed in a single system of interconnecting housings that was nearly gas-tight. Humidity in the enclosure was monitored and recorded by means of a humidigraph which records temperature and humidity. Immediately before a test the enclosure was purged with "super-dry" nitrogen, free from carbon dioxide, which was fed into the enclosure through several inlets, at a slow, constant rate, so that the enclosure was maintained at a slight positive pressure relative to the surrounding atmosphere. Tests were not started until the recorded humidity was less than 5%.

B. Blackbody Furnace and Specimen Enclosure

Two small laboratory blackbody furnaces were designed and built. Figure 3 is a sectional drawing of a furnace. The core was a casting of 80 nickel-20 chromium alloy 1 3/16 inches in diameter and 4 inches long. The cavity was 3/4 inch in diameter and 3 3/8 inches deep, threaded with 13 threads to the inch. The threads were cast in place. The 80 nickel-20 chromium alloy oxidizes to produce a high-emittance surface in the cavity.

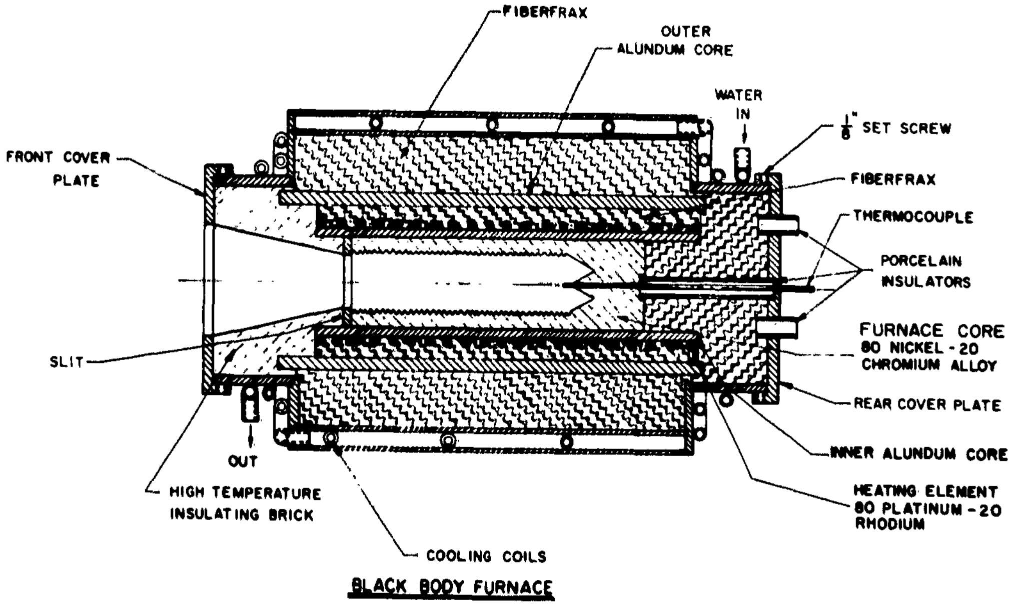

Fig. 3 Sectional drawing of a blackbody furnace.

The furnace was heated by means of a platinum-20% rhodium winding. There were two taps on the heating coil approximately one inch from each end. Shunts across the taps and leads were used to reduce thermal gradients in the cavity, as shown in figure 5. The aperture in the cavity was reduced to a slit approximately 1/4 by 3/4 inches in size by means of a Nichrome cover plate.

The temperature of the blackbody furnace was measured by means of a platinum, platinum-10% rhodium thermocouple, the bare bead of which extended about 1/4 inch into the cavity from the rear. The thermocouple leads were insulated from the core by high-alumina refractory tubing, which was surrounded by a platinum tube that was grounded, in order to prevent pickup by the thermocouple of spurious signals due to electrical leakage from the winding.

The effective emittance of the blackbody furnace, computed from the Gouffe [5] equation, assuming that the interior of the cavity is at uniform temperature, and is a completely diffuse reflector, was better than 0.999. Both of these assumptions are known to be only approximations, so that the actual effective emittance was somewhat less than the computed value. The thermocouple bead in the back of the cavity cannot be seen, even with an optical pyrometer, when the furnace is in operation, which indicates that the effective emittance is very high.

The specimens were strips of metal, 1/4 inch wide by 8 inches long, of any convenient thickness in the range of approximately 0.010 to 0.060 inch. They were heated by passing a current through them. A sketch of the specimen enclosure is shown in figure 4. The outer shell was water cooled, and its inner surface was of a nickel - chromium-iron alloy that had been threaded with a No. 80 thread and then oxidized in air at a temperature above 1350°K for 6 hours to produce a surface having a reflectance of less than 0.05 at the operating temperature of the water-cooled walls. The specimen was positioned off-center in the cylindrical enclosure, so that any radiant flux specularly reflected from the walls would be reflected twice before hitting the specimen.

The electrodes were of water-cooled copper, and were insulated from the brass end caps of the furnace by means of bakelite sleeves. The lower electrode fitted loosely in the hole through the end cap to permit the specimen to expand without buckling when heated. The specimen was viewed through a window about 3/4 by 1 inch in size. A viewing window insert reduced the opening to about 1/4 by 3/4 inch.

Adjustable baffles above and below the viewing window were used to reduce convection and the resulting temperature fluctuations and thermal gradients. Adjustable telescoping cylindrical platinum reflectors surrounded the specimen at each end. These were used to reduce heat loss at the ends of the specimen, and hence the thermal gradient along the specimen.

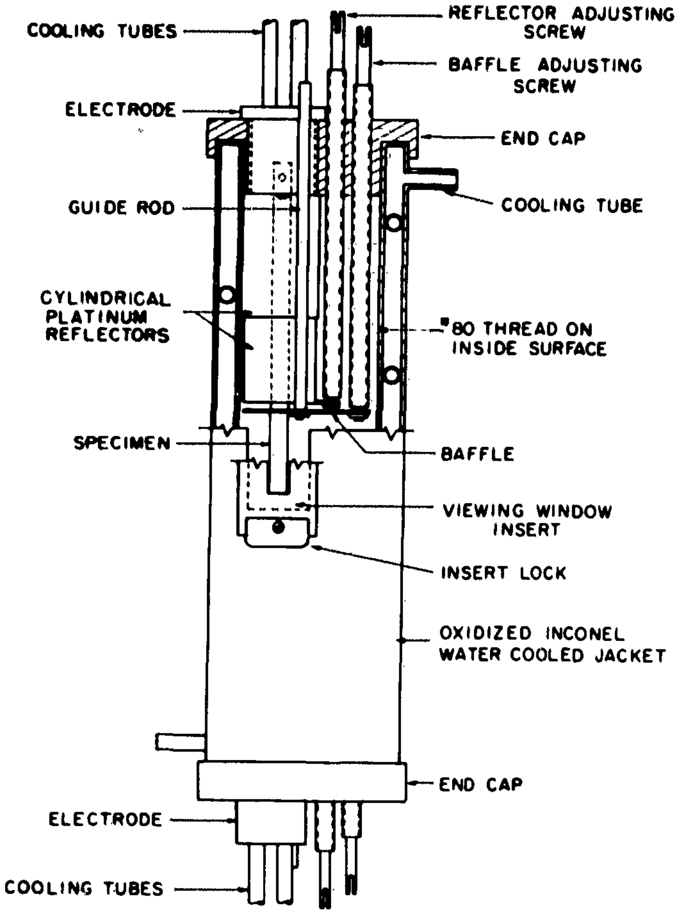

Fig. 4 Sketch of the specimen enclosure. Symmetrical about the mid-length.

C. Temperature Control Equipment

The power input to the comparison blackbody furnace was adjusted manually by means of an autotransformer. The heater winding of the furnace had two taps, located approximately one inch from each end of the winding. Variable resistors were connected as shunts across the taps and from the taps to the input leads, as indicated in the wiring diagram, figure 5. Adjustment of these resistors permitted variation of the power distribution along the cavity of the furnace by means of which thermal gradients in the cavity could be minimized. It was found by experience that the heat capacity of the blackbody furnace was large enough to practically eliminate temperature fluctuations due to momentary voltage fluctuations in the power supply. A cold furnace could be brought to 1400°K and stabilized at that temperature in about six hours, and only about 30 minutes was required to achieve stability after a temperature change of up to about 30°K. Normally the blackbody furnaces were heated overnight before use.

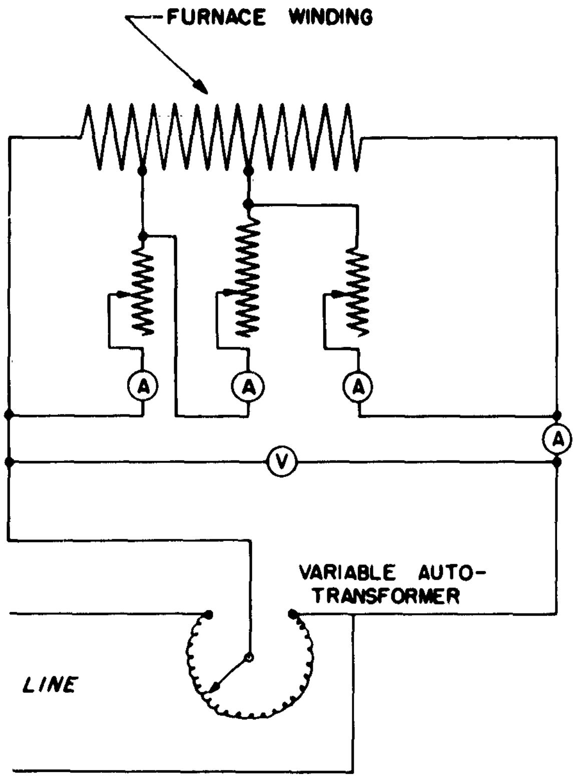

Fig. 5 Wiring diagram of power supply to comparison blackbody furnace.

The power supply for the reference blackbody furnace was identical to that shown in figure 5, except that when the temperature was to be controlled a saturable-core reactor was substituted for the autotransformer, as is described below.

The temperature of the specimen (or reference blackbody furnace) was controlled to that of the comparison blackbody furnace, within narrow limits, by means of a differential thermocouple. One bead of the differential thermocouple was in the cavity of the comparison blackbody furnace, and the other was attached to the back of the specimen, in the center of the area being viewed, as described later in this report. The signal from the differential thermocouple was amplified by a d.c. amplifier and fed to a center-zero recorder-controller. The output of the recorder-controller is proportional to the distance between the control pointer and the recorder pointer on the scale, which is in turn proportional to the temperature difference between blackbody furnace and specimen. The output of the recorder-controller was fed to a current-actuating-type controller, the output of which was separated into three portions, each of which could be varied as desired. One portion was proportional to the input signal, one was proportional to the first time derivative of the input signal, and one was proportional to the second time derivative of the input signal. The output of the current-actuating-type control was fed to the coil of a saturable core reactor which varied the power input to the specimen. It was possible to reduce undershoot and overshoot of the controlled temperature by proper adjustment of the three components in the output of the current-actuating-type control. A block diagram of the temperature control equipment is shown in figure 6.

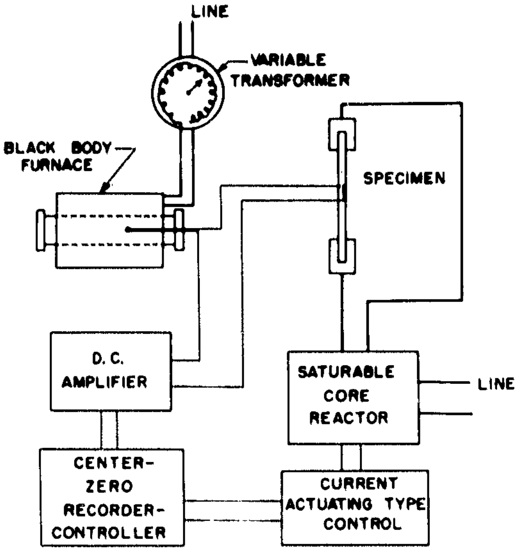

Fig. 6 Block diagram of temperature control equipment. The controller operates from a signal produced from a differential thermocouple.

With the described control equipment it has been possible to hold the temperature of a specimen as indicated by the welded thermocouple to well within ± 1°K of that of the comparison blackbody furnace, and the temperature of the reference blackbody furnace to within ± 0.5°K of that of the comparison blackbody furnace.

VII. CALIBRATION OF EMITTANCE EQUIPMENT

A. Wavelength Calibration of Monochromator

A complete wavelength calibration was made of the spectrometer with the fused silica and sodium chloride prisms, respectively, mounted in the monochromator. In calibrating the equipment with the fused silica prism, emission spectra of a helium arc and a mercury arc, and absorption spectra of a didymium glass and a polystyrene film were recorded. The emission and absorption peaks having known wavelengths were identified in the respective curves, and for each peak the observed wavelength drum position at which the peak occurred was plotted as a function of the known wavelength of the peak [6]. A total of 66 such points, at wavelengths in the range 0.24 to 2.2 microns, was plotted, and a smooth curve was drawn between the points to produce a calibration curve.

A similar procedure was followed in calibrating the equipment with the sodium chloride prism mounted in the monochromator. In this case, the atmospheric absorption curve replaced the absorption curve for didymium glass. A total of 52 points, at wavelengths from 0.4 to 15 microns, was plotted to produce the calibration curve.

B. Calibration for Linearity of Response

All of the work done with the spectrometer had been based on the assumption that the response of the instrument (the height of the recorded emittance curve above the recorded "zero curve") was linear with (1) the radiant flux (within the varying wavelength interval encompassed by the exit slit) passing through the monochromator, when the instrument is operated in single-beam mode, or (2) the ratio of the fluxes (within the varying wavelength interval encompassed by the exit slit) in the respective beams that pass through the monochromator when the instrument is operated double-beam in ratio mode. This assumption had not been checked, and a confirmation of (1) and (2) above was considered desirable.

Linearity Calibration by Varying Slit Width

The entrance and exit slits of the monochromator open and close simultaneously, and both are controlled at the same width by the slit micrometer. Because of this construction, when a true image of a source is formed at the entrance slit of the monochromator, somewhat larger than the slit at its maximum width, the radiant flux reaching the detector from the monochromator varies as the square of the slit width. This relationship was used to check the linearity of detector response when the instrument is used single-beam in direct mode (item (1) above). A single blackbody furnace, at 1400°K, was used as a source, and each series of measurements was made at a number of central wavelengths throughout the sensitive range of the thermocouple detector. Experimental results were in conformity with the theoretical relationship. In every case, when the height of the recorder curve was plotted against the square of the slit width, the points obtained with the sodium chloride prism and thermocouple detector fell on a straight line intersecting the origin, within the error of measurement.

Similar measurements were also made at several wavelengths when the spectrometer was operated with the fused silica prism and the lead sulfide detector. Again experimental results were in conformity with the theoretical relationship.

When the spectrometer was used with the fused silica prism and 1P21 detector, appreciable deviations from the theoretical relationship were found at first, but after careful realignment of the monochromator optics, all of the points again fell on a straight line, within experimental error.

Calibrations with Sector-Disc Attenuator

A sector-disc attenuator for use in calibrating the normal spectral emittance equipment was designed and built. The attenuator consists of a variable speed motor, 0 to 4000 rpm, with an attenuator disc mounted on its shaft.

Five interchangeable attenuator discs were prepared, having nominal transmissions of 75, 50, 25, 12.5 and 5.0 percent, respectively. The discs were machined from sheet aluminum 0.065 inch thick. The 5% disc is 10 inches in diameter, and has four equally spaced radial notches, each 4.5° wide, extending inward from the rim for 3 inches. The other discs are 9 inches in diameter, and have eight notches each, extending inward from the rim for 2 1/2 inches. The notches are 33 3/4° wide in the 75% disc, 22 1/2° wide for the 50% disc, 11 1/4° wide for the 25% disc, and 5 5/8° wide for the 12.5% disc.

The attenuator is normally operated at about 1300 rpm, and the direction of rotation is opposite to that of the chopper of the spectrometer. At this speed the beam is interrupted at a frequency of more than 85 cycles per second by the 5% disc, and more than 170 cycles per second by the other discs. The chopper in the spectrometer interrupts the beam at a frequency of 13 cycles per second. No coupling has been observed between the attenuator and chopper frequencies.

The attenuator discs were calibrated in the Engineering Metrology Section of NBS by measuring the angular width of the notches and blades on each disc, at two positions corresponding to the radial positions at which the top and bottom, respectively, of the interrupted beam strike the discs when in use. The unobstructed area of the disc between the two circles was computed as a percentage of the total area between the circles, with the results shown below:

Nominal Transmittance %	Measured Unobstructed Area %
75	75.10 ± 0.02
50	50.00 ± 0.02
25	25.28 ± 0.14
12.5	12.73 ± 0.14
5	5.07 ± 0.03

The measured values were assigned to the respective sector-disc attenuators.

In the next group of experiments, made for additional check of item (1) above, the sector-disc attenuator was introduced into the beam near the blackbody furnace. Each series of measurements was made at a single wavelength, a single slit width, and a single gain setting. In each case the gain was adjusted to give a reading of slightly less than 100 units on the strip chart without the attenuator. The attenuator was then introduced into the beam, and operated with each of the discs in turn. The height of the recorder curve was plotted against the previously measured fraction of the beam passed by the attenuator. In every case the points fell on a straight line passing through the origin, indicating linear detector response for every combination of slit width and wavelength tested, with both the sodium chloride and fused silica prisms, and with the thermocouple, as well as the lead sulfide and photomultiplier detectors.

In the preceding experiments for which the instrument was being used in direct mode, with single beam, the height of the recorder curve varied linearly with the signal produced by the detector. This signal was proportional to the radiant flux passing through the monochromator. Normally, however, the instrument is used in ratio mode, with double beam. In this case the height of the recorder curve should vary linearly with the ratio of the two signals produced by the detector when it is receiving flux alternately from the respective beams.

In order to check item (2) above, the two blackbody furnaces, controlled very closely to the same temperature (about 1400°K), were used as sources for the two beams. The instrument was adjusted so that the "100% curve" would actually fall between 90 and 100 on the chart, after which such a curve was obtained over the wavelength range of interest. The sector-disc attenuator was then introduced into the specimen beam near the blackbody furnace, and operated with each of the discs in turn, to obtain "75%, 50%, 25%, 12.5% and 5% curves", each over the wavelength range of interest. The heights of the respective curves were then measured at 100 selected wavelengths, and the height of each curve above the experimentally obtained zero for the pertinent wavelength was plotted against the percentage of the flux in the specimen beam that was passed by the attenuator. In every case the points fell on a straight line intersecting the origin, within the error of measurement. No significant departures from linearity of response were detected for any combination of prism and detector, at any point within the wavelength range at which they could be used.

The data for the thermocouple detector and sodium chloride prism are shown in figure 7. In this case, the "apparent emittance" of the combination of the reference blackbody furnace and each attenuator disc is plotted as a function of wavelength. Every value of apparent emittance was within ± 0.01 of the measured transmittance of the respective disc.

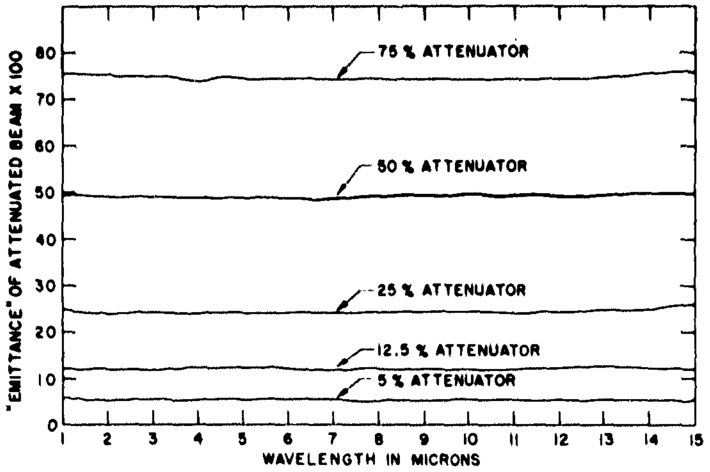

Fig. 7 Spectral "emittance" of the combination of the reference blackbody furnace and sector-disc attenuator when using the 75%, 50%, 25%, 12.5% and 5% attenuator discs. Data are for the spectrometer with the sodium chloride prism and thermocouple detector.

VIII. EXPERIMENTAL PROCEDURE

It was found by experience that the "100% curve", obtained when the two blackbody furnaces at the same temperature served as sources for the respective beams of the spectrometer, deviated appreciably from flatness. These deviations may be due to either (1) variations in spectral absorption or other losses along the respective optical paths from source to detector, or (2) variations in spectral sensitivity of the detector to radiant flux from the two beams. There are two more mirrors in the specimen beam than in the comparison beam, as is shown in figure 1. The two beams follow different paths from the sources to the spherical mirror in the combining optics, and are reflected by different mirrors in this portion of the path. From the spherical mirror in the combining optics to the detector, the two beams follow the same general path and are reflected by the same mirrors. However, the paths are not identical, and the beams are reflected by slightly different areas of each mirror, and are transmitted by different areas of the prism and the detector window. These differences could account for spectral differences in losses in the two beams, due to absorption, and to scattering, for instance by dust particles on the mirrors. The two beams are also focused on slightly different areas of the sensitive surface of the detector. Variations in spectral response over the sensitive surface of the detector could be responsible for part of the observed effect.

It was also found by experience that the zero curve, obtained when the specimen beam was blocked near the specimen furnace, deviated from flatness. These deviations are undoubtedly due to stray radiation in the monochromator, which produces a spurious signal when there is in fact no radiant energy being supplied by the specimen.

A test procedure was developed to correct for the errors which result in the deviations of the "100% Line" and "zero Line" referred to above. The procedure is as follows:

(1) The two blackbody furnaces are placed in position to act as sources for the respective beams of the spectrometer, and are brought to the same temperature. The "Full Scale" control of the spectrometer is adjusted to bring the "100% Line" to a position between 90 and 100 on the chart. The specimen beam is blocked, and the "Ratio Zero" control on the spectrometer is adjusted to bring the "Zero Line" to a position between 1 and 3 on the chart. The specimen beam is unblocked, and the position of the "100% Line" is checked. These instrument settings then remain fixed throughout the emittance determinations on the specimen being tested.

(2) The 100% Line", over the wavelength range of interest, is obtained by automatic recording on the strip chart, after which the chart paper is rerolled.

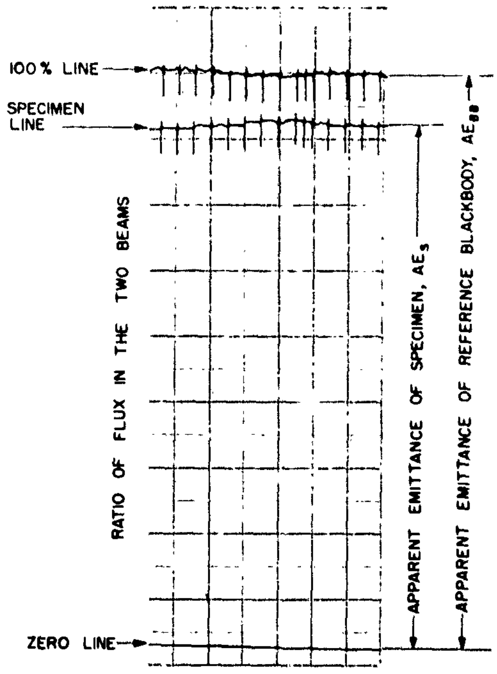

Fig. 8 A section of recorder chart, showing segments of a "100% Line", "Specimen Line" and "Zero Line." The normal spectral emittance at each wavelength is the ratio AE_S/AE_{BB}.

(3) The specimen beam is blocked near the source, and the "Zero Line" is similarly obtained over the wavelength range of interest, after which the chart paper is again rerolled.

(4) The specimen enclosure is next substituted for the reference blackbody furnace, in position to act as source for the specimen beam of the spectrometer. The temperature of the specimen is brought to and held at the temperature of the comparison blackbody furnace. The specimen beam is unblocked, and the "Specimen Line" is obtained over the wavelength range of interest. A section of the completed recorder chart is shown in fig. 8.

The heights of the respective curves are measured at preselected positions of the wavelength drum (corresponding to known wavelengths), and the normal spectral emittance is computed for each such wavelength. If Z_λ is the height of the "Zero Line", S_λ the height of the "Specimen Line", and H_λ the height of the "100% Line", at some wavelength λ, the normal spectral emittance, $E(\lambda)$, is given by

$$E(\lambda) = \frac{S_\lambda - Z_\lambda}{H_\lambda - Z_\lambda} \qquad (7)$$

Values of $E(\lambda)$ are computed for each of 100 wavelengths in the range of 1 to 15 microns, and $E(\lambda)$ is plotted as a function of wavelength. A variable scale[1/] has been found useful for making this computation. Zero on the scale is set at the zero line, 100 on the scale on the 100% line, and $E(\lambda)$ is read on the scale at the position of the specimen line. A curve is drawn through the plotted points to represent the spectral emittance curve of the specimen.

IX. SELECTION AND CALIBRATION OF WORKING STANDARDS

The selection and calibration of suitable working standards of normal spectral emittance, to be used for the comparison of results in several different laboratories, was one of the objectives of this program.

Working standards having high, intermediate and low emittance, respectively, were desired. In addition to having the desired normal spectral emittances, the working standards, to be useful, should be stable on heating in air at temperatures up to the maximum temperature at which they can be used, for times of several hundred hours. They should also be of a material that is not easily damaged in use. In order to be suitable for measurement with the equipment described in this report, the specimens are required to have electrical properties that will permit them to be heated by passing a current through them.

Specimens machined from sheet material of uniform thickness, three of each material in each of several different sizes and shapes were desired, suitable for measurement in the equipment used by different laboratories, as follows:

[1/] The Gerber scale was used in these measurements.

Strips, 1/4 x 8, 3/4 x 10 and 1 x 10 inches in size
Squares, 2 x 2 inches in size
Discs, 7/8, 1, 1 1/8 and 1 1/4 inches in diameter.

Because it was not possible to measure the normal spectral emittance of specimens of all of the above shapes and sizes with the equipment described in this report, it was decided that the measurements would be confined to six 1/4 x 8 inch strip specimens of each material. All of the specimens of a single material were cut from a single sheet of metal, and all were treated as nearly alike as possible during surface preparation.

After an extensive series of tests, the following materials were selected on the basis of the above criteria, for use in preparing the working standards:

1. For standards of low normal spectral emittance, 0.035-inch platinum sheet that had been polished and then annealed.

2. For standards of intermediate normal spectral emittance, 0.043-inch Kanthal sheet that had been sandblasted and then oxidized.

3. For standards of high normal spectral emittance, 0.053-inch Inconel sheet that had been sandblasted and then oxidized.

The tests indicated that specimens of these three materials, when prepared as outlined below, were stable in total hemispherical emittance to better than 0.02 on heating in air at the maximum temperature at which they were calibrated for periods of 200 hours.

A. Platinum Working Standards

The platinum specimens were received from the fabricator as 0.035-inch sheet, six 1/4-x-8-inch strips and three each in the following shapes and sizes: discs 7/8, 1, 1 1/8 and 1 1/4 inches in diameter, 2-x-2-inch squares, and strips 1 x 10 and 3/4 x 10 inches in size. It had been specified that the specimens were to be supplied with highly polished surfaces. The finish actually supplied was not as smooth as had been desired, but it was decided to use the finish supplied, rather than send the specimens back for reworking. A 1/8-inch hole was drilled in one end of each strip specimen, to facilitate hanging during annealing.

Each specimen was washed in hot tap water to which a commercial detergent had been added, rinsed in running hot tap water, then in distilled water, and finally in ethyl alcohol. Rubber surgical gloves were worn at all times while handling the specimens, and the central portion, observed for emittance determinations, was not touched after cleaning. The specimens were dried in air and placed in a closed container, supported by the ends or edges only, for storage prior to annealing.

All specimens were annealed in an electrically-heated, silicon-carbide-element furnace. The strip specimens were hung by means of platinum hooks suspended from aluminum oxide rods in the furnace; the square and disc specimens were supported by the edges only on ceramic forms resting on a flat ceramic slab. All of the specimens were then enclosed in a ceramic muffle. Starting with a cold furnace, the temperature of the furnace was raised to 1523°K (1250°C) over a period of six hours, and held at that temperature for one hour. The power was then turned off, and the specimens were allowed to cool in the furnace, which required two days.

The specimens were removed from the furnace by means of cleaned platinum-tipped tongs and were placed in individual plastic holders, in which they were supported only by the ends or edges. Each plastic holder, containing a specimen, was then placed in an individual cardboard box, to protect the specimen from contamination.

The six 1/4-x-8-inch strips were prepared for measurement by welding a platinum-platinum, 10% rhodium thermocouple to each specimen. A shallow groove was scratched in each specimen, normal to its axis and located at the mid-length. The 10-mil thermocouple wires were separately welded to the specimen by means of a condenser-discharge type of electronic spot welder. Each wire was laid in the shallow groove to position it for welding, and the welding operation was observed through a low-power microscope.

Precautions were taken at all times to avoid contamination of the specimens. They were handled as little as possible, and when handling was unavoidable the use of rubber gloves was continued, and even then the center portion of the specimen was not touched.

Three sets of curves were made for each strip specimen at each of three temperatures, 800°K, 1100°K, and 1400°K. Each set of curves consisted of (1) a "100% curve", obtained when the two blackbody furnaces at the test temperature were the sources for the respective beams, (2) a "zero curve", obtained when the specimen beam was blocked near the specimen furnace, and (3) a "specimen curve", obtained with the comparison blackbody at the test temperature as one source and the specimen at the same temperature as the other. Each curve was recorded over the range of wavelength drum settings corresponding to a wavelength range of approximately 1.0 to 15.0 microns.

The normal spectral emittance was computed at wavelengths approximately uniformly spaced, from 1 to 15 microns.

The 18 values (3 each on 6 specimens) at each temperature and wavelength drum setting were tabulated, and the following values were computed: (1) E, the arithmetic average of the 18 measured values, (2) e, the 95% confidence error of E, (3) σ_m, the average of six standard deviations[1], each computed from the three measured values on one of the six specimens, and (4) σ_s, the standard deviation of the six average values, one for each of the six specimens, about the grand average for all six. The values for platinum at the respective temperatures are given in Table I.

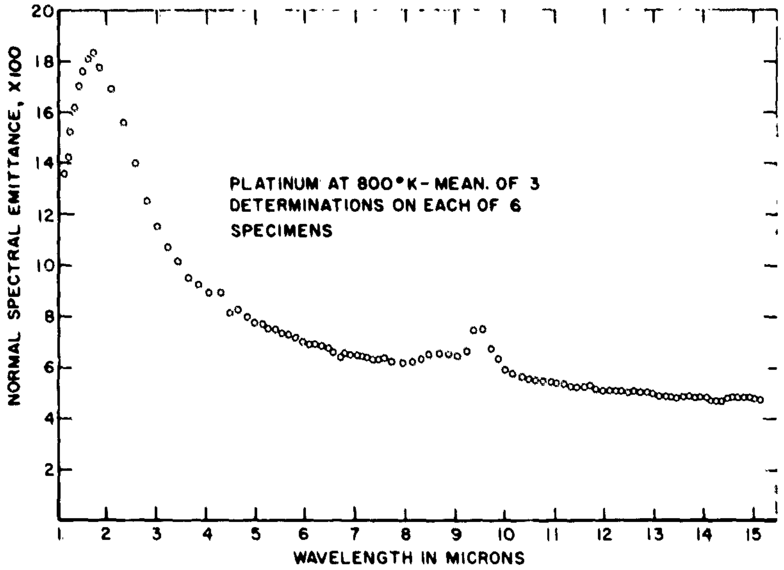

Fig. 9 Normal spectral emittance at 800°K of platinum working standards. The points on the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error[2] of the points was 0.75.

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[1] All standard deviations computed in this study are precisely defined as "estimates of the standard deviation of the parent population from which the measurements were drawn." This quantity is assigned the symbol σ, and is computed as $\sigma = \sqrt{\frac{\Sigma(x - \bar{x})^2}{n - 1}}$, where $\bar{x}$ is the average of n individual values, x.

[2] The 95% confidence error has the following statistical significance. If the measurements were repeated a large number of times, say 1000 times, and the average and 95% confidence error was computed for each group of 18 measurements, then the limits of the group average ± the 95% confidence error would bracket the overall average of the 1000 groups of measurements about 19 times out of 20.

The average normal spectral emittance, E, of the six platinum specimens is plotted as a function of wavelength for readings at 800°K in figure 9 at 1100°K in figure 10 and at 1400°K in figure 11.

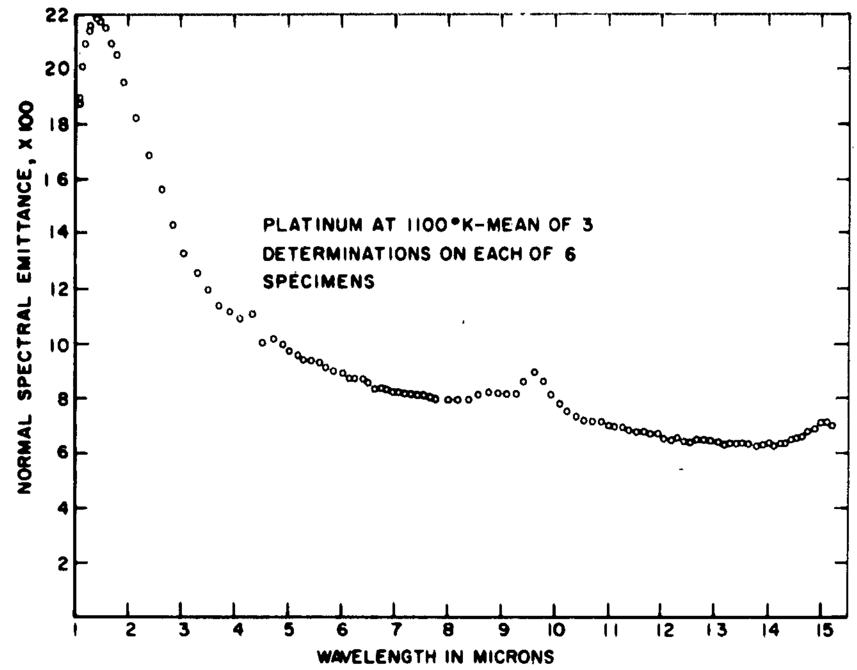


Fig. 10 Normal spectral emittance at 1100°K of platinum working standards. The points on the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 0.78.

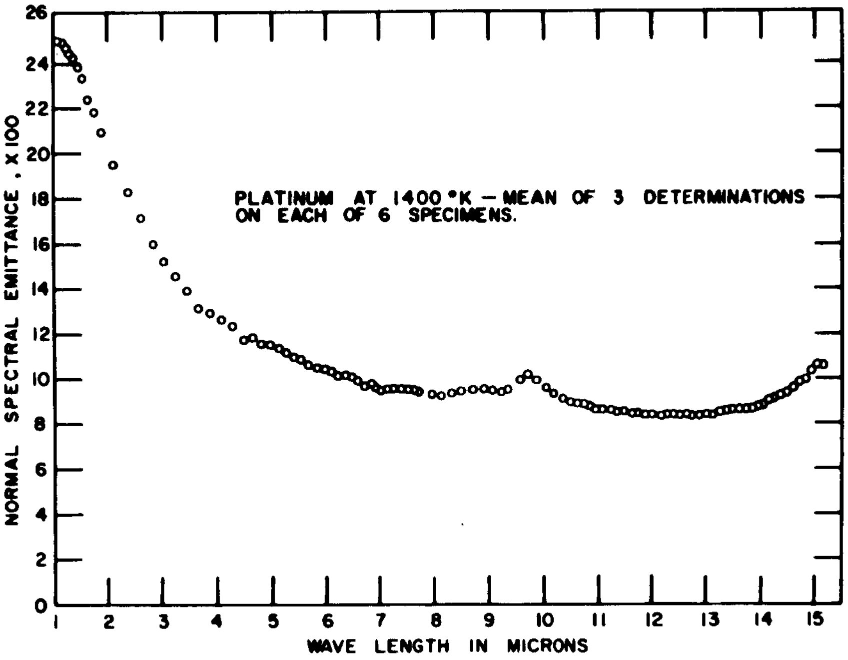


Fig. 11 Normal spectral emittance at 1400°K of platinum working standards. The points on the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 0.72.

It is apparent that the normal spectral emittance of the platinum specimens at each wavelength increases with an increase in temperature. The average values for emittance X100 at the 100 wavelengths were 7.49 at 800°K, 9.69 at 1100°K and 11.60 at 1400°K. This effect would be predicted from the Hagen-Rubens equation on the basis of the known variation in electrical resistivity of platinum with temperature.

A pronounced maximum in the spectral emittance curve occurred at a wavelength of about 1.8 microns at 800°K. This peak shifts to shorter wavelengths with an increase in temperature. This maximum is attributed to resonance of bound electrons, as discussed in more detail in a later section of this report.

A second, less prominent, maximum occurred at a wavelength of about 9.5 microns. In this case the wavelength of the peak did not change appreciably with temperature, but the peak became less prominent with increasing temperature. This peak has been observed by other workers in the field.[7] There is evidence in the curves at 1100° and 1400°K of a third maximum at a wavelength of 15 microns or beyond. The observed increasing upward sweep, with increasing temperature, of the spectral emittance curve near 15 microns could be caused by a maximum beyond 15 microns that moves to shorter wavelengths at increasing temperatures, or to a peak at or near 15 microns that does not change wavelength, but becomes more prominent with increasing temperature.

The peaks at about 9.5 microns and at 15 microns or beyond are probably caused by resonance effects, but the frequencies are below those that would be expected for bound electrons. The fact that the peaks are found on heating in air, but are not reported by other investigators who heated samples in vacuum, suggests that they may be due to an impurity, such as an adsorbed layer of gas on the surface of the specimen.

The value σ_m (the average of the six standard deviations, each computed from the three measured emittance values on one of the six specimens) is a measure of the overall reproducibility of the test procedure, or the precision of measurement. The average value of σ_m at the 100 wavelengths at 800°K was 0.35, at 1100°K, 0.45, and at 1400°K, 0.39, expressed as emittance X100. Thus the overall precision of a single measurement of normal spectral emittance of platinum is better than 0.005 in emittance, expressed as a standard deviation.

The value σ_s (the standard deviation of the six average values, one for each of the six specimens, about the grand average for all six) is a measure of the differences in emittance of the specimens that were measured. The average value of σ_s at the 100 wavelengths at 800°K was 0.70, at 1100°K, 0.74, and at 1400°K was 0.68, in units of emittance X100. A comparison of the average values of σ_s and σ_m at each temperature indicates that the measured differences between specimens are real. Such differences were regularly observed, but could not occur through chance fluctuations in the error of measurement as frequently as one time in 10,000.

In order to show any trend of σ_m and σ_s with wavelength, the moving averages at 5 adjacent wavelengths were computed and plotted as a function of the central wavelength to produce the curves in figure 12 at 800°K, figure 13 at 1100°K and figure 14 at 1400°K. There appears to be significant variation in σ_s with wavelength at each temperature. The variation in σ_m with wavelength is much smaller. The value of σ_m is smaller than the corresponding value of σ_s at each wavelength at each temperature.

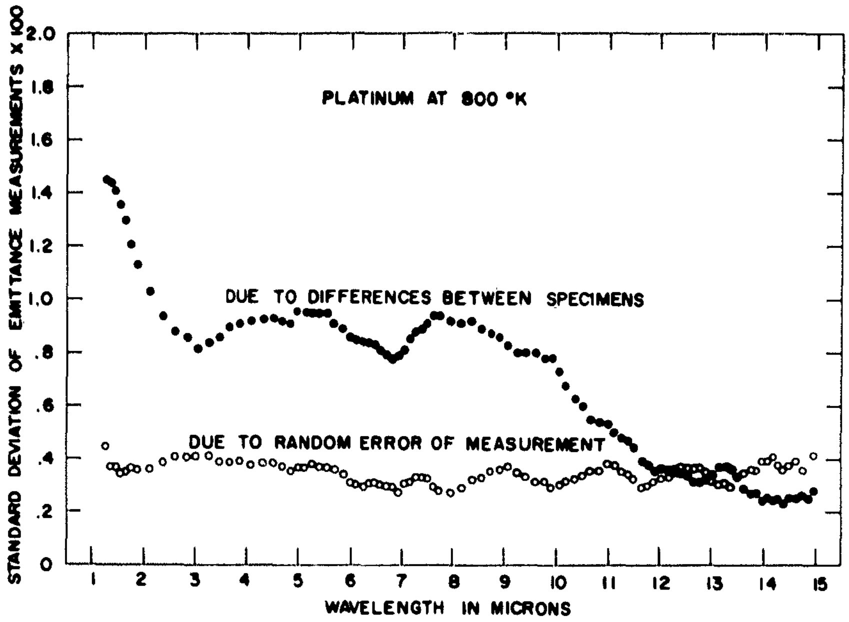


Fig. 12 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 800°K, three each on six platinum working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

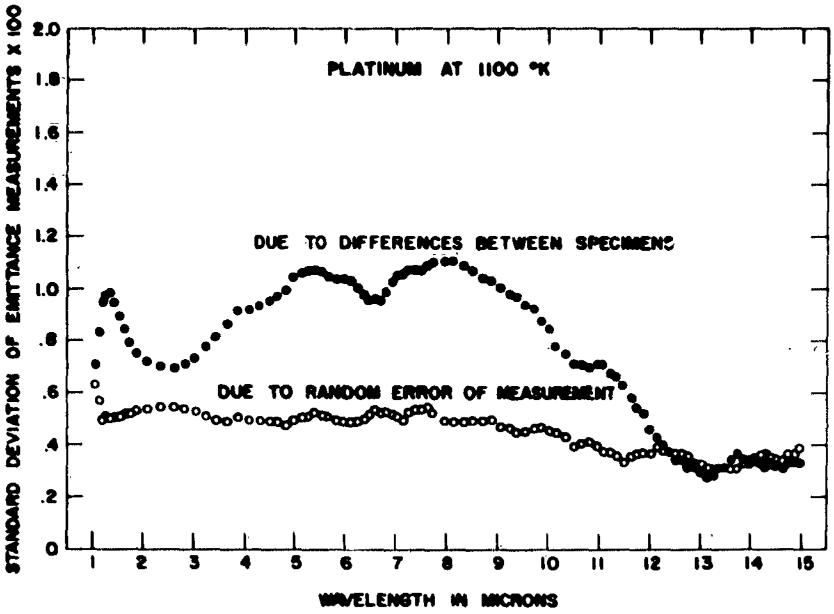


Fig. 13 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1100°K, three each on six platinum working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

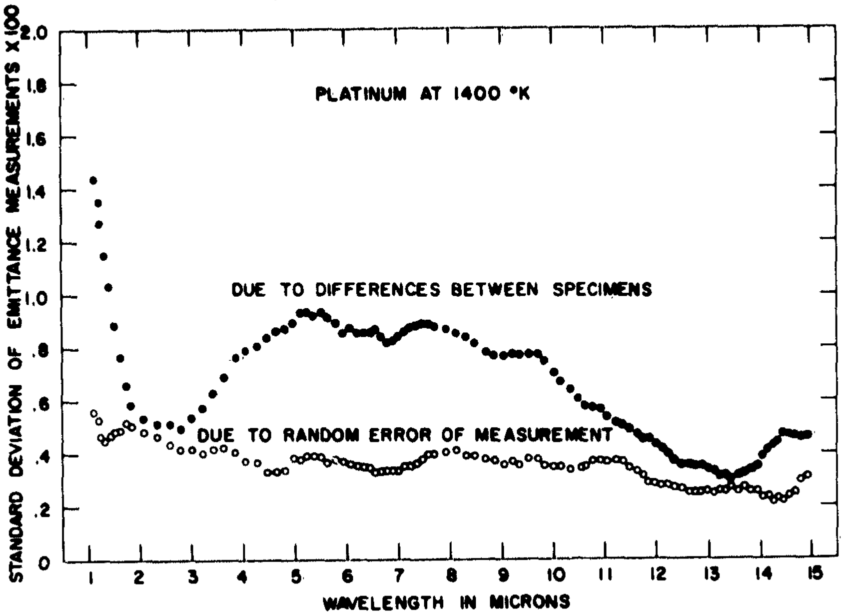


Fig. 14 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1400^{o}K, three each on six platinum working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

B. Oxidized Kanthal Working Standards

Specimens of the sizes and shapes referred to above were machined from 0.043-inch Kanthal sheet, marked for identification, and then cleaned with acetone to remove any oil or grease from the machining operation. They were sandblasted with 60-mesh fused alumina grit at an air pressure of approximately 70 psi. The sandblasted specimens were cleaned ultrasonically in acetone, passivated for one minute in 10% nitric acid at 316^{o}K (43^{o}C), rinsed in distilled water and then in freshly distilled acetone. The cleaned specimens were subjected to a minimum of handling. When handling was unavoidable, surgical rubber gloves were worn to eliminate fingerprints, and the specimens were touched only by the ends or edges. The strip specimens were suspended from a metal rack by means of oxidation-resistant metal hooks, and the rack was inserted into a cold furnace. The disc specimens were supported by the edges only on special ceramic supports placed on the hearth of the furnace. The 2 x 2-inch square specimens were also supported by the special ceramic supports, which made line contact with the specimen in a 1 3/4-inch diameter circle. The furnace was brought to 1340°K and held at that temperature for 400 hours, after which the power was cut off, and the specimens were allowed to cool in the furnace.

The specimens were removed from the furnace by means of cleaned stainless-steel tongs, and were placed in individual plastic holders, in which they were supported by the ends or edges. Each plastic holder, containing a specimen, was then placed in an individual cardboard box, to protect the specimen from contamination.

The six 1/4 x 8-inch strips were prepared for measurement by welding a platinum-platinum 10% rhodium thermocouple to each specimen. The oxide layer was removed in a narrow strip and a shallow groove was scratched in each specimen near its mid-length and normal to its axis. The oxide was also removed by grinding for a distance of approximately one inch at each end, to ensure good electrical contact with the electrodes. The thermocouples were welded by means of a condenser-discharge type of electronic spot welder, as described for the platinum specimens. Surgical rubber gloves were worn at all times while handling the specimens, and care was taken to prevent contamination of the center four inches of each specimen.

The normal spectral emittance of each of the six specimens was measured three times at each of three temperatures, 800°, 1100° and 1300°K, and the data were reduced and analyzed statistically, as is described in more detail for the platinum specimen.

The values at each wavelength and temperature are given in Table II for E, σ_t, e, σ_m and σ_s, as previously defined.

The normal spectral emittance, E, is plotted as a function of wavelength for measurements at 800°K in figure 15, 1100°K in figure 16 and 1300°K in figure 17. The 95% confidence errors associated with the plotted emittances are also plotted in the same figures. Again the emittance increased at all wavelengths with an increase in temperature. The average values at the 100 wavelengths are 60.7 at 800°K, 65.2 at 1100°K and 66.9 at 1300°K, expressed as emittance X100.

There is no pronounced maximum or minimum in the spectral emittance curve. Two broad maxima occur at about 1.25 and 11 microns, respectively, and there is a shallow minimum at about 7 microns. The oxidized Kanthal specimens are comprised of a transmitting oxide layer over a rough metal substrate. The thickness of the oxide layer is such that on a polished substrate, interference effects due to multiple reflections within the layer produce maxima at several wavelengths in the 1 to 15 micron range. Such effects do not appear with the sandblasted substrate.

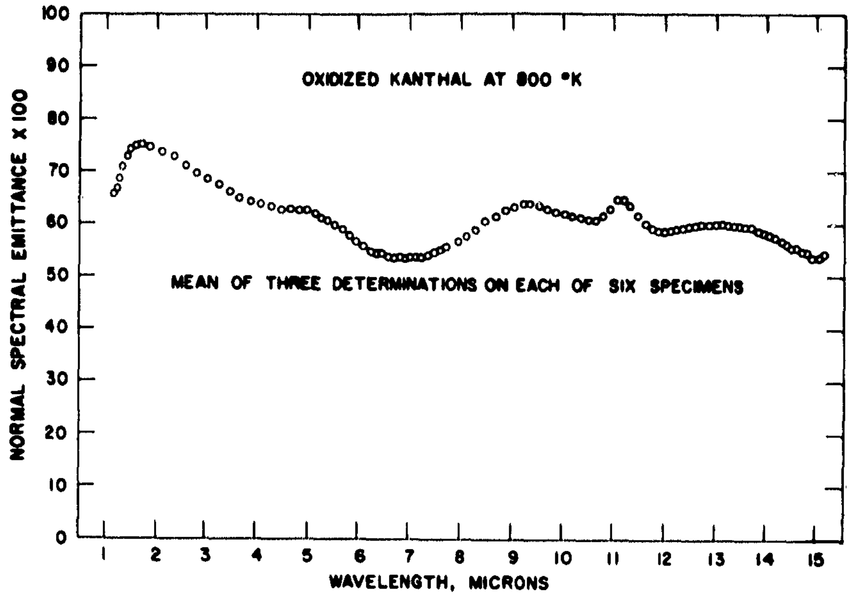


Fig. 15 Normal spectral emittance at 800°K of oxidized Kanthal working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 1.70.

The average values for the standard deviation σ_m for the 100 wavelengths were 0.53 at 800°K, 0.85 at 1100°K and 0.70 at 1300°K, expressed in units of emittance X100. Thus the overall precision of measurement, expressed as a standard deviation, is better than 0.009 in emittance. The corresponding average values for σ_s were 1.62 at 800°K, 2.09 at 1100°K and 2.32 at 1300°K. This indicates that the differences in emittance between specimens of oxidized Kanthal were more than twice as great as the corresponding differences with the platinum specimens. Again the differences are real, and could not occur due to chance fluctuations of the error of measurement as frequently as one time in 10,000.

The moving averages of σ_m and σ_s at five adjacent wavelengths were computed and plotted as a function of the central wavelength to produce the curves shown in figure 18 for values at 800°K, figure 19 at 1100°K and figure 20 at 1300°K. There appears to be significant fluctuation of σ_s with wavelength at each temperature. The variations of σ_m with wavelength are much smaller.

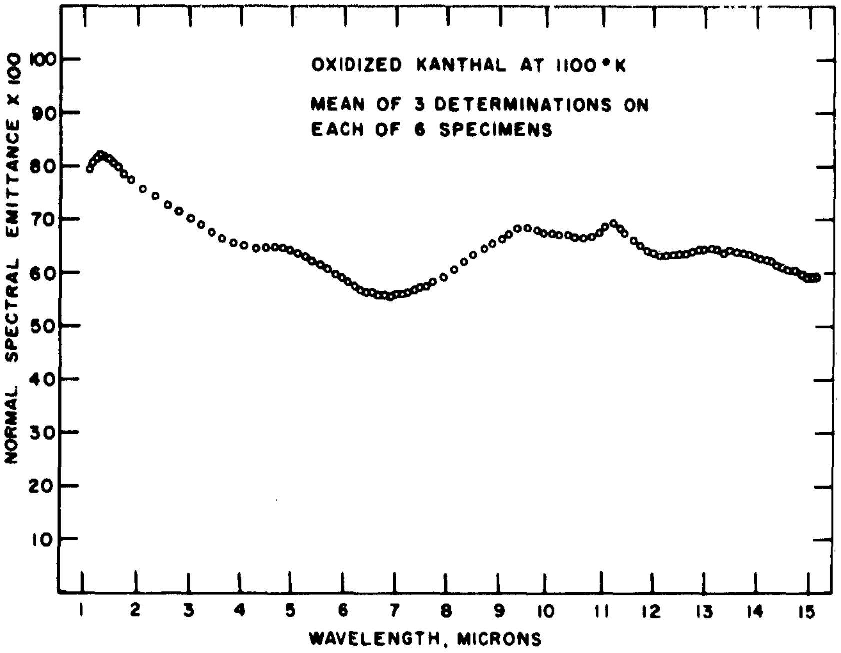


Fig. 16 Normal spectral emittance at 1100^{o}K of oxidized Kanthal working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 2.26.

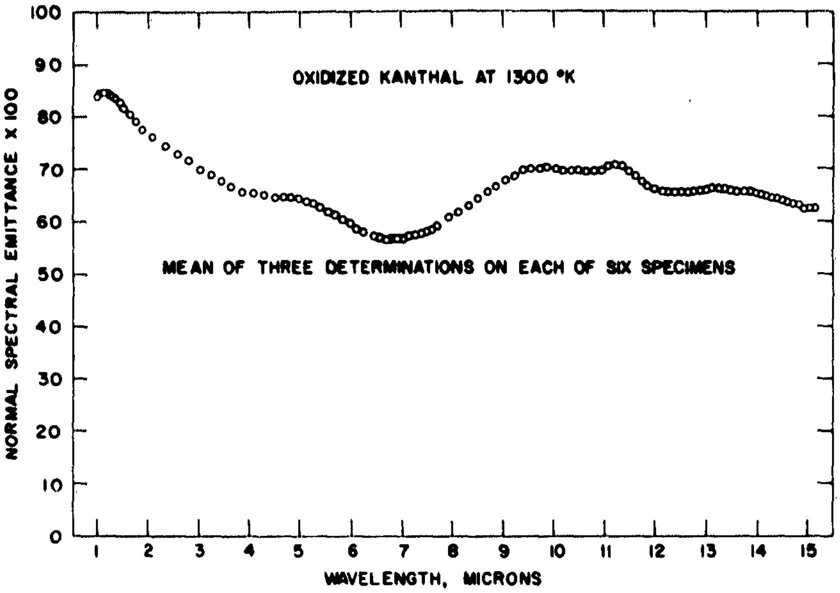


Fig. 17 Normal spectral emittance at 1300°K of oxidized Kanthal working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 2.45.

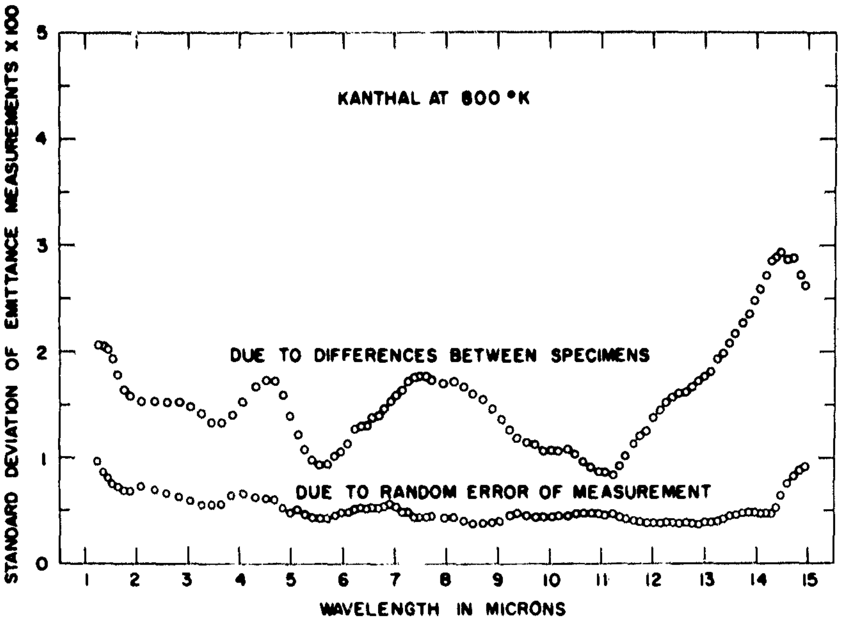


Fig. 18 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 800°K, three each on six oxidized Kanthal working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

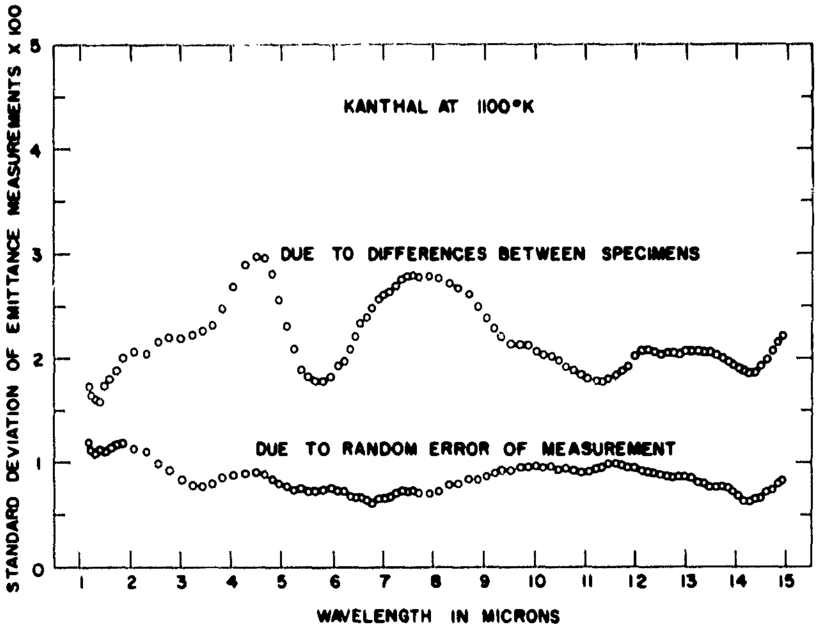


Fig. 19 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1100°K, three each on six oxidized Kanthal working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

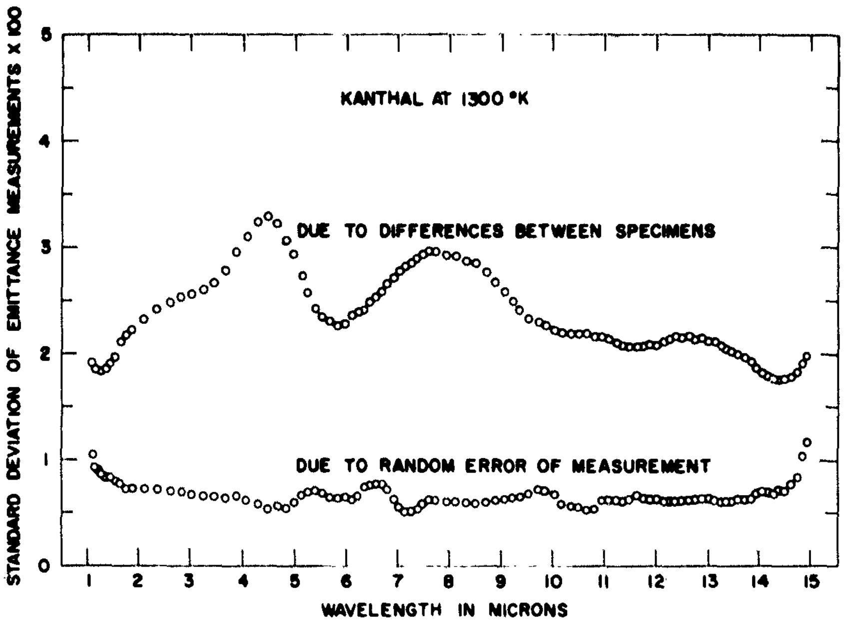


Fig. 20 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1300°K, three each on six oxidized Kanthal working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

C. Oxidized Inconel Working Standards

Specimens of the same sizes and shapes referred to above were machined from 0.053-in. Inconel sheet, and were cleaned and sandblasted as described above for the Kanthal specimens. The cleaned specimens were placed in a cold furnace, following the procedure previously described. The temperature of the furnace was brought to 1340°K (1067°C) and held for 24 hours, then dropped to 1100°K (827°C) and held for an additional 24 hours. The specimens were then allowed to cool in the furnace.

The normal spectral emittance of the six 1/4 x 8-in. specimens was measured, following the procedure described above for the oxidized Kanthal specimens, and the data were reduced and analyzed statistically as before. The values at each wavelength and temperature are given in Table III for E, σ_t, e, σ_m and σ_s, as previously defined.

The normal spectral emittance, E, is plotted as a function of wavelength for measurements at 800°K in figure 21, at 1100°K in figure 22 and at 1300°K in figure 23. The 95% confidence errors associated with the

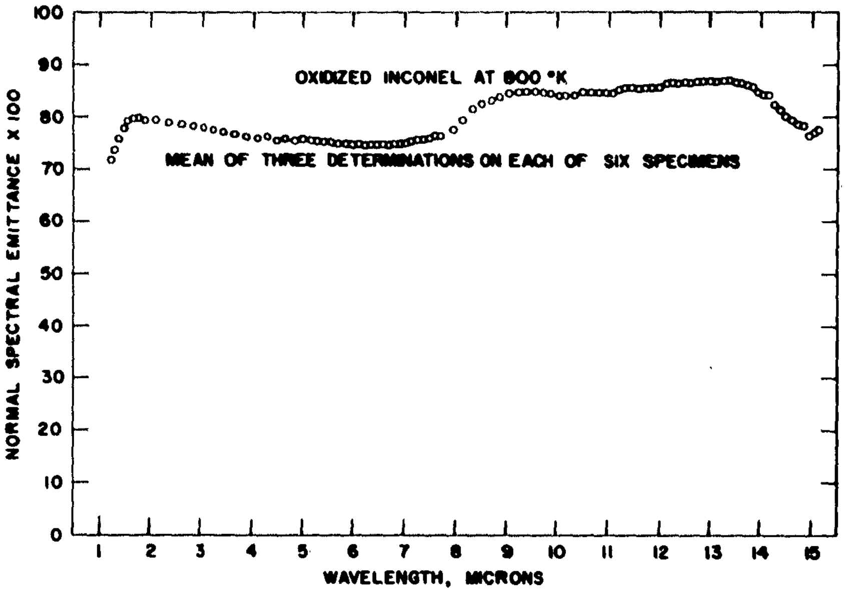


Fig. 21 Normal spectral emittance at 800°K of oxidized Inconel working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 2.87.

plotted values are also included in the same figure. Again emittance increased with an increase in temperature, at all wavelengths. The average values at the 100 wavelengths were 80.3 at 800°K, 83.2 at 1100°K and 84.9 at 1300°K, expressed as emittance X100. The spectral emittance curve is relatively flat, with a small maximum at about 1.4 microns and a second very broad maximum at about 13.5 microns. The oxide layer on the Inconel specimen was thick enough to be opaque. The oxide layer is a complex mixture of the oxides of nickel, chromium and iron, including some spinels, for which it would be very difficult to predict the occurrence of emission and absorption peaks.

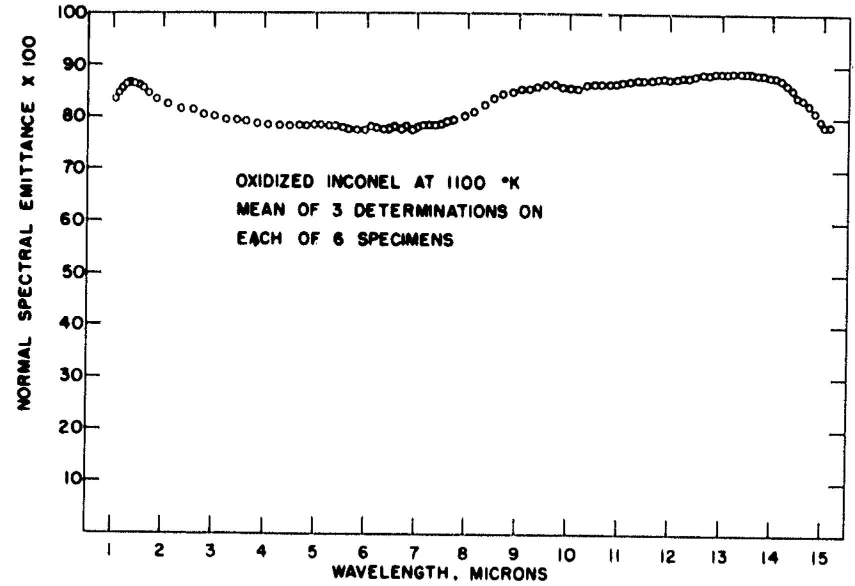


Fig. 22 Normal spectral emittance at 1100°K of oxidized Inconel working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 2.82.

The average values for the standard deviations σ_m for the 100 wavelengths were 0.74 at 800°K, 0.74 at 1100°K and 0.89 at 1300°K, expressed in units of emittance X100. Thus the overall precision of measurement, expressed as a standard deviation, is better than 0.009 in emittance. The corresponding average values for σ_s were 2.74 at 800°K, 2.64 at 1100°K and 2.24 at 1300°K, again expressed in units of emittance X100. The differences are real, and could not occur due to chance fluctuations in the error of measurement as frequently as one time in 10,000.

The moving averages of σ_m and σ_s at five adjacent wavelengths were computed and plotted as a function of the central wavelength to produce the curves shown above in figure 24 for values at 800°K, 25 at 1100°K and 26 at 1300°K. There appears to be significant fluctuation of σ_s with wavelength at each temperature. The fluctuations of σ_m with wavelength are much smaller.

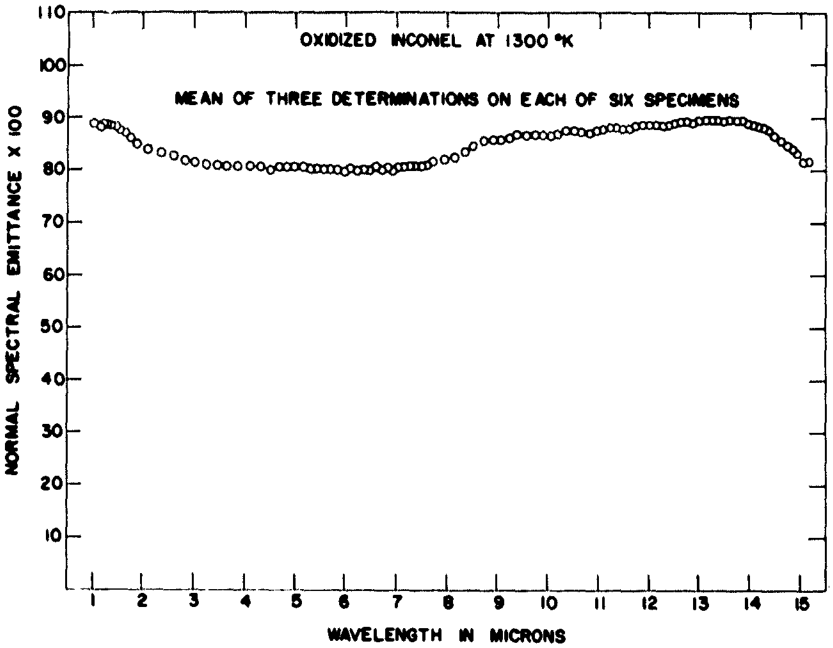


Fig. 23 Normal spectral emittance at 1300°K of oxidized Inconel working standards. The points in the upper curve represent averages of 18 measured values, three each on six specimens. The average 95% confidence error of the points was 2.34.

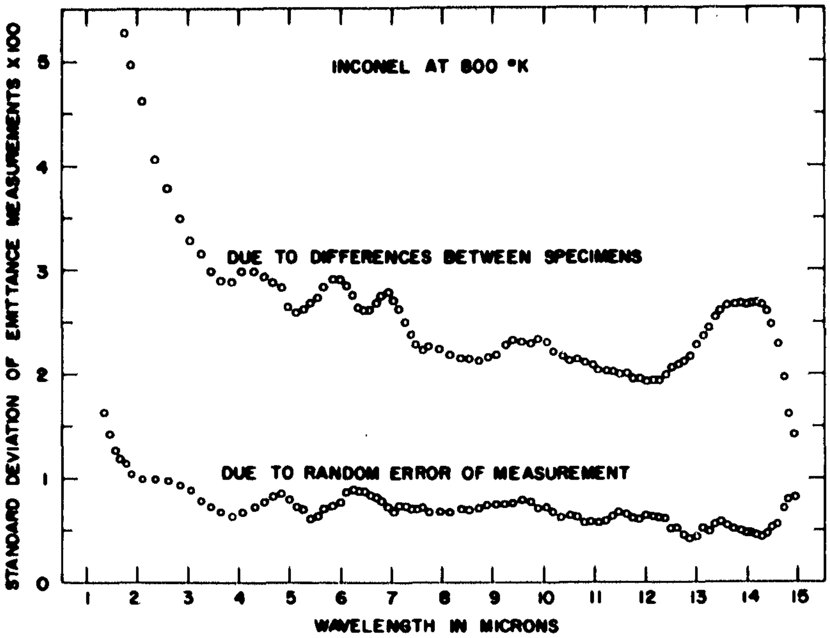


Fig. 24 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 800°K, three each on six oxidized Inconel working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

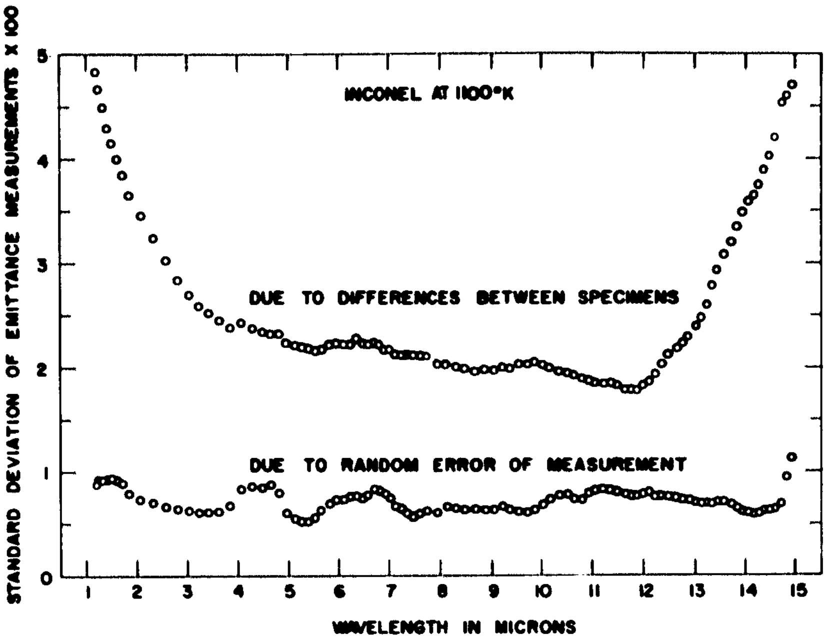


Fig. 25 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1100°K, three each on six oxidized Inconel working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

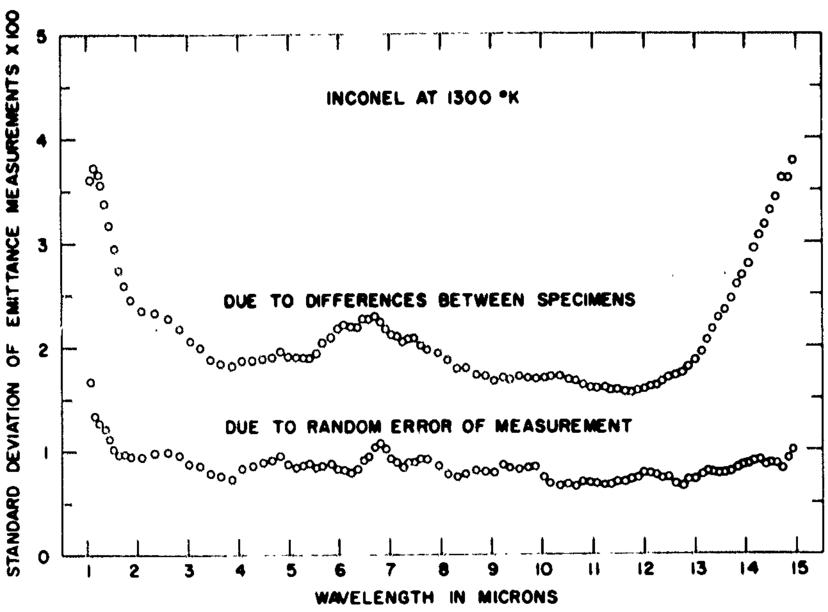


Fig. 26 Spectral distribution of two categories of standard deviations, each computed from 18 measured emittance values obtained at 1300°K, three each on six oxidized Inconel working standards. The upper curve represents standard deviations due to real differences in emittance between specimens, identified as σ_s in the text. The lower curve represents standard deviations due to random error, identified as σ_m in the text. In both curves each point represents the moving average of five adjacent values.

X. COMPUTATION OF TOTAL EMITTANCE AND ABSORPTANCE

A. Computation by the Weighted-ordinate Method

Two steps are necessary in order to compute the total normal emittance or absorptance of a specimen for radiant flux having a specified spectral distribution from its spectral emittance curve. These steps are described in relation to figure 27, which represents an actual case.

The first step is to weight a series of ordinates chosen at uniform wavelength intervals along the spectral emittance curve for the specimen (Curve A) according to the spectral distribution of flux from a blackbody at the temperature of the specimen, which can be represented by a second Curve, B. The weighted ordinates, which are the products of ordinates at identical wavelengths for Curves A and B, provide points for Curve C, which

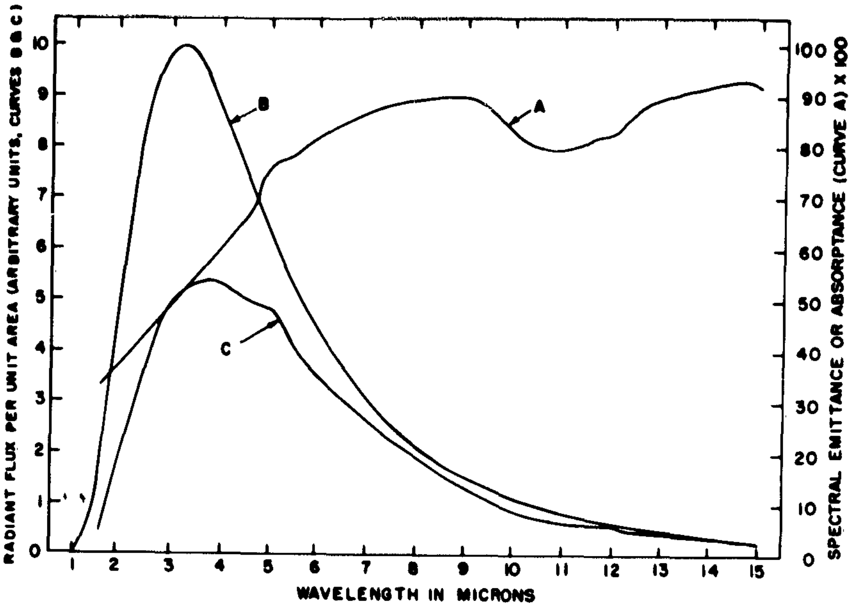


Fig. 27 Graphical form of data and derived values used in computing from the spectral emittance of a specimen its total emittance, its total absorptance, or its total emissive power. Curve A represents spectral emittance values obtained on a specimen at 650°K (about 1200°F). Curve B represents the spectral distribution of radiant flux from a blackbody at the same temperature. The values represented by Curve C are in each case the product of the values represented by Curves A and B at the same wavelength. Curve C represents the spectral distribution of flux emitted by the specimen having the spectral emittance indicated by Curve A.

indicates the spectral distribution and amount of radiant energy emitted by the specimen in unit time. In the case of absorptance, Curve B represents the spectral distribution and amount of incident flux, and Curve C represents the spectral distribution and amount of absorbed flux.

The second step in computing the total emittance or absorptance of a specimen consists of determining the ratio of the area under Curve C to that under Curve B. A rigorous mathematical expression of the quantity sought is as follows:

$$E_{ts} = \frac{\int_0^\infty \epsilon_{b\lambda} \, E_s(\lambda) \, d\lambda}{\int_0^\infty \epsilon_{b\lambda} \, d\lambda} \tag{8}$$

where: E_{ts} = total Emittance of specimen

$\epsilon_{b\lambda}$ = rate of energy emission per unit wavelength interval, of a blackbody, for the increment λ to $(\lambda + d\lambda)$

$E_s(\lambda)$ = Emittance of the specimen, at wavelength λ.

In practice, with a sufficient number of uniformly-spaced ordinates (which are taken at the same set of wavelengths for all the curves) this ratio of areas is approximated with the required precision by dividing the sum of the ordinates for Curve C by the sum of the ordinates for Curve B. The mathematical expression of this operation is given below.

$$E_{ts} = \frac{\sum_{\lambda_1}^{\lambda_2} \epsilon_{b\lambda} E_s(\lambda) \Delta\lambda}{\sum_{\lambda_1}^{\lambda_2} \epsilon_{b\lambda} \Delta\lambda} \qquad (9)$$

Since all values of $\Delta\lambda$ are equal, they cancel out numerically as well as dimensionally.

The units in which the ordinates of Curve A are expressed are pure numbers, representing spectral-emittance values. The units in which the ordinates for Curve B are expressed occur in both the numerator and denominator of the final ratio; hence it is of no consequence what units are used, provided they are the same for the numerator and denominator, or whether the ordinates for Curve B are expressed simply as numbers of the correct relative magnitudes. The final answer in either case is a number signifying the total absorptance of the specimen for radiant flux of the specified spectral distribution.

The procedure is identical for computing either total emittance of the specimen, or its absorptance for radiant energy from any source of known spectral distribution. To compute total emittance, Curve B represents the spectral distribution of a blackbody at the temperature of the specimen (as was done for figure 27). To compute absorptance, Curve B represents the spectral distribution of flux from the source.

When it is desired to compute the total amount of radiant energy, for unit time and area, emitted by the specimen at a given temperature, then Curve B will represent blackbody radiation and its ordinates will be expressed in energy per unit time and area; hence those of Curve C will also. In this case the quantity sought is represented by the area under Curve C, which can be obtained by integration. The equation that rigorously describes this relationship for all possible wavelengths is:

$$\epsilon_{ts} = \int_0^\infty E_s(\lambda) \epsilon_{b\lambda} d\lambda \qquad (10)$$

ϵ_{ts} = total emissive power of the specimen.

In practice the value can be computed with the required precision by the following approximation:

$$\epsilon_{ts} = \sum_{\lambda_1}^{\lambda_2} E_s(\lambda) \epsilon_{b\lambda} \Delta\lambda \qquad (11)$$

As in the case of emittance and absorptance, the procedure is the same whether the object is to compute the total radiant flux emitted by unit area of the specimen or the total radiant flux absorbed upon exposure to a specified source. In the former instance, Curve B represents blackbody radiation; in the latter case it represents radiant flux from the specified source that is incident upon the specimen.

B. Computation by the Selected Ordinate Method

Regardless of what method of computation is chosen, the objects remain (1) to obtain the ratio of areas under two Curves, B and C, for total emittance or total absorptance, and (2) to evaluate the area under one Curve, C, for total radiant flux per unit area of the specimen, absorbed from a specified source, or emitted. Such values characterize the specimen at a given temperature only.

Ordinarily it is preferable to use no more ordinates for the calculations than are needed to give the required accuracy. The optimum number of ordinates can be chosen by spacing them to represent equal areas under Curve B, a device which results in unequal values of $\Delta\lambda$. When this method is used, the first step is to choose ordinates for Curve B at increments of λ such that the areas between all adjacent pairs of these ordinates correspond to a constant amount, k, of radiant flux per unit area. Then the median wavelengths within the respective intervals between these adjacent pairs of ordinates determine the locations of the selected ordinates. When the ordinates of Curve A are read at these specified values of λ, the rate at which energy is emitted per unit area of the specimen can be obtained with the required accuracy simply by adding up these ordinates and multiplying the sum by the constant, k. The basic equation is·

$$\epsilon_{ts} \approx \sum_{\lambda_1}^{\lambda_2} E_s(\lambda)\ (\epsilon_{b\lambda}\Delta\lambda) \tag{12}$$

But since $(\epsilon_{b\lambda}\Delta\lambda)$ has the constant value k, independent of wavelength, the equation becomes:

$$\epsilon_{ts} \cong k \sum_{\lambda_1}^{\lambda_2} E_s(\lambda) \tag{13}$$

Often, for convenience, ordinates are selected at intervals such that $k = 1$.

The economy in number of ordinates required for a given precision makes this method especially advantageous in the absence of electronic computers. Like the weighted-ordinate method, it is applicable to calculation of total emittance or total absorptance from the spectral data, as well as to calculation of rate of emission or absorption of energy by unit area of the specimen.

XI. DEVELOPMENT OF DATA-PROCESSING EQUIPMENT

A. Operation of Spectrometer

The spectrometer generates two d. c. potentials, one, V_c, proportional to the flux reaching the detector by way of the comparison (blackbody) beam, and the other V_s, proportional to that reaching the detector by way of the specimen beam. The ratio V_s/V_c is measured and recorded by the instrument, and is here referred to as the apparent emittance. This ratio is measured by applying potential V_c to the slidewire of a self-balancing recording potentiometer and utilizing the servo-balancing to position the potentiometer arm so that its potential is equal to the potential V_s. As the wavelength is scanned this position is recorded on a chart as a decimal fraction of the total range, representing the apparent emittance as a function of wavelength. This apparent emittance must be corrected for the "100% error" and "zero error", as described in Section VIII - Experimental Procedure.

Reading the emittance from the potentiometer charts by means of a variable scale as described in Section VIII is time-consuming, and somewhat subject to error. One of the objectives of this project was to obtain automatic data-processing equipment to perform these and certain other operations automatically, and thus reduce the time and labor cost required to obtain the spectral emittance data.

B. Requirements of Data-Processing Equipment

The requirements for the data-processing equipment include performance of the following functions:

(1) To produce a corrected graphical record of the normal spectral emittance of a specimen as a function of wavelength, (2) to record on punched paper tape the digitized, corrected spectral emittance and wavelength values, in form suitable for direct entry into a separate electronic digital computer, and (3) to accumulate the digitized emittances at wavelengths which have been preselected to yield total emittance or absorptance information, as discussed in the preceding section of this report.

These functions could be performed by an all-digital system, or by an analog-digital system. An analog-digital system was finally selected, as described below.

C. Operation of Data-Processing Attachment

The input to the data-processing attachment consists of the recording potentiometer arm displacement, which is proportional to the ratio V_s/V_c. The data-processing equipment utilizes an analog-digital system to correct the V_c and V_s potentials, in accordance with the results of the previous "100%" and "zero" calibration runs, before their ratio is measured on the potentiometer, as described below. The result tends to be systematically correct with only random instrumentation and digitization errors remaining.

The position of the recording potentiometer arm is digitized by a shaft encoder actuated by the potentiometer arm position. The encoder comprises two axially centered discs, one stationary and one mounted on the potentiometer shaft. Each disc is made of transparent material, on which curved, but nearly radial, opaque stripes of a black coating have been applied. A glowing lamp filament supplies light that passes through the space between stripes. Those spaces are alternately open and blocked as the movable disc rotates. This light is sensed by two photoelectric cells, so placed that one cell receives light first when the movable disc is rotated in the clockwise or "forward" direction, and the other cell receives light first when the direction of rotation is reversed. A directional flip-flop is operated by the pulse from the cell first detecting light. A pulse is produced for each increment of rotation corresponding to 0.1 scale division on the chart, or 0.001 in emittance. The pulses are counted in a reversible counter that is gated so that it increases in count when actuated by pulses received in the forward direction of the flip-flop, and decreases in count when actuated by pulses received in the opposite direction.

A synchronous motor drives a wavelength drum whose position is geared to that of the Littrow mirror, and hence determines the wavelength of the radiant flux being measured. The shaft position of the drum is digitized in the same manner as the potentiometer arm position, and the resulting pulses are counted on a second reversible counter.

During calibration runs the pulses produced by the encoder on the potentiometer arm shaft are recorded on 16-mm-wide four-channel magnetic tape, which is perforated along one side in the same manner as 16 mm movie film and driven by a synchronous motor through a sprocketed capstan to prevent slippage. The equipment is connected as indicated in the block diagram, figure 28. Since the magnetic tape and the wavelength drum are each driven by a synchronous motor, and the tape motor is always started by an automatic switch tripped by the wavelength drum, pulses on the tape correspond to the same position on the wavelength drum in repeated runs.

The reference blackbody furnace is substituted for the specimen and controlled at the same temperature as the comparison blackbody furnace during the 100% calibration run. The function selector switch is turned to the "record 100%" position, thus bypassing the "ratio zero" adjustment in the spectrometer, as indicated in figure 29. The 100% line is then recorded on the magnetic tape, the "forward" pulses on one channel and those in the other direction on a second channel. Only the pulses, and hence only the deviations in the 100% line, not the position of the line, are recorded. Thus it is necessary to note the reading on the potentiometer at the start of the 100% line calibration.

During the "zero line" calibration the specimen beam is blocked near the specimen furnace. The procedure described above is used to record the zero line deviations on the second pair of channels on the magnetic tape. The initial reading on the potentiometer must also be noted.

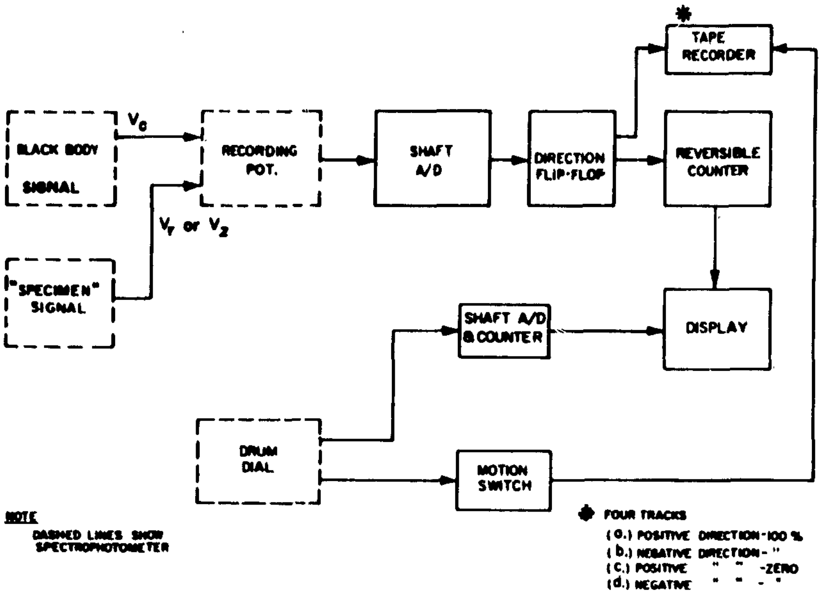


Fig. 28 Block diagram of data-processing attachment during recording of "100% line" and "zero line" deviations.

When a specimen is tested, the recorded emittance is corrected automatically for deviations in the "100% line" by modifying the V_c potential as follows: the V_c potential is fed to the 100%-line potentiometer, connected as indicated in figure 30. The arm of this potentiometer is driven by a ratchet motor, actuated by two monostable multi-vibrator circuits, one for each direction of rotation. During a specimen determination run the magnetic tape, on which the calibrations have been previously recorded, is played back synchronously with the wavelength drive. The pulses on the tape are amplified and those from the forward channel actuate the multivibrator that drives the arm of the potentiometer upward by increments of 0.1%, and those from the other channel drive it downward by equal increments. The 100%-line potentiometer overall resistance is adjusted to maintain constant load on the input circuit regardless of selector switch position. At the start of a determination, the 100%-line potentiometer is set to the value that was noted at the start of the 100%-line calibration. During the measurement, the magnetic tape playback continually modifies the V_c signal, in the amount and direction determined by the deviation from ideal of the V_r/V_c ratio that was recorded during the 100%-line calibration. V_r is proportional to the flux from the reference blackbody furnace reaching the detector by way of the specimen beam. This modified V_c signal is applied to the higher-voltage end of the slide wire of the recorder potentiometer. The effect is to introduce into the V_c signal the same systematic errors that were observed in the V_r signal, in order to correct the recorded ratio of V_s to V_c to equal the ratio of V_s to V_r. A mathematical analysis of the operation of the data-processing equipment in making corrections is given in Appendix A.

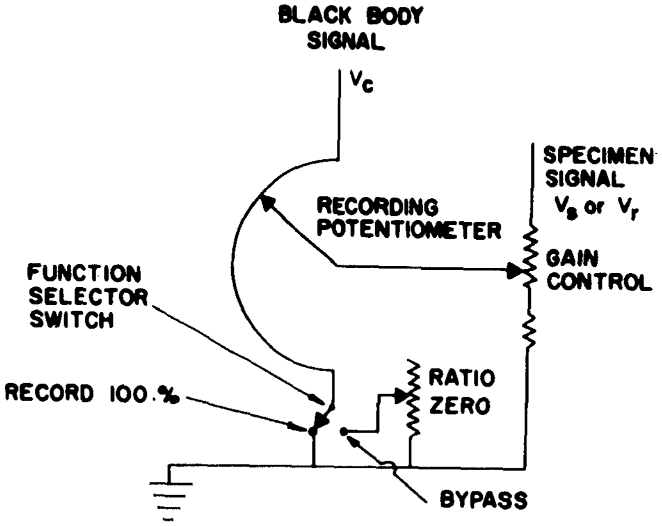


Fig. 29 Schematic diagram of recording potentiometer connections during use of data-processing attachment.

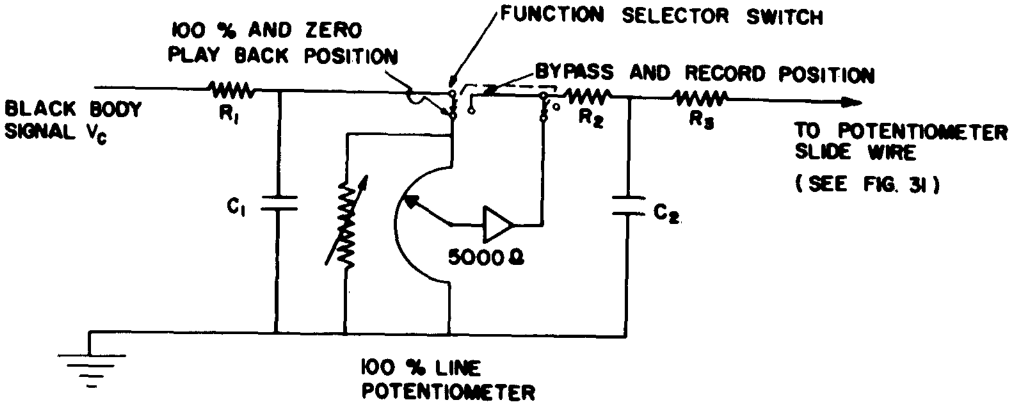


Fig. 30 Schematic wiring diagram of 100%-line potentiometer and filter circuit.

The zero-line correction is made through a similar zero-line potentiometer, connected as shown in figure 31, and driven by a similar ratchet motor and multi-vibrator circuits, actuated by pulses from the zero-line channels on the magnetic tape. The zero-line potentiometer also is set at the value that was noted at the start of the zero-line calibration, before starting the wavelength drive. The zero-line potentiometer, as controlled by the magnetic tape during playback, produces a negative signal representing the V_z signal, which is applied to the high-voltage end of the slidewire of the recorder potentiometer and also to the potentiometer arm. The net effect is to subtract this zero-line potential from both the V_c and V_s potentials, thus compensating for the zero-line errors. (See Appendix A.)

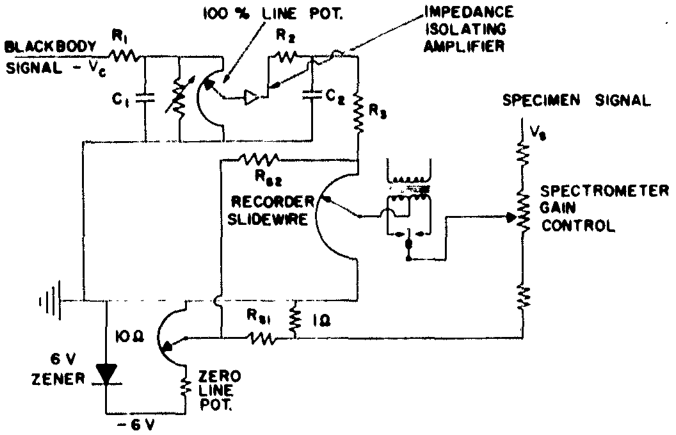
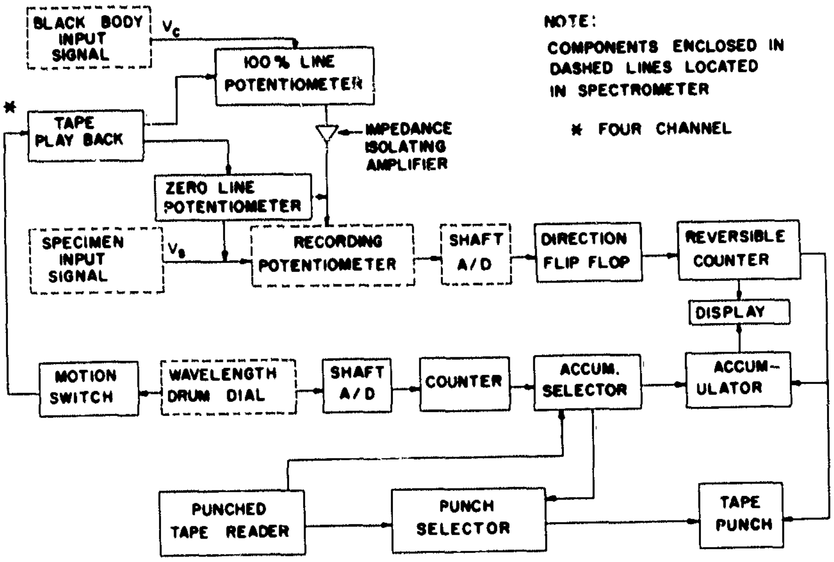


Fig.31 Schematic wiring diagram of potentiometer circuits during playback of "100% line" and "zero line" deviations. The variable resistor shunt around the 100%-line potentiometer is set to give an overall resistance of the parallel combination of the 100%-line potentiometer slidewire and shunt that is equal to the sum of the resistances of R_2, R_3 and the recording potentiometer slidewire.

In practice the potential from the 100%-line potentiometer is applied to the recorder potentiometer through a unity-gain impedance isolating amplifier to prevent reduction in potential due to load. A block diagram of the equipment during a specimen run is shown in figure 32.



NOTE:
COMPONENTS ENCLOSED IN DASHED LINES LOCATED IN SPECTROMETER

* FOUR CHANNEL

Fig. 32 Block diagram of data-processing attachment during a specimen run.

The corrected emittance appears as a shaft position of the recording potentiometer arm and pen, which is encoded as before for the calibration runs. The pulses from the analog-to-digital converter on the recording potentiometer are counted on the reversible counter, which has previously been adjusted so that a count of zero corresponds to the zero position of the pen on the chart and a count of 1000 corresponds to the 100% position of the pen on the chart. The pulses from the analog-to-digital converter on the wavelength drive drum shaft are counted on a second reversible counter, which has previously been adjusted so that a count of zero corresponds to the 0.000 position of the wavelength drum dial, and a count of 20,000 corresponds to the 20.000 position of the dial. The numbers on the two counters are punched in Friden programmatic single case code on paper tape at preset intervals of drum rotation. These digits are punched in a word group whose first four characters are the drum dial division numbers, and the last three characters are the pen position. The eighth digit is always a "carriage return."

The numbers in either counter may be displayed as decimal digits on an electric register. The numbers in the emittance counter can also be accumulated at preselected wavelengths to give a single value for total emittance or absorptance.

The accumulation is actuated as the spectrometer reaches each one of a series of wavelength which are preselected as outlined in Section X-B "Computation by the Selected Ordinate Method." The systematically varying increments between the preselected wavelengths are prerecorded on punched paper tape, as described in Appendix B, in terms of the number of pulses from the shaft encoder on the wavelength drive drum. The punched holes represent coded numbers; a number is impressed onto the binary counter at the beginning of a recording cycle, after which pulses from the shaft encoder are counted until the number of these pulses, added to the number originally impressed on the register, reaches a total of 4096, thus completing the cycle. At this time an output pulse from the register-counter triggers the accumulation, starts the reading of the next number from the tape, representing the next and probably different preselected wavelength interval, and impressing it onto the binary register. The process is repeated until all of the 100 accumulations in the program have been completed. The sum of the 100 accumulated emittances is displayed as five decimal digits on the electronic register, and is the total emittance or absorptance x 10^5.

XII. EQUATIONS RELATING SPECTRAL EMISSIVITY OF METALS TO OTHER PROPERTIES

Simple equations relating the emissivity of metals to their electrical resistivities have been available for more than half a century. The contributions of Drude and of Hagen and Rubens were classic, and a series of refinements of the Hagen-Rubens equation led to the Schmidt and Eckert modification of Davisson and Weeks' version of the equation. The Schmidt and Eckert equation is quite useful and applies especially well to platinum. The known temperature dependency of the electrical resistivity of platinum made it possible to compute the spectral thermal emissivity of platinum (or its spectral reflectance) with reasonably good accuracy over a wide range of wavelengths, but the lower limit of the wavelength range in which this accuracy prevails is strictly limited, and may be taken roughly as about 2μ for temperatures of incandescence and about 7μ for room temperature.

This entire family of equations gives smooth, uninflected curves that conform in a general way with the drastic increase in emissivity (decrease in reflectivity) of metals that occurs within or near the range of visible radiation (0.4 to 0.7μ). But it does not take into account the inflections in experimentally obtained spectral emissivity (reflectivity) curves, mostly at wavelengths shorter than 2μ and to a significant extent at longer wavelengths. The opinion has repeatedly been expressed that these inflections at the shorter wavelengths are controlled by bound electrons, whereas the electrical resistivity of a metal, upon which the conventional calculation is based, is controlled by free electrons. Nevertheless it was not until recent years that the literature has recorded attempts to combine the effects of both free and bound electrons in equations relating the spectral emissivity (reflectivity) of metals to other properties.

Notable among recent attempts are those of S. Roberts [8] and T. R. Harrison [9], who proposed an extension of the Drude model, based on classical electron theory. The formulas they propose contain, as parameters, several quantities which measure certain physical properties of the various families of bound and free electrons in the metal. In the present state of our knowledge, these parameters must be obtained empirically, from the experimentally observed reflectivity (emissivity) values, by a curve fitting procedure. In this way Roberts was able to obtain spectral emittance curves that accord fairly well with observed data on metals at wavelengths significantly shorter than those for which the Hagen-Rubens equation provides any useful results. However his curves left considerable room for improvement. Harrison also gives curves (figure 16 of his book) using assumed values of the parameters to show how the new bound-electron terms introduced enable the curves to better fit the experimental data than was possible with the Drude theory; but does not attempt to fit the observed curves in detail.

Use was made of equations suggested by T. R. Harrison that have terms to provide for the effects of both free and bound electrons. They are based upon classical electron theory. A solution of these equations, based upon assumed parameters that are applicable to typical metals, was given graphically in Harrison's book (figure 16). The results illustrated the effects of bound electrons in producing inflections of a magnitude, and at a wavelength interval, that closely resembled curves of observed spectral reflectivity (emissivity) within and near the wavelength limits of visible radiation.

Attempts were made in this study to compute good values of the parameters from experimentally obtained spectral reflectivity (emissivity) curves. The metal rhodium was chosen as the subject of the study because of the availability of accurate reflectance data at room temperature. First only one category of free electrons and one of bound were used. Within the wavelength range of visible radiation a curve obtained in this way gave a very creditable fit, and followed the inflection corresponding to a maximum in emittance at about 0.45 micron. In the attempt to extend the range of good fit out to about 10μ, it became evident that additional parameters, making at least 10 in all, would be required, for insertion into more than one term for free electrons and more than one for bound electrons.

Within the fraction of total effort on this study that could be devoted to this aspect, no set of parameters was found that will produce a spectral reflectance (emittance) curve that fits the observed data both generally and in detail. However the findings were not negative since they gave promise that further exploration would probably produce one. The work completed indicates that a satisfactory fit throughout the wavelength range of interest would involve an equation with one or two terms for free electrons and two or three for bound electrons.

XIII. REFERENCES

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XIV. APPENDIX A

Mathematical Analysis of Operation of Data Processing Equipment

Let V_c = comparison blackbody signal.

V_r = reference blackbody signal.

V_z = zero signal (spurious signal when specimen beam is blocked).

V_s = specimen signal.

W_b = radiant flux from blackbody entering the optical system to produce V_c or V_r. (The flux from the comparison and blackbody furnaces are equal if they are at the same temperature.)

W_s = radiant flux entering the optical system from the specimen.

a = proportionality factor between flux entering specimen beam of spectrometer and signal produced. $W_b = aV_r$, $W_s = aV_s$, when $V_z = 0$.

Note: All of the above terms are functions of wavelengths, and are referred to at a specific wavelength λ, but for simplicity the subscript λ is omitted in the discussion that follows. The signals V_c, V_r, V_z and V_s appear as potentials in the output of the spectrometer amplifier, before entry into the data-processing attachment.

Let us first consider what is needed, in terms of signals, to give the true emittance of a specimen. The zero signal, V_z, is measured only in the specimen beam, and is independent of whether the reference blackbody or specimen serves as the source, since in either case it is measured while the specimen beam is blocked near its source. Therefore, for each wavelength

$$W_b = a(V_r - V_z) \tag{A1}$$

and
$$W_s = a(V_s - V_z) \tag{A2}$$

Since the spectral emittance E is defined as

$$E = W_s/W_b \tag{A3}$$

the desired equation, in terms of signals is

$$E = \frac{a(V_s - V_z)}{a(V_r - V_z)} \tag{A4}$$

the factor a cancels out, and need not be considered further.

The spectrometer is used in the double-beam mode, and measures the ratio of the signals in the two beams. We must use these instrumentally obtained ratios to obtain the desired corrected emittance.

First, assume that $V_z = 0$. Then from equation (A4)

$$E = V_s/V_r \tag{A5}$$

The output of the spectrometer is the ratio of the signal from the specimen beam to that from the comparison beam, recorded on the chart as a decmal fraction, f.

During the 100%-line calibration (figure 28) the two signals are V_r in the specimen beam and V_c in the comparison beam. Consequently the 100%-line

$$f^{i} = V_r/V_c \tag{A6}$$

Deviations in this ratio f^{i} are recorded on the 100%-line channels of the magnetic tape, and the ratio itself may be recorded on the potentiometer chart as the "100% line." During testing of a specimen, the playback signals from the magnetic tape control the position of the arm on the 100%-line correction potentiometer to the position representing the fraction f^{i} of its range, while the potential applied to its slidewire is the signal V_c. Hence the output of the 100%-line potentiometer is

$$f^{i}V_c = V_c \frac{V_r}{V_c} = V_r \, , \tag{A7}$$

which is applied to the recording potentiometer slidewire through the impedance isolating amplifier. The signal V_s is balanced against the potential arm of the recording potentiometer, and for this condition

$$f^{ii} = V_s/V_r = E \, , \tag{A8}$$

the corrected emittance, for $V_z = 0$.

The situation is more compled when $V_z > 0$, (as it usually is). During zero-line calibration the two signals are V_z in the specimen beam and V_c in the I_o beam. Hence

$$f^{iii} = V_z/V_c \tag{A9}$$

Deviations in this ratio, f^{iii}, are recorded on the zero-line channels on the magnetic tape, and the ratio itself may be recorded on the potentiometer chart as the "zero line." During testing of a specimen, the playback from the magnetic tape controls the position of the arm on the zero-line potentiometer to the position representing the fraction f^{iii} of its range, while the potential applied to its slidewire represents the signal V_c. Hence the output of the zero-line potentiometer is proportional to

$$f^{iii}V_c = \frac{V_z}{V_c} V_c = V_z \tag{A10}$$

During testing of a specimen the potential from the 100%-line potentiometer is applied, through an impedance isolating amplifier, to the top of the recorder potentiometer slidewire, and the negative of the potential from the zero-line potentiometer, $-V_z$, is added to the top end of the slidewire. Under these conditions, the potential drop across the slidewire is $(V_r - V_z)$.

Similarly $-V_z$ is added to V_s and the resultant potential is balanced against the arm potential. The result is

$$V_s - V_z = f^{iv} (V_r - V_z) \tag{A11}$$

Consequently

$$f^{iv} = \frac{V_s - V_z}{V_r - V_z} = E, \tag{A12}$$

the spectral emittance corrected for both 100%-line and zero-line errors, as indicated in equation (A4).

XV. APPENDIX B

Preparing Punched Paper Tape

A fairly complex method for preparation of the tape has been accepted, both because of the infrequent need for such work, and the desire to avoid the additional costs involved in the more elaborate circuits that would be required if a simpler tape preparation were employed. This complexity results from the use of the sexa-decimal number system in the instrumentation.

The wavelength drum dial numbers corresponding to the preselected wavelengths at which emittances are to be accumulated for the determination of total emittance are punched into a paper tape which is read by a tape reader and entered into the data-processing equipment to control the wavelengths at which either punched paper tape recording and/or accumulation take place (see figure 32).

Before preparing the punched paper tape it is necessary to select the wavelengths at which the emittances are to be accumulated, as outlined in Section IX, and then to record these values on the punched paper tape in the manner given below.

A twelve-binary-stage electronic counter is used to count every second pulse from the shaft encoder attached to the shaft of the drum dial. The encoder is arranged to produce a pulse for each 0.1 division of the drum dial, i. e., for each .001 revolution. Since every second pulse is counted, each .002 revolution is counted. Because there are 12 stages, the counter recycles when $2^{12} = 4096$ counts have occurred, and produces an output pulse. The counter generally does not start at zero, but starts at the number read from the tape. The counting pulses resulting from drum dial rotation are added to the initial number. When the following condition is met:

$N_t + N_c = 4096$, where N_t = tape number, and N_c = number of counted pulses, or drum dial increment, the recycling pulse occurs. This pulse actuates the reading of the next number, the addition of the emittance indication into the accumulator, and/or the recording of the drum dial position and emittance on punched paper tape as selected.

The circuit is set to respond to four channels, i.e., 4-bit binary numbers. In consequence each taped number consists of three 4-bit digits. Because the circuit responds to every binary combination, all of the 16 combinations of a 4-bit number are used. For this reason the directions given below for deriving the code to be punched into the tape amount to finding the 16^3 complement in sexa-decimal numbers. The procedures involved are as follows:

1. Convert the selected wavelengths into wavelength drum positions, by means of a prism calibration chart, to the nearest 0.2 division on the scale (0.002 drum revolution).

2. Compute the increments between successive wavelength drum positions, in scale divisions and the nearest 0.2 part of a division.

Note: The first increment is that between the starting position of the wavelength drum and the position of the first preselected wavelength.

3. Multiply the increments by 5 to convert them to integral numbers.

4. Convert the integral decimal numbers obtained in step 3 to three-digit sexa-decimal numbers, i. e., base 16 numbers. The digits in this system are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E, and F. The number 108_{10} then becomes $06C_{16}$, or 3118_{10} becomes $C2E_{16}$.

5. Subtract the sexa-decimal number from 1000_{16}. Thus $108_{10} = 06C_{16}$ becomes $F94_{16}$, and $3118_{10} = C2E_{16}$ becomes $3D2_{16}$. (An alternative procedure is to subtract the original decimal number from 4096 and convert the difference to sexa-decimal notation.)

6. Prepare an 8-channel punched paper tape in word groups of four characters each, in Friden programmatic single case code. The first character of the word is the most significant digit, the next one is the middle digit, followed by the least significant digit, and the last character is a carriage return. For the two examples cited above, one would use for 108_{10} - $F94^{C}_{R}$ and for 3118_{10} - $3D2^{C}_{R}$. The bits that are read into the counter from the tape are contained in tape channels 1, 2, 3 and 4. (The sprocket holes lie between tape channels 3 and 4. The channel numbers read from the left edge to the right.) Bits in the other channels are ignored with the single exception of channel number 8 for the carriage return. In consequence, it is possible to select characters from the code that contain the correct bits for reading in sexa-decimal numbers. The characters used are shown in Table IV.

FOOTNOTES FOR TABLES I, II and III

1/ Emittance was computed at uniform increments of wavelength drum positions, which are not uniform increments of wavelength.

2/ Average of 18 measurements, 3 each on 6 specimens.

3/ 95% confidence error of the average of 18 measurements.

4/ Average standard deviation of the 3 measured values for each specimen about the average for that specimen.

5/ Standard deviation of the 6 average values for the 6 specimens about the overall average.

TABLE I

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 800°K

Wavelength[1]	Emittance[2]	e[3]	σ_m[4]	σ_s[5]
Microns	X100	X100	X100	X100
1.04				
1.09				
1.15	13.5	1.50	.71	1.43
1.22	14.3	1.52	.38	1.45
1.28	15.2	1.57	.44	1.50
1.36	16.2	1.52	.31	1.45
1.44	17.0	1.51	.36	1.44
1.52	17.6	1.42	.36	1.35
1.63	18.0	1.33	.34	1.27
1.74	18.3	1.34	.35	1.28
1.88	17.7	1.23	.37	1.17
2.10	16.9	1.00	.39	.95
2.36	15.5	1.01	.34	.96
2.60	14.0	.81	.34	.77
2.81	12.5	.87	.48	.83
3.02	11.5	.91	.46	.87
3.25	10.7	.91	.38	.87
3.45	10.1	.80	.36	.76
3.65	9.5	.90	.35	.86
3.87	9.2	1.00	.37	.95
4.09	8.9	1.02	.44	.97
4.30	8.9	.96	.43	.91
4.50	8.1	.82	.29	.78
4.67	8.2	.96	.38	.91
4.83	7.9	1.00	.37	.95
4.99	7.8	.98	.37	.93
5.13	7.7	.99	.36	.94
5.27	7.6	.99	.33	.94
5.40	7.5	.93	.38	.89
5.54	7.3	1.01	.43	.96
5.69	7.3	.94	.34	.90
5.83	7.1	.99	.34	.94
5.97	7.0	.81	.28	.77
6.10	6.9	.84	.30	.80
6.22	6.9	.85	.31	.81

1/, 2/, 3/, 4/, 5/ - See footnotes on page 62

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	6.8	.98	.29	.93
6.47	6.8	.96	.29	.91
6.58	6.6	.80	.36	.76
6.70	6.4	.77	.30	.73
6.80	6.5	.78	.25	.74
6.91	6.5	.84	.29	.80
7.01	6.4	.90	.28	.86
7.13	6.4	.88	.27	.84
7.25	6.4	.86	.42	.82
7.37	6.3	1.00	.31	.95
7.49	6.3	1.00	.34	.95
7.60	6.3	.92	.28	.88
7.71	6.2	.98	.26	.93
7.94	6.2	1.02	.26	.97
8.12	6.2	.99	.23	.94
8.32	6.3	.91	.33	.87
8.50	6.5	.88	.36	.84
8.70	6.5	1.01	.38	.96
8.88	6.5	.89	.31	.85
9.05	6.4	.86	.40	.82
9.22	6.6	.85	.34	.81
9.38	7.4	.77	.41	.73
9.55	7.4	.85	.29	.81
9.71	6.7	.86	.23	.82
9.87	6.3	.85	.29	.81
10.03	5.9	.77	.33	.73
10.18	5.8	.76	.31	.72
10.34	5.6	.61	.33	.58
10.50	5.6	.59	.31	.56
10.64	5.5	.61	.32	.58
10.80	5.4	.60	.41	.57
10.94	5.4	.50	.38	.48
11.08	5.4	.51	.36	.49
11.22	5.3	.57	.42	.54
11.35	5.3	.46	.30	.44

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	5.3	.46	.28	.44
11.62	5.2	.44	.33	.42
11.74	5.2	.38	.29	.36
11.87	5.2	.30	.26	.29
12.00	5.1	.40	.34	.38
12.13	5.1	.31	.36	.30
12.26	5.1	.46	.36	.44
12.38	5.1	.40	.31	.38
12.50	5.0	.34	.39	.32
12.63	5.1	.31	.41	.30
12.75	5.0	.25	.33	.24
12.88	5.0	.30	.35	.29
13.00	5.0	.43	.32	.41
13.12	4.9	.40	.29	.38
13.24	4.9	.39	.28	.37
13.36	4.9	.40	.25	.38
13.48	4.8	.34	.38	.32
13.60	4.9	.36	.28	.34
13.72	4.9	.23	.40	.22
13.84	4.8	.22	.39	.21
13.95	4.9	.27	.43	.26
14.06	4.9	.31	.36	.30
14.17	4.8	.23	.33	.22
14.28	4.7	.25	.42	.24
14.38	4.8	.21	.45	.20
14.49	4.8	.28	.29	.27
14.60	4.8	.21	.27	.20
14.71	4.8	.34	.42	.32
14.82	4.8	.26	.45	.25
14.92	4.8	.24	.32	.23
15.03	4.8	.23	.46	.22
15.14	4.7	.40	.39	.38

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1100°K

Wavelength[1] Microns	Emittance[2] X100	e[3] X100	σ_m[4] X100	σ_s[5] X100
1.04	18.9	.37	.82	.35
1.09	20.0	.85	.48	.81
1.15	20.8	1.00	.53	.95
1.22	21.4	1.08	.49	1.03
1.28	21.6	1.26	.51	1.20
1.36	21.8	.96	.48	.91
1.44	21.6	1.04	.52	.99
1.52	21.4	1.00	.50	.95
1.63	20.8	.89	.52	.85
1.74	20.4	.80	.54	.76
1.88	19.4	.70	.53	.67
2.10	18.1	.78	.51	.74
2.36	16.8	.78	.55	.74
2.60	15.5	.75	.55	.71
2.81	14.2	.70	.59	.67
3.02	13.2	.67	.51	.64
3.25	12.5	.84	.49	.80
3.45	11.9	.91	.50	.87
3.65	11.3	.94	.46	.90
3.87	11.1	.90	.50	.86
4.09	10.8	1.03	.48	.98
4.30	11.0	1.02	.59	.97
4.50	10.0	.90	.45	.86
4.67	10.1	1.05	.47	1.00
4.83	9.9	1.01	.47	.96
4.99	9.7	1.10	.47	1.05
5.13	9.5	1.15	.53	1.10
5.27	9.4	1.17	.53	1.11
5.40	9.3	1.11	.52	1.06
5.54	9.2	1.06	.49	1.01
5.69	9.0	1.13	.57	1.08
5.83	8.9	1.09	.46	1.04
5.97	8.8	1.06	.50	1.01
6.10	8.7	1.09	.47	1.04
6.22	8.6	1.06	.48	1.01

1/, 2/, 3/, 4/, 5/ - See footnotes on page 62

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1100°K

Wavelength	Emittance	e	σ_m	σ_s
Microns	X100	X100	X100	X100
6.35	8.6	1.08	.53	1.03
6.47	8.5	1.00	.46	.95
6.58	8.4	.92	.56	.88
6.70	8.3	.95	.58	.90
6.80	8.2	1.09	.57	1.04
6.91	8.2	1.04	.44	.99
7.01	8.2	1.16	.49	1.11
7.13	8.1	1.12	.52	1.07
7.25	8.1	1.09	.54	1.04
7.37	8.0	1.12	.50	1.07
7.49	8.0	1.12	.58	1.07
7.60	8.0	1.15	.56	1.10
7.71	7.9	1.13	.52	1.08
7.94	7.9	1.17	.52	1.12
8.12	7.9	1.19	.43	1.14
8.32	7.9	1.14	.48	1.09
8.50	8.0	1.15	.50	1.10
8.70	8.2	1.09	.51	1.04
8.88	8.1	1.03	.55	.98
9.05	8.1	1.05	.45	1.00
9.22	8.1	1.07	.46	1.02
9.38	8.6	1.01	.38	.96
9.55	8.9	.98	.48	.93
9.71	8.6	.98	.47	.93
9.87	8.0	.89	.48	.86
10.03	7.7	.99	.49	.94
10.18	7.4	.79	.42	.75
10.34	7.3	.79	.39	.75
10.50	7.2	.67	.43	.64
10.64	7.1	.70	.42	.67
10.80	7.1	.79	.33	.75
10.94	6.9	.78	.45	.74
11.08	6.9	.73	.43	.70
11.22	6.8	.73	.36	.70
11.35	6.8	.70	.32	.67

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	6.7	.61	.33	.58
11.62	6.7	.68	.35	.65
11.74	6.7	.58	.30	.55
11.87	6.6	.48	.47	.46
12.00	6.4	.49	.35	.47
12.13	6.4	.49	.39	.47
12.26	6.5	.37	.36	.35
12.38	6.4	.41	.37	.39
12.50	6.4	.31	.39	.30
12.63	6.4	.35	.35	.33
12.75	6.4	.35	.38	.33
12.88	6.4	.38	.32	.36
13.00	6.3	.27	.35	.26
13.12	6.2	.31	.26	.30
13.24	6.3	.26	.33	.25
13.36	6.3	.24	.33	.23
13.48	6.3	.39	.32	.37
13.60	6.3	.43	.34	.41
13.72	6.2	.34	.26	.32
13.84	6.3	.39	.26	.37
13.95	6.3	.37	.35	.35
14.06	6.2	.30	.42	.29
14.17	6.3	.40	.33	.38
14.28	6.3	.36	.39	.34
14.38	6.4	.31	.32	.30
14.49	6.5	.28	.37	.27
14.60	6.6	.38	.34	.36
14.71	6.7	.35	.35	.33
14.82	6.8	.34	.34	.32
14.92	7.0	.36	.45	.34
15.03	7.0	.30	.34	.29
15.14	7.0	.39	.44	.37

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1400°K

Wavelength Microns	Emittance 1/ X100	e 2/ X100	σ_m 3/ X100	σ_s 4/ X100
1.04	24.9	1.64	.68	1.56
1.09	24.9	1.61	.70	1.53
1.15	24.8	1.48	.59	1.41
1.22	24.7	1.43	.44	1.36
1.28	24.4	1.41	.41	1.34
1.36	24.3	1.20	.49	1.14
1.44	23.8	1.14	.38	1.09
1.52	23.3	.85	.51	.81
1.63	22.4	.82	.55	.78
1.74	21.8	.64	.48	.61
1.88	20.7	.57	.52	.53
2.10	19.5	.59	.53	.56
2.36	18.3	.46	.42	.44
2.60	17.1	.57	.45	.54
2.81	16.0	.52	.41	.50
3.02	15.2	.54	.37	.51
3.25	14.6	.51	.42	.49
3.45	13.9	.66	.42	.63
3.65	13.2	.77	.41	.73
3.87	13.0	.80	.47	.76
4.09	12.6	.86	.40	.82
4.30	12.4	.91	.31	.87
4.50	11.7	.82	.26	.78
4.67	11.8	.82	.36	.78
4.83	11.6	.99	.33	.94
4.99	11.5	.98	.39	.93
5.13	11.3	.97	.40	.92
5.27	11.2	.94	.43	.90
5.40	11.0	1.00	.34	.95
5.54	10.8	1.02	.40	.97
5.69	10.6	.90	.36	.86
5.83	10.5	1.01	.40	.96
5.97	10.4	.88	.34	.84
6.10	10.3	.84	.36	.80
6.22	10.1	.85	.37	.81

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1400°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	10.1	.97	.33	.92
6.47	10.0	.96	.34	.91
6.58	9.9	.86	.33	.82
6.70	9.7	.84	.35	.80
6.80	9.7	.90	.32	.86
6.91	9.6	.85	.33	.81
7.01	9.5	.83	.34	.79
7.13	9.5	.88	.35	.84
7.25	9.6	.93	.31	.89
7.37	9.6	.99	.38	.94
7.49	9.5	.92	.36	.88
7.60	9.5	.88	.39	.84
7.71	9.4	.91	.45	.87
7.94	9.3	.90	.37	.86
8.12	9.2	.96	.39	.91
8.32	9.4	.87	.40	.83
8.50	9.4	.82	.41	.78
8.70	9.5	.82	.36	.78
8.88	9.5	.81	.37	.77
9.05	9.5	.76	.34	.72
9.22	9.4	.81	.34	.77
9.38	9.5	.83	.35	.79
9.55	10.0	.86	.41	.82
9.71	10.2	.78	.31	.74
9.87	10.0	.80	.46	.76
10.03	9.6	.78	.34	.74
10.18	9.3	.71	.25	.68
10.34	9.1	.61	.35	.58
10.50	9.0	.61	.32	.58
10.64	8.9	.65	.42	.62
10.80	8.8	.58	.36	.55
10.94	8.7	.60	.32	.57
11.08	8.6	.58	.42	.55
11.22	8.6	.56	.34	.53
11.35	8.5	.51	.38	.49

TABLE I cont'd.

NORMAL SPECTRAL EMITTANCE OF PLATINUM WORKING STANDARDS AT 1400°K

Wavelength Microns	Emittance X100	$\bar{e}$ X100	σ_m X100	σ_s X100
11.49	8.5	.48	.38	.46
11.62	8.4	.51	.31	.49
11.74	8.4	.49	.32	.47
11.87	8.4	.43	.37	.41
12.00	8.4	.48	.31	.46
12.13	8.4	.45	.24	.43
12.26	8.4	.39	.29	.37
12.38	8.4	.42	.27	.40
12.50	8.4	.36	.29	.34
12.63	8.4	.36	.28	.34
12.75	8.4	.35	.18	.33
12.88	8.4	.39	.21	.37
13.00	8.5	.38	.28	.36
13.12	8.4	.36	.26	.34
13.24	8.5	.28	.32	.27
13.36	8.5	.30	.17	.29
13.48	8.6	.33	.26	.31
13.60	8.6	.37	.28	.35
13.72	8.6	.28	.30	.27
13.84	8.7	.35	.27	.33
13.95	8.8	.36	.22	.34
14.06	8.9	.41	.21	.39
14.17	9.0	.43	.26	.41
14.28	9.1	.48	.18	.46
14.38	9.2	.48	.30	.46
14.49	9.4	.43	.14	.41
14.60	9.6	.49	.25	.47
14.71	9.9	.57	.23	.54
14.82	10.0	.45	.26	.43
14.92	10.3	.47	.34	.45
15.03	10.6	.43	.40	.41
15.14	10.5	.49	.29	.47

TABLE II

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance[1/] X100	e[2/] X100	σ_m[3/] X100	σ_s[4/] X100
1.04				
1.09				
1.15	65.8	1.89	1.24	1.80
1.22	66.5	2.01	.85	1.91
1.28	68.4	2.31	.98	2.20
1.36	70.7	2.37	.85	2.26
1.44	72.7	2.24	.89	2.13
1.52	74.1	1.84	.72	1.75
1.63	74.8	1.87	.61	1.78
1.74	75.0	1.82	.70	1.73
1.88	74.3	1.62	.70	1.54
2.10	73.5	1.50	.71	1.43
2.36	72.7	1.53	.68	1.46
2.60	71.0	1.54	.83	1.47
2.81	69.4	1.84	.56	1.75
3.02	68.2	1.64	.52	1.56
3.25	67.2	1.46	.55	1.39
3.45	66.0	1.28	.51	1.22
3.65	64.8	1.20	.60	1.14
3.87	64.0	1.44	.56	1.37
4.09	63.3	1.61	.61	1.53
4.30	63.1	1.83	.94	1.74
4.50	62.5	1.96	.57	1.87
4.67	62.8	1.93	.44	1.84
4.83	62.5	1.82	.51	1.73
4.99	62.2	1.47	.59	1.40
5.13	61.8	1.13	.46	1.08
5.27	61.1	.98	.50	.93
5.40	60.3	1.01	.45	.96
5.54	59.6	1.01	.30	.96
5.69	58.8	.96	.50	.91
5.83	57.8	.99	.37	.94
5.97	56.7	.99	.47	.94
6.10	55.7	1.40	.62	1.33
6.22	54.8	1.24	.49	1.18

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	54.4	1.30	.50	1.24
6.47	54.2	1.40	.47	1.33
6.58	53.5	1.45	.55	1.38
6.70	53.2	1.46	.55	1.39
6.80	53.4	1.61	.58	1.53
6.91	53.1	1.49	.48	1.42
7.01	53.4	1.67	.57	1.59
7.13	53.6	1.82	.58	1.73
7.25	53.7	1.73	.46	1.65
7.37	53.9	1.83	.40	1.74
7.49	54.3	1.92	.41	1.83
7.60	54.8	1.86	.39	1.77
7.71	55.4	1.90	.50	1.81
7.94	56.5	1.75	.52	1.67
8.12	57.5	1.65	.44	1.57
8.32	58.6	1.81	.30	1.72
8.50	60.1	1.88	.44	1.79
8.70	61.2	1.66	.33	1.58
8.88	62.1	1.42	.37	1.35
9.05	63.0	1.38	.50	1.31
9.22	63.7	1.26	.34	1.20
9.38	63.8	1.42	.47	1.35
9.55	63.3	1.12	.59	1.07
9.71	62.8	1.08	.48	1.03
9.87	62.2	1.08	.39	1.03
10.03	61.8	1.25	.29	1.19
10.18	61.5	1.09	.49	1.04
10.34	61.0	1.13	.59	1.08
10.50	60.5	1.06	.49	1.01
10.64	60.6	1.11	.42	1.06
10.80	61.5	1.00	.36	.95
10.94	62.9	.75	.50	.71
11.08	64.3	.84	.57	.80
11.22	64.5	.80	.47	.76
11.35	63.2	1.11	.41	1.06

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	61.5	.97	.36	.93
11.62	59.9	1.14	.43	1.09
11.74	59.0	1.33	.44	1.27
11.87	58.6	1.44	.36	1.37
12.00	58.4	1.44	.36	1.37
12.13	58.4	1.45	.37	1.38
12.26	58.7	1.56	.38	1.49
12.38	59.0	1.71	.45	1.63
12.50	59.3	1.80	.38	1.71
12.63	59.5	1.72	.34	1.64
12.75	59.8	1.65	.37	1.57
12.88	59.9	1.70	.42	1.62
13.00	59.9	1.91	.42	1.82
13.12	59.8	1.97	.32	1.88
13.24	59.7	1.99	.40	1.90
13.36	59.6	1.92	.40	1.83
13.48	59.5	2.26	.47	2.15
13.60	59.3	2.32	.54	2.21
13.72	59.1	2.41	.44	2.30
13.84	58.6	2.47	.48	2.35
13.95	58.2	2.43	.50	2.31
14.06	57.9	2.72	.52	2.59
14.17	57.4	2.99	.50	2.85
14.28	56.7	2.98	.41	2.84
14.38	56.0	3.13	.42	2.98
14.49	55.6	3.12	.54	2.97
14.60	55.5	2.89	.78	2.75
14.71	54.4	3.31	1.09	3.15
14.82	54.6	2.55	.96	2.43
14.92	53.7	3.18	.74	3.03
15.03	53.7	2.28	.85	2.17
15.14	54.2	2.43	.86	2.31

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance[1/] X100	e[2/] X100	σ_m[3/] X100	σ_s[4/] X100
1.04				
1.09	79.4	2.02	1.35	1.92
1.15	80.9	1.88	1.29	1.79
1.22	81.8	1.80	1.16	1.71
1.28	82.2	1.76	1.18	1.68
1.36	81.9	1.61	.99	1.53
1.44	81.2	1.64	.99	1.56
1.52	80.6	1.64	1.12	1.56
1.63	79.7	1.62	1.25	1.54
1.74	78.7	2.59	1.11	2.47
1.88	77.4	1.94	1.22	1.85
2.10	75.9	2.06	1.10	1.96
2.36	74.3	2.22	1.17	2.11
2.60	72.9	1.98	1.05	1.89
2.81	71.6	2.51	.89	2.39
3.02	70.1	2.55	.73	2.43
3.25	68.9	2.26	.74	2.15
3.45	67.7	2.22	.77	2.11
3.65	66.3	2.18	.78	2.08
3.87	65.6	2.59	.84	2.47
4.09	65.2	2.88	.88	2.74
4.30	64.8	3.10	1.04	2.95
4.50	64.6	3.33	.88	3.17
4.67	64.8	3.27	.81	3.11
4.83	64.5	2.97	.87	2.83
4.99	64.2	2.80	.74	2.67
5.13	63.7	2.31	.86	2.20
5.27	63.1	2.03	.71	1.93
5.40	62.3	1.95	.68	1.86
5.54	61.4	1.80	.71	1.71
5.69	60.6	1.80	.80	1.71
5.83	59.8	1.96	.70	1.87
5.97	59.0	1.84	.75	1.75
6.10	58.2	1.96	.74	1.87
6.22	57.4	2.02	.73	1.92

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	56.9	2.31	.68	2.20
6.47	56.5	2.19	.71	2.09
6.58	56.3	2.44	.51	2.32
6.70	56.0	2.61	.66	2.49
6.80	56.1	2.71	.73	2.58
6.91	55.8	2.57	.60	2.45
7.01	56.0	2.65	.57	2.53
7.13	56.3	2.87	.66	2.73
7.25	56.6	2.86	.70	2.72
7.37	56.9	2.87	.77	2.73
7.49	57.2	2.89	.82	2.75
7.60	57.0	2.93	.66	2.79
7.71	58.2	3.01	.65	2.89
7.94	59.4	2.90	.72	2.76
8.12	60.7	2.81	.67	2.68
8.32	62.0	2.92	.80	2.78
8.50	63.3	2.83	.81	2.70
8.70	64.5	2.77	.88	2.64
8.88	65.6	2.64	.84	2.52
9.05	66.5	2.53	.88	2.41
9.22	67.5	2.32	.81	2.21
9.38	68.3	2.25	.95	2.14
9.55	68.4	2.24	1.04	2.13
9.71	68.0	2.18	1.00	2.08
9.87	67.6	2.17	.82	2.07
10.03	67.5	2.34	.94	2.23
10.18	67.3	2.11	.94	2.01
10.34	67.2	1.97	1.07	1.88
10.50	66.9	2.04	1.00	1.94
10.64	66.7	2.14	.85	2.04
10.80	67.0	2.08	.84	1.98
10.94	67.7	1.82	.96	1.73
11.08	68.8	1.83	.96	1.74
11.22	69.1	1.78	.92	1.70
11.35	68.5	1.94	.88	1.85

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	67.3	1.97	.99	1.88
11.62	66.2	1.78	1.02	1.70
11.74	65.1	1.95	1.08	1.86
11.87	64.4	1.98	.94	1.89
12.00	63.8	2.11	.84	2.01
12.13	63.4	2.27	.87	2.16
12.26	63.4	2.22	.99	2.11
12.38	63.6	2.20	.93	2.10
12.50	63.7	2.14	.89	2.04
12.63	63.8	1.98	.81	1.89
12.75	64.0	2.13	.76	2.03
12.88	64.3	2.29	.97	2.18
13.00	64.5	2.23	.84	2.12
13.12	64.4	2.10	.89	2.00
13.24	64.4	2.14	.82	2.04
13.36	63.4	2.12	.71	2.02
13.48	64.1	2.28	.80	2.17
13.60	63.9	2.14	.76	2.04
13.72	63.8	2.13	.78	2.03
13.84	63.4	1.94	.83	1.85
13.95	63.0	2.03	.70	1.93
14.06	62.8	2.05	.67	1.95
14.17	62.5	2.02	.66	1.92
14.28	62.2	1.93	.52	1.84
14.38	61.6	1.85	.63	1.76
14.49	61.0	1.90	.63	1.81
14.60	60.7	2.06	.82	1.96
14.71	60.3	2.33	.73	2.22
14.82	59.8	2.26	.77	2.15
14.92	59.1	2.26	.74	2.15
15.03	59.3	2.38	.91	2.27
15.14	59.3	2.39	.94	2.28

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 1300°K

Wavelength Microns	Emittance1/ X100	e2/ X100	σ_m3/ X100	σ_s4/ X100
1.04	84.4	2.29	1.12	2.18
1.09	84.7	1.98	1.07	1.89
1.15	84.7	1.83	.97	1.74
1.22	84.6	1.88	.68	1.79
1.28	84.0	1.82	.82	1.73
1.36	83.4	1.85	.91	1.76
1.44	82.6	2.02	.93	1.92
1.52	81.6	2.18	.81	2.08
1.63	80.4	2.16	.66	2.06
1.74	79.1	2.22	.73	2.11
1.88	77.6	2.48	.73	2.36
2.10	76.0	2.41	.71	2.30
2.36	74.4	2.46	.82	2.34
2.60	72.8	2.61	.64	2.49
2.81	71.5	2.70	.69	2.57
3.02	69.9	2.83	.66	2.70
3.25	68.8	2.68	.65	2.55
3.45	67.6	2.65	.68	2.52
3.65	66.5	2.79	.60	2.66
3.87	65.6	3.08	.68	2.93
4.09	65.1	3.35	.62	3.19
4.30	65.0	3.67	.73	3.50
4.50	64.6	3.39	.44	3.23
4.67	64.8	3.50	.44	3.33
4.83	64.5	3.30	.48	3.14
4.99	64.1	3.07	.68	2.92
5.13	63.7	2.81	.67	2.68
5.27	63.1	2.69	.73	2.56
5.40	62.5	2.53	.78	2.41
5.54	61.8	2.40	.60	2.29
5.69	61.1	2.28	.77	2.17
5.83	60.2	2.41	.58	2.30
5.97	59.5	2.48	.52	2.36
6.10	58.6	2.33	.76	2.22
6.22	57.9	2.50	.62	2.38

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED KANTHAL WORKING STANDARDS AT 1300°K

Wavelength Microns.	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	57.4	2.69	.66	2.56
6.47	57.1	2.60	.73	2.48
6.58	56.8	2.60	.93	2.48
6.70	56.5	2.68	.85	2.55
6.80	56.8	2.77	.71	2.64
6.91	56.6	2.89	.62	2.75
7.01	56.8	2.91	.54	2.77
7.13	57.1	2.96	.47	2.82
7.25	57.3	3.00	.45	2.86
7.37	57.8	3.01	.47	2.87
7.49	58.0	3.13	.63	2.98
7.60	58.4	3.17	.68	3.02
7.71	59.0	3.13	.70	2.98
7.94	60.4	3.11	.64	2.96
8.12	61.7	3.07	.41	2.92
8.32	62.9	2.99	.62	2.85
8.50	64.2	2.99	.67	2.85
8.70	65.4	2.97	.65	2.83
8.88	66.7	2.91	.60	2.77
9.05	67.6	2.65	.48	2.52
9.22	68.6	2.56	.70	2.44
9.38	69.4	2.46	.74	2.34
9.55	69.8	2.44	.73	2.42
9.71	69.9	2.47	.63	2.35
9.87	70.0	2.29	.68	2.18
10.03	69.8	2.30	.84	2.19
10.18	69.6	2.31	.66	2.20
10.34	69.5	2.36	.57	2.25
10.50	69.5	2.34	.20	2.23
10.64	69.3	2.23	.58	2.12
10.80	69.4	2.24	.76	2.13
10.94	69.7	2.37	.58	2.26
11.08	70.2	2.23	.61	2.12
11.22	70.5	2.28	.58	2.17
11.35	70.4	2.11	.60	2.01

TABLE II cont'd.

NORMAL SPECTRAL EMITTANCE OF
OXIDIZED KANTHAL WORKING STANDARDS AT 1300°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	69.5	2.10	.73	2.00
11.62	68.5	2.25	.58	2.14
11.74	67.5	2.13	.68	2.03
11.87	66.6	2.26	.70	2.15
12.00	66.0	2.18	.54	2.08
12.13	65.6	2.18	.70	2.08
12.26	65.4	2.17	.55	2.07
12.38	65.3	2.37	.62	2.26
12.50	65.3	2.36	.66	2.25
12.63	65.5	2.31	.56	2.20
12.75	65.6	2.25	.69	2.14
12.88	65.9	2.26	.63	2.15
13.00	65.9	2.27	.66	2.16
13.12	66.0	2.37	.70	2.26
13.24	66.0	2.18	.55	2.08
13.36	66.0	2.09	.58	1.99
13.48	65.9	2.05	.59	1.95
13.60	65.8	2.12	.69	2.02
13.72	65.6	2.19	.67	2.09
13.84	65.5	2.03	.64	1.93
13.95	65.3	1.94	.60	1.85
14.06	65.0	1.85	.63	1.76
14.17	64.9	1.81	.93	1.72
14.28	64.5	1.91	.71	1.82
14.38	64.2	1.92	.61	1.83
14.49	63.9	1.80	.52	1.71
14.60	63.5	1.78	.78	1.70
14.71	63.2	1.87	.90	1.78
14.82	63.0	2.01	1.07	1.91
14.92	62.4	2.16	.95	2.06
15.03	62.4	2.24	1.57	2.13
15.14	62.3	2.12	1.38	2.02

TABLE III

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance[1] x100	e[2] x100	σ_m[3] x100	σ_s[4] x100
1.04				
1.09				
1.15				
1.22	71.8	6.47	2.46	6.16
1.28	73.4	7.06	1.65	6.72
1.36	75.7	6.70	1.43	6.38
1.44	77.6	6.39	1.21	6.09
1.52	79.0	5.88	1.44	5.60
1.63	79.6	5.58	1.39	5.31
1.74	79.7	6.82	.92	6.50
1.88	79.2	4.83	.99	4.60
2.10	79.1	4.56	.92	4.34
2.36	78.8	4.27	.96	4.07
2.60	78.7	3.72	1.16	3.54
2.81	78.1	3.82	.96	3.64
3.02	77.7	3.41	.83	3.25
3.25	77.3	3.11	.74	2.96
3.45	76.9	3.13	.70	2.98
3.65	76.5	3.04	.68	2.90
3.87	76.2	2.97	.65	2.83
4.09	75.8	2.97	.56	2.83
4.30	76.1	2.93	.52	2.79
4.50	75.2	3.76	.94	3.58
4.67	75.5	2.97	.94	2.83
4.83	75.3	2.72	.90	2.59
4.99	75.3	2.72	.87	2.59
5.13	75.4	2.71	.63	2.58
5.27	75.3	2.67	.64	2.54
5.40	75.2	2.73	.70	2.60
5.54	75.0	2.81	.66	2.77
5.69	74.8	2.98	.42	2.84
5.83	74.6	2.99	.72	2.85
5.97	74.6	3.21	.99	3.06
6.10	74.8	3.11	.88	2.96
6.22	74.5	2.90	.83	2.76

1/, 2/, 3/, 4/- See footnotes on page 62

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	74.7	2.70	.91	2.57
6.47	74.8	2.60	.82	2.38
6.58	74.7	2.68	.94	2.46
6.70	74.6	3.02	.86	2.88
6.80	75.0	2.88	.68	2.74
6.91	74.7	3.03	.77	2.89
7.01	75.0	2.88	.67	2.74
7.13	75.1	2.77	.61	2.64
7.25	75.3	2.62	.70	2.50
7.37	75.5	2.47	.90	2.35
7.49	75.9	2.32	.75	2.21
7.60	76.2	2.27	.56	2.16
7.71	76.4	2.23	.58	2.12
7.94	77.5	2.45	.81	2.33
8.12	79.4	2.62	.61	2.50
8.32	81.4	2.18	.79	2.08
8.50	82.5	2.02	.55	1.42
8.70	83.0	2.03	.74	1.93
8.88	83.9	2.44	.77	2.32
9.05	84.3	2.48	.73	2.36
9.22	84.8	2.37	.93	2.26
9.38	84.8	2.15	.57	2.05
9.55	84.7	2.60	.73	2.38
9.71	84.6	2.65	.79	2.53
9.87	84.4	2.41	.97	2.30
10.03	83.9	2.28	.74	2.17
10.18	84.0	2.31	.36	2.20
10.34	84.2	2.39	.75	2.28
10.50	84.4	2.20	.54	2.10
10.64	84.8	2.18	.76	2.08
10.80	84.7	2.08	.83	1.98
10.94	84.6	2.36	.30	2.25
11.08	84.6	2.23	.42	2.12
11.22	85.0	2.05	.65	1.95
11.35	85.2	1.96	.73	1.87

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 800°K

Wavelength Microns	Emittance X100	$\bar{e}$ X100	σ_m X100	σ_s X100
11.49	85.5	2.04	.89	1.94
11.62	85.5	2.33	.45	2.22
11.74	85.3	2.11	.62	2.01
11.87	85.6	2.05	.56	1.95
12.00	85.9	1.74	.65	1.66
12.13	86.1	2.02	.74	1.92
12.26	86.3	2.22	.67	2.11
12.38	86.3	2.19	.53	2.09
12.50	86.5	2.04	.56	1.94
12.63	86.6	2.01	.55	1.91
12.75	86.9	2.31	.20	2.20
12.88	86.9	2.41	.72	2.30
13.00	86.8	2.36	.21	2.25
13.12	86.9	2.36	.43	2.25
13.24	87.0	2.51	.67	2.39
13.36	86.9	2.81	.58	2.68
13.48	86.6	2.77	.52	2.64
13.60	86.2	2.82	.56	2.69
13.72	85.9	2.72	.58	2.59
13.84	85.5	2.76	.50	2.63
13.95	84.8	2.94	.43	2.80
14.06	84.2	2.83	.41	2.70
14.17	84.0	2.72	.42	2.59
14.28	82.4	2.79	.65	2.66
14.38	81.1	2.80	.41	2.67
14.49	80.0	2.83	.33	2.70
14.60	79.3	2.50	.50	2.38
14.71	78.6	2.06	.75	1.96
14.82	78.2	1.77	.84	1.69
14.92	76.7	1.20	1.09	1.14
15.03	76.8	.94	.81	.90
15.14	77.2	1.47	.55	1.40

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 1100°K

Wavelength	Emittance1/	e2/	σ_m3/	σ_s4/
Microns	X100	X100	X100	X100
1.04				
1.09	83.4	5.24	.80	4.99
1.15	84.5	5.35	1.06	5.10
1.22	85.6	5.14	1.09	4.90
1.28	86.2	4.85	.70	4.62
1.36	86.4	4.75	.79	4.52
1.44	86.3	4.42	.96	4.21
1.52	86.0	4.40	1.06	4.19
1.63	85.3	4.12	1.08	3.92
1.74	84.4	4.12	.81	3.92
1.88	83.2	3.88	.75	3.70
2.10	82.3	3.67	.71	3.50
2.36	81.5	3.32	.62	3.16
2.60	81.2	3.09	.78	2.94
2.81	80.5	3.04	.67	2.90
3.02	79.9	2.78	.52	2.65
3.25	79.6	2.68	.55	2.55
3.45	79.2	2.54	.59	2.42
3.65	79.0	2.60	.67	2.48
3.87	78.8	2.63	.73	2.51
4.09	78.6	2.45	.49	2.33
4.30	78.5	2.28	.85	2.17
4.50	78.4	2.81	1.48	2.68
4.67	78.2	2.35	.73	2.24
4.83	78.2	2.38	.68	2.27
4.99	78.2	2.33	.66	2.22
5.13	78.3	2.37	.46	2.26
5.27	78.1	2.26	.47	2.15
5.40	78.0	2.22	.49	2.11
5.54	77.9	2.31	.56	2.20
5.69	77.8	2.22	.61	2.11
5.83	77.6	2.29	.66	2.18
5.97	77.5	2.29	.85	2.18
6.10	78.0	2.56	.82	2.44
6.22	77.8	2.41	.76	2.30

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF
OXIDIZED INCONEL WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	77.7	2.17	.58	2.07
6.47	77.7	2.29	.77	2.18
6.58	78.0	2.53	.88	2.41
6.70	77.6	2.28	.76	2.17
6.80	78.2	2.37	.88	2.26
6.91	77.4	2.29	.87	2.18
7.01	78.0	2.15	.73	2.05
7.13	78.3	2.26	.66	2.15
7.25	78.4	2.28	.62	2.17
7.37	78.5	2.17	.47	2.07
7.49	78.8	2.30	.75	2.19
7.60	79.2	2.15	.51	2.05
7.71	79.5	2.23	.52	2.12
7.94	80.2	2.24	.73	2.13
8.12	81.0	2.15	.61	2.05
8.32	82.4	1.95	.70	1.86
8.50	83.5	2.09	.72	1.99
8.70	84.3	2.07	.50	1.97
8.88	84.9	2.19	.64	2.09
9.05	85.2	1.95	.66	1.86
9.22	85.6	2.11	.63	2.01
9.38	85.9	2.04	.77	1.94
9.55	86.2	2.18	.60	2.08
9.71	86.3	2.17	.52	2.07
9.87	85.9	2.20	.58	2.10
10.03	85.7	2.11	.58	2.01
10.18	85.8	2.09	.89	1.99
10.34	86.1	2.08	.88	1.98
10.50	86.3	2.05	.76	1.95
10.64	86.4	1.96	.74	1.87
10.80	86.4	2.05	.62	1.95
10.94	86.5	1.93	.72	1.84
11.08	86.7	1.94	.87	1.85
11.22	87.0	1.99	1.03	1.90
11.35	87.1	1.87	.86	1.78

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF
OXIDIZED INCONEL WORKING STANDARDS AT 1100°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	87.1	1.98	.69	1.89
11.62	87.2	1.92	.70	1.83
11.74	87.4	1.85	.77	1.76
11.87	87.6	1.74	.91	1.66
12.00	87.6	1.94	.71	1.85
12.13	87.7	1.98	.78	1.89
12.26	87.9	2.15	.77	2.05
12.38	87.9	1.95	.84	1.86
12.50	88.1	2.16	.68	2.06
12.63	88.3	2.34	.74	2.23
12.75	88.4	2.57	.77	2.45
12.88	88.6	2.40	.71	2.29
13.00	88.6	2.29	.81	2.18
13.12	88.7	2.50	.64	2.38
13.24	88.7	2.82	.58	2.69
13.36	88.9	2.99	.72	2.85
13.48	88.8	3.08	.76	2.93
13.60	88.5	3.18	.77	3.03
13.72	88.4	3.34	.73	3.18
13.84	88.4	3.55	.59	3.38
13.95	88.0	3.66	.57	3.49
14.06	87.8	3.83	.58	3.65
14.17	87.1	3.86	.59	3.68
14.28	86.3	3.95	.65	3.76
14.38	85.5	3.90	.63	3.71
14.49	84.3	4.19	.55	3.99
14.60	83.4	4.51	.73	4.30
14.71	82.3	4.60	.61	4.38
14.82	81.2	4.85	.74	4.62
14.92	79.3	5.61	.81	5.34
15.03	78.3	4.59	1.85	4.37
15.14	78.4	5.06	1.63	4.82

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF
OXIDIZED INCONEL WORKING STANDARDS AT 1300°K

Wavelength	Emittance[1]	e[2]	σ_m[3]	σ_s[4]
Microns	X100	X100	X100	X100
1.04	88.1	3.90	1.53	3.71
1.09	88.3	3.91	1.23	3.72
1.15	88.0	4.20	1.24	4.00
1.22	88.6	3.93	1.38	3.74
1.28	88.4	3.61	1.31	3.44
1.36	88.4	3.55	1.17	3.38
1.44	88.0	3.35	.97	3.19
1.52	87.6	3.28	1.20	3.12
1.63	86.9	2.78	.94	2.65
1.74	86.0	2.52	.83	2.40
1.88	84.8	2.47	.84	2.35
2.10	83.8	2.49	1.02	2.37
2.36	83.0	2.57	1.09	2.45
2.60	82.3	2.29	.93	2.18
2.81	81.7	2.43	1.04	2.31
3.02	81.1	2.09	.89	1.99
3.25	80.8	1.99	.84	1.90
3.45	80.7	1.95	.68	1.86
3.65	80.5	1.91	.85	1.82
3.87	80.5	1.91	.64	1.82
4.09	80.4	1.88	.78	1.79
4.30	80.4	1.83	.69	1.74
4.50	79.9	2.31	1.26	2.20
4.67	80.3	1.90	.91	1.81
4.83	80.2	1.97	.84	1.88
4.99	80.3	1.96	.80	1.87
5.13	80.2	2.09	.97	1.99
5.27	80.0	2.05	.82	1.95
5.40	80.0	1.88	.77	1.79
5.54	79.9	1.93	.92	1.84
5.69	79.9	1.97	.84	1.88
5.83	80.0	2.38	.84	2.27
5.97	79.7	2.53	.87	2.41
6.10	80.1	2.15	.81	2.05
6.22	79.8	2.34	.75	2.23

1/, 2/, 3/, 4/ - See footnotes on page 62

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 1300°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
6.35	80.0	2.12	.76	2.02
6.47	79.8	2.36	.74	2.25
6.58	80.0	2.47	1.04	2.35
6.70	79.8	2.55	1.21	2.43
6.80	80.1	2.29	.99	2.18
6.91	79.8	2.29	1.16	2.18
7.01	80.1	2.16	.96	2.06
7.13	80.3	2.08	.84	1.98
7.25	80.4	2.28	.69	2.17
7.37	80.7	2.19	.80	2.09
7.49	80.9	2.04	.91	1.94
7.60	80.9	2.28	1.18	2.17
7.71	81.3	2.13	.83	2.03
7.94	81.8	1.84	.89	1.75
8.12	82.1	1.98	.73	1.89
8.32	83.2	1.88	.62	1.79
8.50	84.5	1.94	.78	1.85
8.70	85.1	1.76	.72	1.68
8.88	85.4	1.82	1.03	1.73
9.05	85.5	1.63	.85	1.55
9.22	86.0	1.84	.60	1.75
9.38	86.6	1.78	.73	1.70
9.55	86.5	1.89	1.11	1.80
9.71	86.7	1.78	.92	1.70
9.87	86.6	1.76	.79	1.68
10.03	86.4	1.77	.65	1.69
10.18	86.8	1.80	.76	1.71
10.34	87.2	1.93	.54	1.84
10.50	87.2	1.84	.70	1.75
10.64	87.0	1.74	.74	1.66
10.80	86.8	1.62	.64	1.54
10.94	87.2	1.61	.65	1.53
11.08	87.6	1.75	.76	1.67
11.22	87.9	1.72	.66	1.64
11.35	87.9	1.68	.76	1.60

TABLE III cont'd.

NORMAL SPECTRAL EMITTANCE OF OXIDIZED INCONEL WORKING STANDARDS AT 1300°K

Wavelength Microns	Emittance X100	e X100	σ_m X100	σ_s X100
11.49	87.6	1.64	.57	1.56
11.62	87.8	1.57	.66	1.50
11.74	88.3	1.66	.84	1.58
11.87	88.4	1.70	.69	1.62
12.00	88.4	1.63	.88	1.55
12.13	88.2	1.73	.65	1.65
12.26	88.2	1.66	.89	1.58
12.38	88.6	1.76	.80	1.68
12.50	88.9	1.75	.61	1.67
12.63	89.0	1.85	.78	1.76
12.75	89.0	1.90	.68	1.81
12.88	88.9	1.78	.59	1.70
13.00	89.3	1.91	.64	1.82
13.12	89.4	2.04	.91	1.94
13.24	89.7	2.19	.82	2.09
13.36	89.5	2.32	.91	2.21
13.48	89.1	2.33	.73	2.22
13.60	89.2	2.51	.62	2.39
13.72	89.2	2.54	.85	2.42
13.84	89.3	2.61	.88	2.49
13.95	88.9	2.93	.96	2.79
14.06	88.7	2.99	.92	2.85
14.17	88.2	2.97	.72	2.83
14.28	88.0	3.12	.90	2.97
14.38	87.3	3.40	1.01	3.24
14.49	86.5	3.57	1.03	3.40
14.60	85.5	3.54	.64	3.37
14.71	84.8	3.70	.83	3.52
14.82	84.0	3.81	.88	3.63
14.92	83.0	4.36	.80	4.15
15.03	81.2	3.54	1.49	3.37
15.14	81.7	4.44	1.04	4.23

TABLE IV

CHARACTERS USED IN PREPARING PUNCHED PAPER TAPE

Sexa-decimal Numeral	Decimal Numeral	Code Character Key
0	0	0
1	1	1
2	2	2
3	3	3
4	4	4
5	5	5
6	6	6
7	7	7
8	8	8
9	9	9
A	10	l.c. = lower case
B	11	. (period)
C	12	u.c. = upper case
D	13	Aux./1 = Auxiliary plus numeral one
E	14	F.C./on = Field control on
F	15	T.F. = Tape feed