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A SYSTEM FOR MEASURING NORMAL
SPECTRAL EMITTANCE AT HIGH TEMPERATURES

James O. Hylton

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**OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE**

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ABSTRACT

A system for measuring the normal spectral emittance of refractory materials has been built and tested. Measurements have been made on selected materials at temperatures ranging from 1200 to 2500 degrees Kelvin and at wavelengths ranging from 0.5 to 1.6 microns.

An emissometer was designed and constructed which uses an optical nulling energy measurement system. This method is used successfully in some types of spectrometers and radiation pyrometers, but is not normally used for emittance measurements. In this method the intensity of radiation from a target is measured by matching the intensity of a previously calibrated internal reference lamp. An energy detector serves as a null detector indicating when the intensities are equal. The system calibration is preserved in the reference lamp thus eliminating the need for extremely stable and sophisticated electronic measuring circuits.

The emittance was measured by comparing the energy radiated from a small spot on the sample surface to the energy radiated from a cylindrical cavity in a graphite block which served as the sample holder. The sample and the graphite reference block were heated by radiation in a vacuum furnace. A method was devised to measure the small temperature gradient occurring in the block and correct for its effect. A comparison with literature data shows sufficient agreement to conclude that the measurements made with this system and the analytical corrections are correct.

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CHAPTER I

INTRODUCTION

The concept of heat in thermodynamics was introduced to account for energy interactions between systems in stable thermodynamic equilibrium. Energy is transferred between systems whose temperatures are not equal. When this energy is in the form of electromagnetic radiation it is called "thermal" or "heat" radiation. Thermal radiation is emitted at all frequencies of the electromagnetic spectrum but most of the energy falls in the visible and near infrared portion of the spectrum. The term "thermal" radiation is not intended to refer to a particular portion of the electromagnetic spectrum, but refers instead to the equilibrium nature of the source. This is what distinguishes thermal radiation from that produced by non-equilibrium sources such as fluorescent bulbs or lasers.

The nature of the thermal radiation within an isolated, evacuated enclosure in thermodynamic equilibrium is described by Planck's radiation equation. This equation gives the intensity of radiation as a function of the frequency (or wavelength) and the temperature. It can be shown by the second law of thermodynamics that Planck's equation corresponds to the radiation emitted from a system which does not reflect incident radiation. This is the maximum amount of radiation that can be emitted from a system in equilibrium at a given temperature. Such a system is called a blackbody since it will appear black when viewed by reflected light.

The radiant energy emitted from a black surface in a given direction per unit time per unit area normal to the direction per unit time per unit area normal to the direction per unit solid angle in the infinitesimal wavelength interval λ to $\lambda + d\lambda$ is given by Planck's equation:

$$I_{b\lambda} d\lambda = \frac{C_1 \lambda^{-5}}{e^{C_2/\lambda T} - 1} d\lambda \quad (1)$$

where: C_1 and C_2 are defined as the first and second radiation constants whose values depend upon the units being used.
and: T = absolute temperature of the blackbody.

A surface which is not a blackbody will emit less radiation than that predicted by Planck's equation for a given temperature. The ratio of the intensity of radiation emitted from a surface to that emitted by a blackbody at the same temperature is called the emissivity. The intensity of radiation emitted from any surface can be expressed by the equation

$$I_{\lambda}(T) = \epsilon_{\lambda}(T) I_{b\lambda}(T) \quad (2)$$

The subscript λ indicates that the subscripted quantity is being defined at a particular wavelength. The subscript b on the quantity $I_{b\lambda}(T)$ indicates that the intensity of radiation is given by Planck's equation for a blackbody. The quantity $\epsilon_{\lambda}(T)$ is the emissivity of the surface at the wavelength λ and the temperature T .

For ideal optical surfaces the characteristics of reflected radiation can be predicted from classical electromagnetic theory. The emissivity of a surface depends upon the amount of energy reflected, hence it can be determined from electromagnetic theory. By using the well known Fresnel law of reflection and one of the theoretical models relating electrical and optical properties, expressions for the emissivity of certain materials can be derived.

One of the simplest of these is the Hagen Rubens equation (1, p. 71) which relates the normal emissivity ϵ_n to the wavelength λ and the electrical resistivity r . The relation is

$$\epsilon_n = C_0 \sqrt{\frac{r}{\lambda}}$$

where C_0 is a constant depending on the units of r and λ . This equation is based on the Drude free electron theory (2) which predicts the behavior of the optical constants for metallic conductors. It has provided reasonable engineering estimates for the emissivity of several polished metals at wavelengths greater than five microns. This model has not been successful in predicting short wavelength behavior.

Other theoretical models have been developed to give better agreement between theory and experiment. Roberts (2, 3) postulated a model based on two types of charge carriers in metallic conductors. In addition to the free electrons of the Drude theory, Roberts considered the effect of bound electrons or holes in determining optical behavior. Several investigators have attempted to derive some useful results based on Roberts' model. Seban (4) and Edwards (5) have compared experimental and theoretical values of emissivity for several metals in the near infrared. They report fairly good agreement for some metals at wavelengths as low as 2 microns. In many cases, however, unexplainable departures from theory are observed.

These theoretical treatments assume that all reflecting surfaces are optically smooth and that surface properties are represented by the bulk properties of the material. If these conditions are not met the reflective characteristics and hence the emissivity will be changed.

The emissivity is a property of the surface condition as well as a property of the material. It has become accepted practice (6, p. 43) to use the term emissivity only when referring to ideal optical surfaces. When referring to rough or contaminated surfaces the term emittance is used. The term emittance will be used exclusively hereafter in this paper.

In view of the very limited range of validity of the theoretical models and the fact that they only predict emissivity and not emittance, it is necessary to rely almost completely on experimental data when values of emittance are needed. This information is important in engineering applications where heat transfer by radiation is predominant such as in space vehicles. The space program has motivated a great deal of effort to study the emittance and absorptance characteristics of many materials. The use of refractory metals such as tungsten and tantalum as lamp filaments for illumination has led to a thorough investigation of their optical properties. The measurement and control of process temperatures by the detection of thermal radiation in some industries has resulted in the cataloging of data for many materials.

Since emittance is strongly influenced by such parameters as wavelength, temperature, direction and surface condition, these must be carefully specified for literature data to be useful. When the emittance is measured in a direction normal to the surface and at a particular wavelength, it is reported as the normal spectral emittance. If the total energy at all wavelengths emitted over a hemisphere is measured, it is reported as the hemispherical total emittance.

Although emittance data can be found in the literature for almost any engineering material, its usefulness is limited because of the narrow

range of variables for which they are reported. For many materials only the total emittance at various temperatures is reported and the surface condition may or may not be specified. In some cases the spectral emittance is reported at only one wavelength, usually 0.65 microns which is the effective wavelength of many visual optical pyrometers. A survey published in 1960 by the Honeywell Research Center (7) indicated that a moderate amount of data was available for some of the iron alloys and for a few of the refractory metals such as tungsten and tantalum.

CHAPTER II

EXPERIMENTAL METHODS OF MEASURING EMITTANCE

The emittance of a specimen is measured by heating the material to the desired temperature and measuring the intensity of the emitted radiation. The emittance is determined by comparing the measured intensity to that predicted by Planck's equation (equation 1) for a blackbody at the same temperature. To measure the variation with wavelength, it is necessary to pass the emitted radiation through a dispersing element such as a prism before measuring the intensity. To avoid errors caused by the absorptance of energy by components of the measuring system a reference blackbody at the same temperature as the specimen is used to calibrate the system. The blackbody radiation and the sample radiation traverse the same path through the measuring system. Both beams are attenuated by the same percentage thus their energies have the same ratio when they reach the detector as when they were emitted. If the specimen and the blackbody are at exactly the same temperature, then the emittance is determined by the ratio of the two successive intensity measurements.

In practice, however, serious experimental difficulties arise in applying the above principles. First of all the measurement is so sensitive to specimen and reference temperatures that even small temperature differences can cause large errors in the emittance measurements. For example a blackbody at 1000 degrees C. will emit 5% less energy at some wavelengths than a blackbody at 1005 degrees C.. In this case a $\frac{1}{2}\%$ temperature error would cause a 5% emittance error. The problem of achieving stable and uniform temperatures and of ensuring temperature

equality between the specimen and the reference blackbody is enormous, especially at high temperatures. Measurement of the emitted radiation also presents a few problems. The energy detector must be extremely sensitive and must be sufficiently stable and noise free to permit precise comparison of the sample and reference intensities. The optical system must be designed so that background radiation, reflected radiation, and all unwanted wavelengths are prevented from reaching the detector.

Several investigators have devised methods of overcoming these experimental difficulties. Blau and Fischer (8) have edited some of the published reports in the literature presenting various techniques which have evolved. Some of these will be discussed here.

I. METHODS OF HEATING

The source of heat must be able to bring the sample or the blackbody uniformly to the desired temperature and control at that point until the measurements are made. It is desirable to heat in a vacuum or inert atmosphere to avoid contamination or chemical reactions. Direct heating with electric current or magnetic induction has been used on materials that are conductors or magnetic susceptors. This method enables high temperatures to be easily reached and provides reasonably uniform temperature distributions. Heating by radiation in a furnace has also been used but uniform temperatures are harder to achieve than when heat is generated within the material itself. Laszlo (9) describes the use of a solar furnace to generate high temperatures in small samples. Radiant energy is focused onto a small area achieving heat fluxes corresponding to nearly 5000 degrees K..

Ensuring adequate temperature equality between the sample and the reference blackbody becomes very difficult at temperatures greater than 1000 degrees C.. To overcome this difficulty the sample and the reference blackbody are constructed as a single unit and are heated by the same source. The blackbody is sometimes a small cavity in the sample material itself. This method was proposed in 1911 by LeChatelier but was not successfully applied because of the difficulty in evaluating the quality of the blackbody cavity. DeVos (10), in 1954, proposed a method of accurately evaluating the quality of a blackbody cavity. He used this method to measure the spectral emittance of tungsten ribbon. The data obtained is widely regarded as the best available for smooth tungsten sheet.

II. OPTICAL SYSTEMS

The optical system must accomplish essentially the same function as that of any commercial spectrometer. The radiation emitted from the sample or the blackbody must be dispersed or filtered so that only the wavelength of interest is focused onto the detector. The system must be designed so that the detector can see the proper area on the sample or the reference cavity and eliminate the effect of all other radiation.

The radiation is focused by means of lenses or mirrors. Refractive optical components (lenses) are usually easier to design into the system and provide good images but they have two major disadvantages. Lenses made from materials which are transparent to infrared radiation beyond 3 microns are very expensive. Also the focal length of lenses varies with wavelength which could become a problem if the system is designed to operate over a wide range of wavelengths. Both of these

disadvantages have been offset recently by the availability of less expensive infrared materials of better optical quality.

The wavelength selective element is an essential part of the optical system. The usual device is a dispersing element such as a prism which passes different wavelengths at different angles. The detector is then placed at a position where it sees only a narrow band of wavelengths around the desired wavelength. The resolving power of the device is a measure of the width of the wavelength band. The prism has been replaced in many applications by the diffraction grating as a dispersing element. The diffraction grating is capable of much higher resolving power than the prism (11, p. 41) and can be designed to transmit more energy to the detector. Commercial instruments called monochromators which utilize prisms or gratings or both to pass selected wavelengths are available and can be incorporated into the optical system.

A commonly used method of eliminating the effect of stray or background radiation is to place a chopper or a shutter in the system near the source of radiation to be measured. This radiation is modulated in a prescribed manner and the detector is designed to respond only to this form of modulation. Any radiation not being modulated will not affect the detector.

III. ENERGY DETECTION

Detectors

Thermal radiation detectors are broadly classified into two main categories; thermal detectors and photon detectors. Thermal detectors are those in which the absorption of radiant energy causes a small temperature change which is used as a measure of the radiant

intensity. Photon detectors utilize materials in which a direct photon-electron interaction generates signal voltages or changes in the conductivity.

The thermal detector class includes thermopile detectors, bolometers, gas (Golay) cells, and the pyroelectric detectors. These detectors normally consist of a small chip of absorbing material which will generate an emf or will change resistance as its temperature varies. In gas cells the absorbed radiation changes the temperature and pressure of gas confined in a small volume. The response of thermal detectors depends upon their absorption and heat transfer characteristics. They can be designed to respond uniformly to a wide range of wavelengths. A blackened thermopile detector, for example, has a uniform response throughout the visible and infrared spectrum. Figure 1 shows the relative sensitivity and spectral response for several types of detectors. It can be seen that the thermal detectors are the only ones whose sensitive range extends into the far infrared beyond 10 microns. Their main disadvantages are their lower sensitivities and their slow response times.

The photon detector class includes all types of photocells, photomultiplier tubes, photoconductors, and phototransistors. As is shown in Figure 1 these detectors are generally more sensitive than thermal detectors but are limited in their wavelength ranges. Their response times are also much faster and will permit chopping frequencies up to several thousand hertz. Several materials have been developed which function as photon detectors in the infrared. Lead sulfide or indium antimonide semiconductors are among the most commonly used for wavelengths less than five microns.

FIGURE 1.

RELATIVE RESPONSE CURVES FOR SOME
TYPICAL INFRARED DETECTORS

Electronics

The radiant power reaching the detector in a typical spectrometer application is on the order of 0.1 microwatt (11, p. 61). At this level even the most sensitive of detectors requires the use of high gain electronic amplifiers. If the radiation is being chopped or modulated at a certain frequency, the electrical signal produced by the detector will contain information at this frequency. AC amplifiers with narrow band pass filters are used to amplify the desired signal and reject all unwanted frequencies. The AC signal is then rectified or demodulated to give a readable DC voltage proportional to the radiant intensity incident upon the detector.

Because of the small signal levels and the corresponding high gain amplifiers, noise levels and electronic stability become critical considerations. Even though the detection system functions only as a comparison device when using a reference blackbody it must remain stable during the measurement and the signal to noise ratio must be sufficient to permit a precise comparison. If the measurements are based on the ratio of two successive readings the linearity of the system becomes important. The electronics must be able to retain a calibration for a reasonable period of time. Commercially built amplifiers are available for this purpose but even with the best of these accuracies better than one percent are difficult to attain.

CHAPTER III

DESCRIPTION OF EQUIPMENT

The measurement system developed for this project is described in this chapter. Consideration was given to the experimental difficulties and the methods of overcoming them discussed in the previous chapter in deciding which methods and equipment to use. Maximum utilization of available equipment and budget limitations on the procurement of new equipment were also important considerations. A high temperature vacuum furnace and a 0.25 meter Ebert monochromator were available. These items represent the major expense in an emittance measurement system so it was decided to design the remainder of the system around them. An optical system utilizing the monochromator was designed and built. Infrared detectors were purchased and incorporated into detection circuits made up for this application.

I. THE HEATING SYSTEM

The availability of an ABAR Corporation Series 90 vacuum furnace which was capable of reaching hot zone temperatures in excess of 3000 degrees C. dictated the method of heating. This furnace uses tungsten heating elements supplied by current from a 40 KVA power supply controlled by saturable reactors. Figure 2 shows a representation of the heating elements and the furnace hot zone.

The heating elements form a box like hot zone approximately four inches square and five inches deep. The four sides and the bottom are heated by the electric current. The top of the box (hot zone) is open. The hot zone is completely surrounded by several layers of thin tungsten

FIGURE 2

ABAR FURNACE HOT ZONE AND VACUUM CHAMBER

shields separated by spacers. These shields reduce the heat loss and permit the achievement of 3000 degrees C. temperature within the hot zone. The top shields contain apertures which permit viewing into the hot zone. The shields are enclosed in a water cooled copper enclosure all of which is inside a stainless steel vacuum jacket with a removeable top. The vacuum pumping system consists of two mechanical roughing pumps and a six inch oil diffusion pump which maintain a pressure of about 10^{-5} torr in the furnace.

II. THE SAMPLE AND REFERENCE BLACKBODY

The ABAR furnace offers two methods of heating the sample. For electrical conductors the tungsten elements can be removed and the current applied directly to the sample material. The other method, of course, is to place the sample in the hot zone and heat by radiation from the tungsten elements. This method must be used on non-conductors.

While direct electrical heating is desirable because of higher and more uniform temperatures, it would require some modification of the expensive and delicate tungsten heat shields. For this reason it was decided to heat all samples by radiation, at least during the initial operation. This allows heating of any type of material but makes uniform sample temperatures harder to achieve. The sample inside the hot zone is surrounded by shielding which gets nearly as hot as the sample itself. Care must be taken to prevent radiation emitted from shields or other hot zone components from being reflected by the sample into the optical system.

Figure 3 shows the configuration of the sample and the reference blackbody. The reference blackbody is a small cylindrical cavity with a flat bottom drilled into a block made of commercial grade ATJ graphite.

FIGURE 3
SAMPLE AND REFERENCE CAVITY

A thin sheet of the sample material is placed in the recess on top of the block and secured with tungsten wire. The graphite block is suspended in the hot zone by a mechanism which will allow the block to move laterally by a small distance (see Figure 2). The lateral movement is sufficient to allow the optical system to view either the sample surface or the reference cavity. The block also contains a shallow reference cavity which permits vertical temperature gradients to be measured with an optical pyrometer by measuring the temperature difference between the bottoms of the two cavities.

III. THE OPTICAL SYSTEM

The optical system is designed to collect the radiation from the furnace hot zone and focus it onto the entrance aperture of the monochromator. The detector located at the exit aperture measures the power in the wavelength band passed by the monochromator. The sample emittance is determined by the ratio of the power measured when viewing the sample to that measured when viewing the reference cavity.

As stated earlier the measurement of the small amount of radiation passed through the optical system requires the use of high gain amplifiers and noise rejection techniques for accurate and stable operation. To eliminate the need for precise electrical measurements, it was decided to use a method known as optical nulling which is used in some types of commercial spectrometers.

Optical nulling is accomplished by using two beams of radiation in the optical system. One beam is from the sample being measured and the other is from an internal reference source. Both beams are made to focus onto a detector during alternate time intervals controlled by

choppers or shutters. To measure the energy of the sample beam, the reference beam is adjusted until the detector indicates that the two beams are equal. The energy of the sample is determined by the energy of the reference source. The detector functions only as a null indicator and the measurement does not depend upon the magnitude of its output signal.

In the system described here the internal reference source is a small tungsten filament lamp whose intensity is controlled by varying the filament current. The energy radiated from the lamp is a stable and repeatable function of the filament current. To measure the energy radiated from a sample, the filament current is adjusted until the detector indicates a null or equality between the two beams. The system is calibrated so that the filament current at null is related to the sample energy.

Figure 4 shows the arrangement of the optical system and the monochromator. The sample beam enters the system at A and is alternately blocked or passed by the chopper C. When passed, the beam is focused onto the entrance aperture E of the monochromator by mirrors M_2 , M_3 and M_4 . The reference beam is supplied by the lamp L which is housed in an evacuated chamber. The chopper C is made from a front surfaced optical mirror and is positioned such that when a blade blocks the sample beam it reflects the reference beam along the same path previously followed by the sample beam. As the chopper rotates the detector will alternately be exposed to the sample beam and the reference beam. The chopper and the mirror M_1 are adjusted so that the virtual image of the reference lamp L is at the same location as the sample. The system field stop is at the monochromator exit and limits the field of view to a spot about 3 millimeters (mm) in diameter on the sample.

FIGURE 4
OPTICAL SYSTEM

The intensity of the sample beam is limited by aperture stops at A. The intensity of the reference beam is controlled by varying the current to lamp L. The lamp current is adjusted until the detector indicates that the reference and sample beams are of equal intensity. The lamp current is used as a measure of the power in the sample beam. This is essentially the same principle that is used in a disappearing filament optical pyrometer.

IV. ENERGY DETECTOR AND AMPLIFIER

The energy detector used was a semiconductor photon detector operated as a photoconductor. For wavelengths between .7 microns and 2.5 microns a lead sulfide detector was used. Lead selenide was used between 2.5 and 5 microns. Photomultiplier tubes were used below .7 microns.

Figure 5 shows the detector bias and amplifier circuits along with approximate signal waveforms. The chopper operates at a rate of approximately 100 hertz causing the detector resistance to follow the square wave form shown. This generates an AC voltage at the input to the pre-amplifier which goes to a minimum value when the sample and reference levels become equal.

The General Radio 1232A tuned amplifier uses negative feedback through a Hall null network (12, p. 7) which provides negative feedback at all frequencies except the desired one. This is approximately equivalent to a tuned resonant circuit with a 5 percent bandwidth. The output of the amplifier is fed through a full wave rectifier and a DC microammeter. In operation the reference beam is adjusted (or tuned) until the meter indicates a minimum. The output signal is monitored with an oscilloscope to help detect the null point.

DETECTOR (PHOTOCONDUCTIVE)

FIGURE 5

DETECTOR BIAS AND AMPLIFIER CIRCUIT

CHAPTER IV

SYSTEM CALIBRATION AND OPERATION

The sample and the reference cavity block are heated to the desired temperature inside the furnace hot zone. The sample and the cavity are at approximately the same temperature, thus the sample emittance can be measured by comparing the radiant intensity of the sample to the radiant intensity of the cavity. The radiant energy comparisons were made by first finding the reference lamp null current with the cavity in the field of view, and then finding the null current with the sample in the field of view. The intensity ratio is determined from calibration curves which relate null current to target intensity (Appendix A).

During the initial operation of the system it was observed that a small temperature gradient existed within the reference cavity which had a significant influence upon the effective emittance of the cavity. This temperature gradient was estimated by measuring the temperature difference between the bottom of the reference cavity and the bottom of the shallow cavity. It was also observed that a temperature drop occurred between the graphite reference block and the sheet of sample material, probably because of the thermal contact resistance at the interface.

Although these temperature differences were small in relation to the sample temperature, they were large enough to cause an error of several percent in the measurement of the sample emittance if appropriate corrections were not made. In order to measure the sample emittance it

was necessary to measure the cavity temperature gradient and the sample-reference temperature difference as well as the intensity ratio described above.

The procedures used in calibrating the energy detector and in making the measurements necessary to determine the emittance of a sample are described in this chapter.

I. CALIBRATION OF THE ENERGY DETECTOR

The radiant intensity of a target which fills the field of view of the optical system is shown in Appendix A to be a function of the reference lamp null current and the wavelength. The system can be calibrated by using a stable source of radiant energy as a target and measuring null currents at various intensity levels. Since the system is to be used to determine the ratio of two successive intensity levels, it is not necessary to know the absolute intensity level of the target. As long as the energy source remains stable, the calibration curves can be determined by attenuating the radiation from the source with filters of accurately known transmittance.

A tungsten strip lamp was used as the calibration source. This lamp is normally used as an illumination source for the calibration of optical pyrometers and photometers. It is a highly stable source of radiant energy when supplied by a well regulated power supply. The internal reference lamp (a GE 1630 bulb with the glass removed) was supplied with current from a 0-5amp regulated DC power supply. The current was measured with a standard shunt and a millivolt recorder. Figure 6 illustrates the calibration setup.

FIGURE 6

CALIBRATION OF ENERGY DETECTION SYSTEM

At the beginning of the calibration, the internal lamp was set to a value near the top of its operating range (approximately 2.5 amps). The target lamp was adjusted until a null was indicated on the detector meter. The internal lamp current was read on the millivolt recorder and a value of 1000 was assigned as the intensity level of the target beam. A neutral density filter of known transmittance (say 80%) was then inserted between the target lamp and the optical system. The internal lamp was adjusted to the new null point corresponding to the reduced power level of the filtered beam. The value of 800 (for the 80% filter) was assigned as the new intensity level of the target beam. By using several filters, calibration curves representing the function $f(\lambda, i)$ (normalized to a maximum value of 1000) were determined. Some typical curves are shown in Figure 7.

The neutral density filters were sector disks driven by a high speed motor. The disks were made by a metal photo process in which the disks are constructed geometrically on drafting paper. The drawing is photographed and developed onto a specially coated metal surface. The cut out areas of the disk are then removed by etching. The areas of the sectors can be accurately constructed with drafting tools. The metal photo and etching process faithfully reproduces the drawing so that a sector disk whose transmittance is accurately known is produced.

II. OPERATION OF THE MEASUREMENT SYSTEM

Three measurements were required in order to determine the emittance of a sample. First the ratio of the radiant intensity of the sample to the intensity of the reference cavity was measured with the optical system. Then the temperature gradient in the cavity and the

FIGURE 7 TYPICAL DETECTOR CALIBRATION CURVE
FOR GE 1630 REF. LAMP

temperature difference between the sample and the top of the graphite block were measured with an optical pyrometer. The reference block and sample were arranged so that the three measurements could be made in quick succession.

Sample - Reference Block Configuration

Figure 8 shows how the sample material was placed on the graphite reference block. The sample material was cut into a thin rectangular sheet which would fit into a recess in the top of the block. A notch was cut into the sample so that the shallow reference cavity would be exposed. On top of the sample, a thin sheet of graphite was placed as shown. The purpose of the graphite sheet was to permit the measurement of the sample - reference block temperature difference as explained in a later section of this chapter. The sample and the graphite sheet were tied tightly to the reference block with tungsten wire which extended through holes in the reference block. This assembly was suspended in the furnace hot zone by tungsten holders attached to a slider outside the cooling jacket. By means of the slider, the reference block could be positioned so that any desired portion of the block or sample could be viewed through the aperture at the top of the hot zone.

Determination of Sample Emittance

The spectral emittance of the sample can be calculated from the following relation:

$$\epsilon_{\lambda s} = \bar{g} \frac{f(\lambda, L_s)}{f(\lambda, L_c)} \frac{I_b(\lambda, T_c)}{I_b(\lambda, T_s)} \quad (1)$$

FIGURE 8

ARRANGEMENT OF SAMPLE ON GRAPHITE BLOCK

where $\bar{g}$ = the average effective emittance of the portion of the cavity being viewed by the optical system (see Appendix B).

$f(\lambda, L)$ = the calibration factor corresponding to the wavelength λ and the null current L (see Appendix A).

$I_b(\lambda, T)$ = Planck's function for wavelength λ and temperature T .

L_s = null current obtained when optical system is viewing the sample.

L_c = null current obtained when optical system is viewing the reference cavity.

T_s = Sample temperature.

T_c = Temperature of top of graphite reference block ($\bar{g}$ is based on the temperature of the top of the cavity).

As shown in Appendix B the cavity emittance $\bar{g}$ is determined from the cavity geometry and the cavity temperature gradient. The ratio of the calibration factors $f(\lambda, L)$ can be calculated from the optical system calibration curves (Figure). The ratio of Planck's functions can be calculated after T_s and T_c have been measured. The measurement of the calibration factors is accomplished simply by obtaining null current values with the optical system viewing the reference cavity or the sample. Measurement of the cavity temperature gradient and the sample - graphite temperature difference is more difficult and will be discussed in the following paragraphs.

Measurement of the Cavity Temperature Gradient

If the sample and reference cavity system is completely isothermal the emittance of the sample can be measured accurately without an accurate temperature measurement. The temperature must be measured because the emittance may vary slightly with sample temperature, but the accuracy of

the temperature measurement has almost no influence on the accuracy of the emittance measurement. As is shown in chapter II, however, this is not true when temperature gradients are present.

Referring to Figure 2 which shows the sample block inside the hot zone, it can be seen that most of the heat transfer inside the hot zone will be upward toward the top shields which are unheated. Temperature measurements on the graphite block showed that the only significant gradients in the reference block were in a vertical direction and that it varied approximately in a linear fashion as given in Appendix B, equation B-11.

It was mentioned in Chapter II how a .5 percent temperature difference between the sample and the reference can cause a 5 percent error in an emittance measurement. This means that temperature measurements within .1 percent or better are required to permit emittance measurements within 1 percent. Absolute temperature measurements of this accuracy inside a hot furnace are practically impossible. Heat conduction errors and electrical noise prevent the use of thermocouples to even ten times that accuracy tolerance. Optical pyrometers can not possibly do the job especially after correcting for the transmittance of the furnace window.

If, however, the temperature gradient in equation D11 can be measured, the absolute value of the temperature T_s will have only a small effect on the cavity emittance distribution as calculated from equations B4 and B5. The two holes in the graphite block (Figure 3) are used to measure the temperature gradient. The diameter to depth ratio is the same for the two cavities. It can be shown that the effective emittances are equal and very close to unity. It is possible to obtain an accurate measure of the temperature difference between the cavity bottoms with

an optical pyrometer using the following technique. The pyrometer filament is adjusted to match the brightness of the deep cavity. While the operator continues to view the filament which has disappeared in the background of the deep cavity, the block is shifted so that the shallow cavity comes into view. Although this cavity is only slightly less bright than the deep cavity, the sudden contrast between the two causes the filament to come distinctly into view. A small adjustment makes the filament disappear into the shallow cavity. In this manner temperature differences ranging from 0.5 to 1.0 percent of the sample temperature can be measured with a precision approaching ± 0.1 percent of the sample temperature.

In appendix B the temperature gradient is assumed to be linear and is calculated from the above ΔT measurement as shown in Figure 9. To check this assumption the temperature of the top of the graphite block was also measured with the optical pyrometer. The measured values of emittance for the graphite (Figure 15) were used to correct the pyrometer readings. The resultant temperature agreed with the linear assumption within the precision of the ΔT measurements. Since the shallow cavity is one half as deep as the reference cavity, the ΔT between the two cavities should be one half the ΔT between the reference cavity and the top surface. This is shown in Figure 9.

Measurement of the Sample - Graphite Temperature Difference

The emittance of the reference cavity is normalized to the temperature of the top surface of the graphite reference block. If the sample equalizes at the same temperature as the top of the block, then $T_s = T_c$ in equation 1 and the Planck's function term becomes unity.

$$T_1 = T_3 - T_2$$

$$T_2 = T_3 - T_1$$

FIGURE 9

MEASUREMENT OF CAVITY TEMPERATURE GRADIENT

As previously mentioned, however, a temperature drop was observed across the thermal contact resistance at the graphite - sample interface. To measure this temperature drop, a sheet of graphite was placed on top of the sample as shown in Figure 8. The graphite sheet was approximately $1/16$ of an inch thick and was machined to the same surface finish as the graphite block. If the sample surface characteristics are the same on the top and bottom then the same temperature drop should occur across both contact surfaces. The temperature difference between the top graphite sheet and the surface of the reference block can be measured with an optical pyrometer as described earlier.

Figure 10 depicts the temperature variations through the reference block and the graphite - reference surface junctions. Also shown are some typical values for the observed temperature difference and their influence on the measurement of the sample emittance. As can be seen, the corrections varied from around .01 at long wavelengths to as much as .07 or .08 at the shorter wavelengths..

FIGURE 10

MEASUREMENT OF SAMPLE - GRAPHITE TEMPERATURE DIFFERENCE

CHAPTER V

EXPERIMENTAL PROBLEMS AND SOURCES OF ERROR

The original goal of this project was to develop a system which would measure the normal spectral emittance of any refractory material in the temperature range from 1000 degrees C. to 3000 degrees C. and the wavelength range from .5 microns to 10 microns. It was also hoped that data could be taken on some reference material, such as tungsten which would reproduce within one percent the best available literature data.

Some of these goals have not yet been met because of certain experimental and equipment problems. The maximum temperature is limited to around 2300 degrees C. because of damage to the furnace heat shields. The wavelength range of the monochromator is limited to a maximum of around 1.6 microns for the lack of suitable low pass infrared filters. Equipment is being ordered which should correct these two problems. Other experimental problems and sources of error which influenced the data taken thus far are discussed in this chapter.

I. TEMPERATURE AND WAVELENGTH LIMITATIONS

The heat shields which surround the furnace hot zone are made of tungsten sheet on the order of .025 inches thick. Ten to twelve layers separated by spacers completely surround the hot zone. Access to the hot zone is attained by partially disassembling the top shields. After being heated a few times the tungsten becomes very brittle. Each time the furnace is opened, pieces of the shield break off reducing the effectiveness of the shielding system. This gradually reduces the maximum

temperature attainable in the hot zone. This furnace is also used for thermocouple calibrations and receives a great deal of use. New shields will be ordered soon, but until then the maximum temperature will remain around 2300 to 2500 degrees C..

The monochromator being used is equipped with diffraction gratings designed for use from 0 to 10 microns. The diffraction grating disperses the incident radiation in accordance with the equation:

$$d(\sin a + \sin B) = n\lambda \quad (2)$$

where d is the line spacing and a and B are the angles of incidence and reflection. The integer n is called the order of the reflection. The radiation reflected at a given angle will consist of wavelengths which satisfy λ for integer values of n . For example, if the monochromator is set to pass first order ($n=1$) reflections at a wavelength of 1.8 microns, it also passes the second order ($n=2$) of .9 microns and the third order ($n=3$) of .6 microns. Sometimes these higher order reflections are just as intense as the first order and will have a large influence on the measurement at 1.8 microns. One method of eliminating their influence is to insert a filter which is opaque to the higher orders but is transparent to the first order.

Semiconductor filters or interference filters are available which are effective for this purpose. At the present time the filters being used limit the monochromator range to 1.6 microns but new filters will be purchased in the near future.

II. ENERGY MEASUREMENT PROBLEMS

As shown in equation 11 the optical system and electronics relate the intensity of radiation of the target to the current through the

reference lamp. The measurement depends upon the ability to measure small differences in radiant intensity between the target and the reference lamp. The amount of electrical noise present in the detector output circuit limits the precision with which the null point can be established. The stability of the relationship between the reference lamp current and its radiant intensity determines the accuracy of the target energy measurement. The contribution of these factors to the overall measurement error is discussed here.

Lamp Stability

The reference lamp was a GE 1630 bulb with the glass removed and operated in an evacuated chamber. The lamp was supplied with direct current from 1.0 to 2.5 amps as required to reach the null point. Experience has shown that the relation between radiant intensity and lamp current is very stable for many hours of operation for some lamps. The GE tungsten strip lamps used in optical pyrometer calibrations have remained stable for over 100 hours of operation after proper preparation and annealing.

The GE 1630 bulb was selected as a reference lamp because of availability and convenience. Tests were conducted to determine the stability of these bulbs. When a bulb was installed in the optical system it was immediately calibrated as described in the previous chapter. The calibration was repeated on a daily basis for several days to observe any changes in the calibration functions $f(\lambda, L)$.

It was found the performance varied greatly from bulb to bulb. Some bulbs would change rapidly during the first few minutes of operation and then would burn out. This, however, could be prevented by allowing a new bulb to remain under vacuum with a small current (around 1 amp)

applied for several hours before increasing the current. With this treatment most bulbs would survive the initial calibration and remain stable (within one percent) for several days. Whenever the vacuum chamber was returned to atmospheric pressure and the bulb was not operated for a few days, a shift in the calibration curve was observed on some bulbs. In most cases a significant shift in the calibration curve was a prelude to a burnout.

Preliminary calibrations showed that the short term stability of the GE 1630 bulbs was adequate to permit good measurements. The stability over periods of several days, however, was not reliable especially after periods of not being used. To overcome the long term stability problem, the measurement system was designed so that the sector disks could be inserted in the target beam at any time during operation. The calibration curves could be spot checked before and after a series of measurements.

The major disadvantage to using the lamp current as a measure of the target intensity arises from the fact that the calibration functions $f(\lambda, L)$ depend on wavelength as well as current. This requires a calibration at each wavelength for which measurements are to be made. This disadvantage can be eliminated by designing the optical system so that the lamp can be operated at constant current and its intensity varied by apertures or filters such as is used in many optical nulling double beam spectrometers (11, p.61). This approach will be investigated later. This would also eliminate problems associated with the long term stability of the reference lamp.

Detector and Electronic Noise

Figure 5 shows the detector bias and amplifier input circuit. When the reference and target beams are equal the only AC signal which should be presented to the preamp is electrical noise. This noise is generated by several sources. It is picked up or induced from other electrical equipment operating nearby especially the 40KVA 60 hertz furnace power supply. It is generated in the electrical components themselves by random thermal fluctuations of charge carriers. It is generated by the detector when it sees a flickering image due to vibrations of the lamp filament or misalignment of the two beams.

The random thermal (Johnson) noise in the amplifier input circuit is calculated to be less than one microvolt in this application. The observed noise from other sources was considerably larger than this. The induced noise from other equipment was mainly at 60 hertz and was reduced to an acceptable level by filtering and shielding of the amplifier and detector leads.

The flicker noise generated by the detector was more troublesome because it had a large component at the 100 hertz chopping frequency. If the optical components are not aligned so that the target and the reference beams are exactly coincident upon the detector, the image will flicker even though the intensities are equal. The most crucial component is the chopper. Each blade must be perfectly smooth and must rotate in the same plane. Best results were obtained by using a chopper cut from a $\frac{1}{4}$ inch thick front surface optical mirror. The chopper was mounted on a bearing supported drive shaft which was carefully shimmed and aligned to give the proper image at the exit aperture. The chopper was driven by a synchronous motor coupled to the drive shaft by a flexible rubber tube.

Although the flicker noise was not completely eliminated it was reduced to a level which allowed the null point to be established with a precision slightly better than one percent of the total energy level.

This noise level is considered adequate at present because other sources of error such as temperature gradients will not permit more accurate overall measurements. Future plans are to modify the optical system so that the reflecting chopper can be eliminated thus removing the source of flicker noise. A new amplification system using a synchronous demodulator on the output is also being investigated. Eventually it is hoped that comparisons with a precision of $\pm .1$ percent can be made with this system. This sort of precision is approached in a good quality commercial spectrometer.

III. REFLECTED RADIATION

The thermal radiation leaving any non-black (emittance < 1) surface will consist of emitted radiation and reflected radiation. To measure the emittance, the reflected radiation must be reduced to an insignificant level. This is accomplished by arranging the surface so that it receives a low level of incident radiation which will be reflected in the direction in which the measurements are being made.

Figure 11 illustrates the approximate arrangement of the heat shields at the top of the hot zone. The sample is located directly underneath a circular aperture in the bottom layer of the shield assembly. This layer gets almost as hot as the sample itself. Each successive layer is cooler, but they all emit thermal radiation which could be reflected from the sample and interfere with the measurement of the emitted radiation. To minimize this problem, the circular apertures in each layer of the

HOT ZONE AND TOP SHIELD CONFIGURATION

shield were cut as shown in Figure 11. The lower shields are recessed so that the sample receives direct radiation only from the bottom shield and the upper layers which are much cooler than the lower layers.

An approximate analysis of the influence of reflected radiation was done by considering the interchange of energy between the sample and the concentric rings formed by the portions of the upper shields that the sample sees directly. These areas are numbered in Figure 11. By considering these to be the only surfaces involved in the energy interchange and ignoring specular reflections, a system of linear equations which give the amount of radiant energy leaving the sample surface in the normal direction can be written. Following the methods described by Sparrow and Cess (1, pp. 88-92) for radiant interchange among diffuse surfaces, the equations are

$$[X_{ij}] [R_j] = [E_i]$$

in matrix form.

Where

$$X_{ij} = \delta_{ij} - \rho_i F_{ij}$$

and $\delta_{ij} = \text{Kronecker Delta} = 0, i \neq j$ and $1, i = j$.

ρ_i = Diffuse reflectance of surface i .

F_{ij} = Diffuse geometry factor for surfaces i and j .

$$E_i = \epsilon_i J_i, \quad \epsilon_i = \text{Emittance of surface } i$$

J_i = Planck's function, surface i

The sample surface was considered to be a small disk represented by the spot seen by the detector. The other areas involved in the analysis are rings which are parallel and coaxial with the sample disk. The geometry factors for disks and concentric rings are well cataloged in the literature (6, p. 239) and could be estimated for this situation. Using estimated values for the diffuse reflectance and emittance of the shield

surfaces and a temperature distribution as shown in Figure 11, the amount of energy reflected from the sample surface in the direction of the detector was calculated by solving the above equations. The results showed that if a sample had a diffuse reflectance between .1 and .2, the emittance measurement would be biased high by approximately .01.

This analysis was performed only to get an idea of the order of magnitude of the reflection error. It cannot be used to correct data because several possibly important considerations were neglected or were roughly estimated. The shield layer temperature distribution shown in Figure 11 was estimated from an analysis of the radiant heat transfer from the hot zone to the cooling jacket. By considering the shield layers to be infinite planes and assuming that the heat was radiated from layer to layer and conducted through a layer with no significant temperature drop in the layer, a system of linear equations involving shield temperatures and shield reflectances can be written.

If T_c = Temperature of hot zone

T_n = Temperature of n th shield layer

T_a = Temperature of cooling jacket

and P = reflectance of shield layers (estimated at 0.7 for tungsten)

the equations are:

$$(2+P) T_1^4 - T_2^4 = (1+P) T_c^4$$

$$(1+P) T_1^4 + T_2^4 - T_3^4 = (1+P) T_c^4$$

$$(1+P) T_1^4 + T_{n-1}^4 - T_n^4 = (1+P) T_c^4$$

$$n\text{th equation } (1+P) T_1^4 + T_n^4 = (1+P) T_c^4 + T_a^4$$

Solving these equations for the 10 shield layers gives the distribution shown in Figure 11. This approximation was verified as closely as possible by observing the lower layers with an optical pyrometer.

Another factor which was neglected was specular reflections from the sample and from the shield layers. Since specular reflections from the sample do not enter the optical system and the shields appear to the eye not to be strongly specular reflectors, including specular reflections in the analysis would probably not add significantly to its usefulness.

Only those areas from which the sample receives direct thermal radiation were considered. This means that radiation from other areas which is reflected from the areas shown in Figure 11 toward the sample is neglected. This contribution is also small and would not change the results greatly.

The most important conclusion to be drawn from this discussion is the fact that emittance measurements made on samples with a large diffuse reflectance (0.3 or greater) are likely to be biased high by a few percent. A high value of specular reflectance is no problem since specular reflections from the sample cannot enter the measurement system.

In order to detect those samples which may have a large diffuse reflectance, each sample was checked with a reflectometer prior to testing. This reflectometer measured the specular reflectance for an incident angle of 45 degrees. This value, along with the measured emittance, was used to estimate the diffuse reflectance as follows:

$$P_D = 1 - E - P_S$$

where P_D = diffuse reflectance

P_S = specular reflectance (measured)

and E = emittance (measured)

As an example, the tungsten samples were found to have emittance values near 0.45 in the visible spectrum. This means that their combined diffuse and specular reflectance must be 0.55. The reflectometer measurements gave specular reflectance values ranging from 0.35 to 0.40, which gives for the diffuse reflectance,

$$P_D = 1 - .45 - .40 = .15$$

which should not cause a significant reflection error. On the other hand, materials such as the aluminum oxide for which the emittance fell in the 0.50 to 0.60 range could present a problem. The aluminum oxide samples had no measurable specular reflection component. This means that the diffuse reflectance lies in the 0.40 to 0.50 range and may bias the emittance measurement high by a few percent.

IV. SAMPLE CONTAMINATION

Contamination of the samples being tested by other materials in the furnace is highly undesirable. Small amounts of contamination, especially on the sample surface, will cause unpredictable changes in the emittance. To test for possible contamination, each sample was inspected visually through a microscope prior to testing. The surface roughness was measured with a profilometer and the reflectometer measurements described previously were made. These measurements were repeated after removing the sample from the furnace. Heated and unheated samples were also sent to the chemistry laboratory for spectrographic and x-ray diffraction analysis.

Materials tested to date have been graphite ATJ, tungsten, graphite foam, and aluminum oxide. The graphite (ATJ) reference block was used in every case. The spectrographic analysis indicated that the graphite

components became highly contaminated with tungsten after heating in the furnace. At temperatures above 1500 degrees K., hydrocarbons will be decomposed by tungsten with the carbon taken up to form tungsten carbide. The graphite components initially contain some organic binder material which is decomposed and driven off by heating of the graphite. This is a possible source of carbon for the tungsten carbide reaction as well as the graphite itself.

DeVos (10) reports the formation of a tungsten carbide surface layer on the tungsten when heated in the presence of hydrocarbons. This layer caused a slight increase in the observed emissivity. It was suspected that similar problems may occur here because of the presence of the graphite and the observed formation of tungsten carbide in the graphite. Spectrographic analysis of the tungsten samples after heating revealed no changes in the concentration of trace impurities. X-ray diffraction measurements also failed to produce any evidence of a surface layer of tungsten carbide. As a result it was concluded that no reaction was taking place on the tungsten samples when heated in the presence of pure graphite. It is speculated that the organic binder in the graphite was the source of carbon for the reaction and that once it was driven off, no further reactions took place.

CHAPTER VI

RESULTS OF SYSTEM OPERATION

The results of measurements made on four different materials are presented in this chapter. Most of the data taken thus far has been on graphite and tungsten. The reference cavity block is constructed from graphite and the tungsten data serves as a check of the measurement system by comparison with literature data. Other samples measured and reported are made from aluminum oxide refractory and carbon foam. An estimate of the measurement uncertainty is given for each sample. A discussion of how these uncertainties were determined precedes the presentation of data and results.

I. ERROR ANALYSIS

The major sources of error were discussed in the previous chapter. It is the purpose here to describe how the magnitude of the error was estimated and how it influenced the final results.

To determine the emittance of a sample, three measurements were made. First, the ratio of the radiant energy emitted from the sample to that emitted from the reference cavity was measured with the energy detector. Next an optical pyrometer was used to measure the cavity temperature gradient and the graphite - sample temperature difference as described in Chapter 4. Equation 1 (Chapter 4) shows that the sample emittance is calculated from

$$\epsilon_{\lambda s} = \bar{g} \tau_R. \quad (2)$$

The quantity $\bar{g}$ is the effective cavity emittance as determined from equation B4 and B5. The energy ratio τ is determined from the null currents

obtained by viewing the sample and then the reference cavity with the optical system;

$$\tau = \frac{f(\lambda, L_s)}{f(\lambda, L_c)} . \quad (3)$$

R is the ratio of Planck's function evaluated at the cavity reference temperature and at the sample temperature as determined from the ΔT measurement.

$$R = \frac{I_{b\lambda}(T_c)}{I_{b\lambda}(T_s)} \quad (4)$$

$$\text{and } T_s = T_c - \Delta T .$$

The uncertainty in the value of R is determined primarily by the uncertainty in the measurement of ΔT .

$$R(\lambda, T, \Delta T) = \frac{e^{\frac{C_2/\lambda(T - \Delta T)}{e^{\frac{C_2/\lambda T}{e}} - 1}}}{e^{\frac{C_2/\lambda T}{e^{\frac{C_2/\lambda T}{e}} - 1}}} - 1 \quad (5)$$

The uncertainty in ΔT was estimated by calculating the sample standard deviation of groups of repeated measurements as outlined in National Bureau of Standards Handbook 91 (15, p. 1 - 10),

$$s^2 = \frac{\sum_{i=1}^n \Delta T_i - \overline{\Delta T}}{n - 1}$$

$\overline{\Delta T}$ the mean value of the n measurements

$n = 6$ at each temperature level

The quantity S was determined at several temperature levels throughout the operating temperature range and was used as an estimate of the sample variance which is designated $\sigma_{\Delta T}$. The variance of the quantity R was determined from the relation

$$\sigma_R = \frac{\partial R}{\partial (\Delta T)} \sigma_{\Delta T} .$$

In a similar fashion the uncertainty in $\bar{g}$ is determined primarily by the uncertainty in the measurement of the cavity temperature gradient. The variance of the temperature gradient, σ_s , was determined as was $\sigma_{\Delta T}$, and the variance of $\bar{g}$ calculated from

$$\sigma_{\bar{g}} = \frac{\partial \bar{g}}{\partial s} \sigma_s$$

where s represents the temperature gradient dt/dx in Appendix B, equation B11.

The uncertainty in the energy ratio measurement was determined mainly by the amount of electronic noise present at the null point. The variance of τ was determined during calibration to be approximately

$$\sigma_{\tau} = .01$$

throughout the operating range of the reference lamp.

To determine the overall uncertainty in a single emittance measurement, the above variances were combined as follows:

$$\epsilon_{\lambda s} = \bar{g} \tau R = F(\bar{g}, \tau, R)$$

$$\sigma_{\epsilon}^2 = \left[\frac{\partial F}{\partial \bar{g}} \sigma_{\bar{g}} \right]^2 + \left[\frac{\partial F}{\partial \tau} \sigma_{\tau} \right]^2 + \left[\frac{\partial F}{\partial R} \sigma_R \right]^2$$

The values of σ_{ϵ} are reported along with the values of $\epsilon_{\lambda s}$ given later. Figure 12 and Figure 13 show some typical results for the above variances and the relative contribution of each to the value of σ_{ϵ} . The quantity σ_{ϵ} can be interpreted as a measure of the random error or precision of an emittance value measured with this system. Systematic errors which result in a bias between these measurements and literature data are not estimated. Possible sources could be unwanted reflections from the sample as discussed in Chapter 5 or sample contamination. It is felt that

FIGURE 12

TYPICAL VALUES OF THE VARIANCE IN ΔT MEASUREMENTS

σ_s = Variance of emittance measurements

σ_{τ} = Variance of energy ratio measurements

σ_g = Variance of cavity emittance determination

σ_R = Variance of graphite-sample T correction

FIGURE 13

THE RELATIVE CONTRIBUTION OF INDIVIDUAL COMPONENTS
TO THE OVERALL ESTIMATE OF THE VARIANCE IN
EMITTANCE MEASUREMENTS (TAKEN FROM TUNGSTEN DATA).

reflection errors are well within the random error scatter band. Sample contamination was detected only on the graphite specimens. In either case the true value of the sample emittance at the time of measurement should fall nearly within $\pm \sigma_e$ of the reported value.

II. DATA AND RESULTS

Tungsten

The tungsten samples were prepared from commercial grade tungsten sheets ranging in thickness from .006 inches to .015 inches. Profilometer measurements indicated a surface finish of two or three microinches. The reflectometer measurements gave values of 0.35 to 0.40 for the specular reflectance. The samples were wired down on the graphite reference block as described in Chapter 4 (see Figure 8). The sample surface was cleaned with alcohol before installation in the furnace.

All measurements were made with a furnace pressure of approximately 5.0×10^{-5} torr. The samples tested were subjected to temperatures between 1500 and 2300 degrees K. for a period of about 20 hours while measurements were being made. The results of the before heating and after heating spectrographic analysis are given in Table I. The results of the measurements are given in Table II and plotted in Figure 14.

An explanation of the data reported in Table II will be helpful. The results of the three measurements required to determine sample emittance are given.

τ = the measured intensity ratio as determined from the null currents and calibration curves.

$\bar{g}$ = the effective emittance of the reference cavity as determined from equations B4 and B5 (Appendix B) and the measured temperature gradient.

ΔT = the temperature difference between the sample and the graphite block.

R = the ΔT correction as shown in equation 5.

The sample emittance is the product of the three quantities R , $\bar{g}$ and γ as shown in equation 2.

Graphite ATJ

The reference cavity block (Figure 3) was machined from commercial grade ATJ graphite supplied by Union Carbide Company. The top surface of the block was used as the sample surface. The surface finish measured approximately 30 microinches and there was no measurable component of specular reflection. The furnace pressure during operation remained around 5.0×10^{-5} torr.

Table III gives the results of the spectrographic analysis. Notice the large increase in the content of certain metals after heating, notably tantalum, tungsten, and iron. This problem was discussed in Chapter 5 and it is not known how much the contamination affected these emittance measurements. Some of the data is plotted in Figure 15 along with the best available literature data for comparison. The literature data, taken from Touloukian (16), is for siliconized ATJ of unspecified surface roughness. Most of the emittance data given for the different graphites falls in the 0.75 to 0.95 range depending on composition, surface finish, and temperature.

In Table IV the measurement data is presented in the same form as for tungsten (Table II). Since the top surface of the reference block serves as the sample as well as the reference point for the cavity emittance determination, the ΔT correction is not necessary because ΔT is zero and the factor R is unity.

TABLE I
TRACE IMPURITIES - TUNGSTEN SAMPLES
SPECTROGRAPHIC ANALYSIS

ELEMENT	BEFORE HEATING	AFTER HEATING
Cr	40 PPM	40 PPM
Sb	20	30
V	20	30
Bi	10	10
Cs	200	100
Rb	100	100
Cu	2	10
Mo	60	60
Th	100	100
Ca	10	10
Fe	60	40
Na	20	20
Pb	10	10
Si	6	6
B	10	10
Sn	10	10
Zr	20	20
Co	10	10
U	100	100
WC	0	0

FIGURE 14

NORMAL SPECTRAL EMITTANCE OF TUNGSTEN

ΔT = the temperature difference between the sample and the graphite block

R = the ΔT correction as shown in equation 5.

The sample emittance is the product of the three quantities R , $\bar{g}$ and as shown in equation 2.

Graphite ATJ

The reference cavity block (Figure 3, p. 16) was machined from commercial grade ATJ graphite supplied by Union Carbide Company. The top surface of the block was used as the sample surface. The surface finish measured approximately 30 microinches and there was no measurable component of specular reflection. The furnace pressure during operation remained around 5.0×10^{-5} torr.

Table III gives the results of the spectrographic analysis. Notice the large increase in the content of certain metals after heating, notably tantalum, tungsten, and iron. This problem was discussed in Chapter 5 and it is not known how much the contamination affected these emittance measurements. Some of the data is plotted in Figure 15, p. 59, along with the best available literature data for comparison. The literature data, taken from Touloukian (16), is for siliconized ATJ of unspecified surface roughness. Most of the emittance data given for the different graphites falls in the 0.75 to 0.95 range depending on composition, surface finish, and temperature.

In Table IV the measurement data is presented in the same form as for tungsten (Table II). Since the top surface of the reference block serves as the sample as well as the reference point for the cavity emittance determination, the ΔT correction is not necessary because ΔT is zero and the factor R is unity.

TABLE III

TRACE IMPURITIES - GRAPHITE ATJ
SPECTROGRAPHIC ANALYSIS

ELEMENT	BEFORE HEATING	AFTER HEATING
Ag	1 PPM	1 PPM
Be	1	1
Cr	1	2000
Hf	10	10
Mg	10	10
Sb	1	1
Ta	100	5000
V	10	10
Al	10	10
Bi	10	10
Cs	60	60
Hg	10	10
Mn	1	20
Sc	1	1
W	10	5000
As	10	10
Cu	10	15
Mo	1	2500
P	100	100
Th	4	4
U	40	40
Ca	125	10
Fe	115	5000
Ir	2	2
Na	25	20
Pb	1	1
Si	180	40
Ti	10	600
Zn	60	60
B	5	1
K	20	20
Nb	1	200
Pd	6	6
Zr	2	200
Ba	15	1
Co	20	20
Li	10	10
Ni	4	100

TABLE IV

MEASUREMENT RESULTS - GRAPHITE ATJ

Microns	τ	$\bar{g}$ (λ)	T Deg C	R (λ)	Sample Emittance	Deg K
.5	.77	1.100	0	1.00	.847	1600
.6	.79	1.085	0	1.00	.857	1600
.8	.84	1.068	0	1.00	.889	1600
1.0	.86	1.052	0	1.00	.899	1600
1.2	.88	1.040	0	1.00	.911	1600
1.4	.90	1.033	0	1.00	.925	1600
1.6	.92	1.028	0	1.00	.942	1600
.5	.695	1.120	0	1.00	.778	1900
.6	.745	1.096	0	1.00	.817	1900
.8	.80	1.068	0	1.00	.854	1900
1.0	.825	1.052	0	1.00	.868	1900
1.2	.85	1.040	0	1.00	.884	1900
1.4	.86	1.033	0	1.00	.888	1900
1.6	.90	1.028	0	1.00	.925	1900
.5	.675	1.180	0	1.00	.797	2300
.6	.715	1.146	0	1.00	.820	2300
.8	.81	1.106	0	1.00	.896	2300
1.0	.845	1.082	0	1.00	.914	2300
1.2	.86	1.064	0	1.00	.913	2300
1.4	.88	1.055	0	1.00	.928	2300
1.6	.89	1.047	0	1.00	.932	2300

FIGURE 15
NORMAL SPECTRAL EMITTANCE OF GRAPHITE ATJ

Carbon Foam

The foam samples were cut into rectangular sheets approximately 1/16 inch thick and fastened to the reference block as shown in Figure 8. The furnace pressure during measurement was 5.0×10^{-5} torr. The complete spectrographic analysis is not presented, however the only significant change before and after heating was an increase in the tungsten content from less than 10 parts per million (PPM) to approximately 1000 PPM.

Measurement results are given in Table V and Figure 16. No literature data was available for carbon foam, however the results appear to follow somewhat the emittance of some of the pyrolytic forms of carbon.

Aluminum Oxide

These samples were cut from a block of high purity alumina supplied by a furnace manufacturer. They were approximately 1/16 inch thick and had a surface finish of approximately 90 microinches. Tables VI and VII and Figure 17 give the measurement results. Due to a leak in the furnace, the pressure during measurement rose to approximately 1×10^{-3} torr. Table VI shows that the samples increased greatly in silicon content during heating. The silicon probably came from a vacuum grease which was applied to several "O"-ring seals in an effort to stop the leak which developed.

In Figure 16 the emittance curves for 1600 degrees K. and 1900 degrees K. are seen to crossover at about 0.9 microns. Such a point is common for many materials and represents a wavelength at which the emittance does not vary with temperature. These points are known as "X" points (17). Tungsten exhibits an X point at about 1.3 microns. These data on aluminum oxide, however, are insufficient to say that an X point exists at .9 microns. The precision of the measurements is not really

TABLE V

MEASUREMENT RESULTS - CARBON FOAM

1500 DEG K					
λ Microns	τ	$\bar{\epsilon}$	ΔT deg C	R	Sample Emittance
.5	.26	1.095	31	1.496	.426
.6	.335	1.075	31	1.399	.482
.8	.42	1.052	31	1.286	.568
1.0	.50	1.043	31	1.223	.638
1.2	.57	1.035	31	1.183	.698
1.4	.61	1.027	31	1.155	.724
1.6	.66	1.023	31	1.134	.766
1800 DEG K					
λ Microns	τ	$\bar{\epsilon}$	ΔT deg C	R	Sample Emittance
.5	.32	1.108	35	1.369	.485
.6	.36	1.090	35	1.299	.510
.8	.45	1.062	35	1.217	.582
1.0	.54	1.048	35	1.170	.662
1.2	.62	1.038	35	1.140	.734
1.4	.69	1.029	35	1.119	.795
1.6	.75	1.024	35	1.104	.848
2100 DEG K					
λ Microns	τ	$\bar{\epsilon}$	ΔT deg C	R	Sample Emittance
.5	.35	1.143	41	1.309	.524
.6	.395	1.118	41	1.251	.552
.8	.50	1.083	41	1.183	.641
1.0	.57	1.062	41	1.144	.693
1.2	.65	1.049	41	1.119	.763
1.4	.72	1.043	41	1.102	.828
1.6	.78	1.038	41	1.089	.880

FIGURE 16

NORMAL SPECTRAL EMITTANCE OF CARBON FOAM

TABLE VI

TRACE IMPURITIES - ALUMINUM OXIDE SAMPLE
SPECTROGRAPHIC ANALYSIS

Element	Before Heating	After Heating	Element	Before Heating	After Heating
Ag	< 1PPM	< 1PPM	Ca	2000PPM	2000PPM
Be	1	3	Fe	1000	600
Cr	70	50	Na	3000	100
Hf	< 30	< 30	Pb	30	100
Mg	1000	700	Si	900	>10,000
Sb	< 10	< 10	Ti	3000	3000
Ta	< 100	< 100	Zr	< 100	< 100
V	30	30	K	3000	300
Bi	< 10	< 10	Nb	500	< 30
Cs	< 300	< 300	Pd	< 10	< 10
Mn	10	< 3	Sn	10	< 10
Rb	< 100	< 100	Zr	100	100
W	70	70	Ba	300	300
Cu	200	10	Co	< 10	< 10
Mg	< 10	< 10	Li	100	< 10
Au	3	3	Ni	10	< 10

TABLE VII
MEASUREMENT RESULTS - ALUMINUM OXIDE

1600 DEG K

λ Microns	τ	$\bar{g}$	ΔT Deg C	R	Sample Emittance
.5	.385	1.103	22.5	1.294	.550
.6	.415	1.084	22.5	1.240	.558
.8	.48	1.049	22.5	1.154	.581
1.0	.49	1.043	22.5	1.138	.582
1.2	.51	1.034	22.5	1.114	.587
1.4	.56	1.025	22.5	1.097	.630
1.6	.58	1.022	22.5	1.084	.643

1900 DEG K

λ Microns	τ	$\bar{g}$	ΔT Deg C	R	Sample Emittance
.5	.375	1.121	31	1.284	.540
.6	.41	1.099	31	1.232	.555
.8	.45	1.069	31	1.169	.562
1.0	.50	1.053	31	1.133	.600
1.2	.54	1.043	31	1.110	.625
1.4	.58	1.033	31	1.094	.655
1.6	.62	1.029	31	1.082	.690

FIGURE 17

NORMAL SPECTRAL EMITTANCE OF ALUMINUM OXIDE

good enough and a great deal more data in the vicinity of the X point are required. It is observed that the two curves are so close together at wavelengths below 1.0 microns that they are within the random error scatter band. No reliable literature data could be found to substantiate these measurements. It is possible that the curves are merely close together in this region and do not cross at all.

CHAPTER VII

CONCLUSION

The emittance measuring system described herein can be used to measure the normal spectral emittance of any refractory material at temperatures above 1000 degrees C. With the addition of new heat shields to the vacuum furnace and a series of low pass filters for the monochromator, the high temperature range can be increased from the present 2200 degrees C. to over 3000 degrees C. and the spectral range can be increased from 1.6 microns to 10 microns. The accuracy presently attainable with this system is approximately $\pm .025$ in the visible spectrum decreasing to $\pm .012$ in the infrared.

One goal of this project was to build an emissometer which makes thermal radiation measurements by comparing the intensity of the beam being measured to the intensity of a beam from an internal reference lamp. The intensity of the reference lamp is adjusted to equal the intensity of the target. The radiation detector and the electronic amplifiers serve only to indicate that the equal or "null" point has been reached. The intensity of the reference lamp is used as a measure of the intensity of the target. This technique is called optical nulling and is used successfully in optical pyrometry and in spectrometry. Operation of this system has shown the method to be well suited to making emittance measurements. There are, however, several improvements which need to be made to utilize the method to full advantage.

Commercial optical nulling spectrometers are able to make intensity comparisons with a precision approaching $\pm .1\%$. Figure 13 shows that the

major component of the emittance measurement standard deviation (6) was the energy ratio measurement whose precision was around $\pm .01$. In optical nulling the limiting factor in making precise measurements is the presence of electrical noise at the null point. The present noise level must be greatly reduced if the emittance measurement uncertainty is to be reduced significantly. While the present error levels are comparable with much of the data in the literature, it is not adequate for comparison with the measurements of DeVos (10) or Larabee (14) on tungsten. Their reported standard deviations were less than $\pm .01$ at points where present results were $\pm .02$ or greater.

Several steps are being taken to improve this system. The optical system is being modified to reduce vibration and "flicker" noise described in Chapter 5. The reflecting chopper will no longer be used. Each beam will be modulated independently and then superimposed by an infrared beam splitter. The reference lamp will be operated at constant current with its intensity being attenuated by a variable aperture, possibly controlled by a servo system operated by the null detector. Improvements in the detector and amplifier circuits are also being investigated. One approach will be the use of a detector and preamplifier incorporated into a single unit along with a phase sensitive synchronous null detector similar to those used in commercial "lock in" amplifiers.

Some changes to the furnace hot zone configuration which may reduce or eliminate the temperature gradient problem will also be made. Before the installation of new heat shields, the furnace will be modified to allow the heating of electric conductors by direct application of electric current rather than by radiation from the heating elements. The heat loss from the sample would be more uniform in all directions which should elim-

inate the large vertical temperature gradient. It will also be possible to maintain the sample at a high temperature with the rest of the hot zone at a relatively cooler temperature. This should reduce the possibility of undesirable chemical reactions leading to contamination of the sample.

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APPENDIXES

APPENDIX A

DERIVATION OF RELATION BETWEEN TARGET ENERGY
AND REFERENCE LAMP CURRENT

The radiant intensity of a target which completely fills the optical field of view of the detector can be related to the reference lamp current as follows:

Let T_S = The temperature of the target.

τ_λ = The spectral transmittance of all optical elements passing only the target beam.

τ'_λ = The spectral transmittance of all optical elements passing only the reference beam.

τ''_λ = The spectral transmittance of all optical elements common to both beams.

$\Delta\lambda$ = The spectral slit width of the monochromator.

T_R = The temperature of the reference lamp filament.

F_1 = The fraction of the energy which leaves the target and enters the optical system.

F_2 = The fraction of the energy which leaves the reference lamp and enters the optical system.

$\epsilon_{\lambda S}$ = The spectral emittance of the target.

$\epsilon_{\lambda R}$ = The spectral emittance of the reference lamp filament.

$I_b(\lambda, T)$ Planck's Function (Chapter 1, eq. 1)

The temperature of the reference lamp filament is a complicated, but precise and repeatable, function of the electrical current (I) applied

to the filament. The intensity of radiation emitted from the filament is also a function of the current.

$$\epsilon_{\lambda R} I(\lambda, T_r) = W(\lambda, L)$$

The energy which leaves the reference lamp and finally arrives at the detector surface is

$$Q_R(\lambda, L) = F_2 \int_{\lambda}^{\lambda + \Delta\lambda} \tau_{\lambda}' \tau_{\lambda}'' W(\lambda, L) d\lambda.$$

The energy which leaves the target and finally arrives at the detector surface is

$$Q_S(\lambda) = F_1 \int_{\lambda}^{\lambda + \Delta\lambda} \tau_{\lambda} \tau_{\lambda}'' \epsilon_{\lambda S} I(\lambda, T_s) d\lambda.$$

At the null point, these two quantities are equal,

$$Q_R(\lambda, L) = Q_S(\lambda).$$

For the small spectral width of the monochromator, the wavelength dependent properties can be treated as constants and the following relation can be written:

$$F_2 \tau_{\lambda}' \tau_{\lambda}'' W(\lambda, L) \Delta\lambda = F_1 \tau_{\lambda} \tau_{\lambda}'' \epsilon_{\lambda S} I(\lambda, T_s) \Delta\lambda$$

which reduces to

$$\epsilon_{\lambda S} I_b(\lambda, T_s) = \frac{F_2}{F_1} \frac{\tau_{\lambda}'}{\tau_{\lambda}} W(\lambda, L) = f(\lambda, L) \quad (A-1)$$

The quantity $\epsilon_{\lambda S} I_b(\lambda, T_s)$ is the monochromatic intensity of radiation from the target. Since F_2 and F_1 are geometric terms and remain constant, equation A - 1 expresses the target intensity in terms of lamp current and wavelength.

APPENDIX B

DETERMINATION OF THE EMITTANCE OF THE
REFERENCE CAVITY

A cylindrical hole in the graphite sample holder served as the reference cavity. If the walls of the cavity are diffuse reflectors, the nature of the thermal radiation leaving the cavity can be determined by a relatively simple analytical method. The method, which is described here, follows closely that described by Love (6, pp. 80-94).

Figure 18 shows a cross section of the cylindrical cavity. The wall temperature was uniform in the circular (ϕ) and radial (r) directions but was found to vary slightly in the longitudinal (z) direction. The radiosity of an elemental ring of width dr on the bottom of the cavity can be expressed as

$$R(r) = \pi \epsilon I_{b\lambda}(T_r) + \frac{\rho}{\pi} \int_0^L R(X) K_1(X, r) dX \quad (B-1)$$

where $K_1(X, r) dX$ = the diffuse geometry factor for exchange between the elemental ring at r and the elemental ring at X .

The radiosity of an elemental ring at point Z on the cylinder wall can be expressed as

$$R(Z) = \pi \epsilon I_{b\lambda}(T_z) + \frac{\rho}{\pi} \int_0^R R(r) K_1(r, Z) dr + \frac{\rho}{\pi} \int_0^L R(X) K_2(X, Z) dX \quad (B-2)$$

where $K_2(X, Z) dX$ = the geometry factor for exchange between the elemental rings at X and Z .

$R(r)$ = radiant flux leaving the ring of width dr on the cavity bottom Radiosity at r

$R(X)$ = radiant flux leaving the ring of width dx on the cavity wall Radiosity at X

$R(Z)$ = Radiosity at Z

ϵ = diffuse emittance of the cavity walls.

ρ = diffuse reflectance of the cavity walls.

FIGURE 18

REFERENCE CAVITY ANALYSIS

The radiosities can be expressed in terms of effective emittances by letting

$$R(Z) = \pi h(Z) I_{b\lambda}(T_s) \quad (B-3)$$

$$R(X) = \pi h(X) I_{b\lambda}(T_s)$$

$$\text{and } R(r) = \pi g(r) I_{b\lambda}(T_s),$$

where $h(Z)$, $h(X)$, and $g(r)$ are the effective emittances of rings on the cavity walls at X or Z or rings on the bottom at r in terms of a black-body at the temperature T_s .

Substituting these into B2 and D3, two integral equations with the cavity emittance distribution as an unknown function are obtained.

$$g(r) = \epsilon \frac{I_{b\lambda}(T_r)}{I_{b\lambda}(T_s)} + (1 - \epsilon) \int_0^L h(X) K_1(X, r) dX \quad (B-4)$$

$$\begin{aligned} h(Z) = & \epsilon \frac{I_{b\lambda}(T_z)}{I_{b\lambda}(T_s)} + (1 - \epsilon) \int_0^R g(r) K_1(r, Z) dr \\ & + (1 - \epsilon) \int_0^L h(X) K_2(X, Z) dX \end{aligned} \quad (B-5)$$

If the temperature distribution and the kernel functions can be determined, these equations become linear integral equations of the second kind and can be solved by numerical methods.

Since $K_1(X, r)$ and $K_2(X, Z)$ represent diffuse configuration factors for coaxial annular rings along the cavity interior, they can be obtained by decomposing the configuration factor for coaxial parallel disks (6, p. 93).

$$F_{xz} = \frac{r_x^2 + r_z^2 + d^2 - \sqrt{(r_x^2 + r_z^2 + d^2)^2 - 4r_z^2 r_x^2}}{2r_x^2} \quad (B-6)$$

where

r_x = radius of disk at X .

and

r_z = radius of disk at Z .

$d = |z - x|$ distance between disks.

Applying the basic rules of configuration factor algebra to the elemental rings, the factors K_1 and K_2 are shown to be:

$$K_1(X,r) dX = \frac{-R^2}{2r} \frac{\partial}{\partial X} \left[\frac{\partial F_{xr}}{\partial r} \right] dX \quad (B-7)$$

$$\text{and} \quad K_2(X,Z) dX = \frac{-R}{2} \frac{\partial}{\partial X} \left[\frac{\partial F_{xz}}{\partial Z} \right] dX \quad (B-8)$$

Substituting 17 into 18 and 19,

$$K_1(X,r) = \frac{2R^2X (R^2 + X^2 - r^2)}{\left[(R^2 + r^2 + X^2)^2 - 4r^2 R^2 \right]^{3/2}} \quad (B-9)$$

$$\text{and} \quad K_2(X,Z) = \frac{1}{2R} \left[\frac{1 - \frac{d(6R^2 + d^2)}{(4R^2 + d^2)^{3/2}}}{\left[(R^2 + r^2 + X^2)^2 - 4r^2 R^2 \right]^{3/2}} \right] \quad (B-10)$$

The axial temperature distribution was found to increase linearly from the top to the bottom of the cavity. The temperature at each point Z on the cavity wall was expressed as

$$T(Z) = T_s - (Z - L) \frac{dT}{dZ} \quad (B-11)$$

The reference temperature T_s was taken at the top of the graphite block where the sample was located.

From equations B-9, B-10, and B-11, the integral equations B-4 and B-5 were solved numerically for the unknown emittance functions $g(r)$ and $h(z)$. An initial solution was assumed for the function $h(z)$. This solution was substituted into B-4 and B-5 to obtain new solutions for $g(r)$ and $h(z)$. The definite integrals were evaluated by Simpson's Rule. The new solutions were substituted back into the equations and a third set of solutions obtained. This process was repeated until successive solutions were sufficiently close together.

A computer program was written to perform the above calculations. The program listing is shown in Table VIII. Typical solutions are shown in Figure 8. The program is written in FORTRAN for a small general purpose

laboratory computer (a DEC PDP-5 with 4K memory). It was intended to use this program for testing only and later write a more general cavity analysis program for a larger computer. This program, however, yielded results well within the overall experimental error so a new program was not written.

In figure 19 graph C, a series of typical solutions for $g(r)$ are shown for different wavelengths. In graphs A and B, successive iterations are shown for different values of emittance E which show how the solutions converge. As can be seen in graph B the iterations converge very rapidly for an emittance of .8 which is about the correct value for graphite ATJ. Three iterations were nearly always sufficient.

It should be noted that although the emittance of the graphite must be known to solve the equations, its influence is so slight that only a rough estimate (within ten percent) will yield good results. This can be seen by considering equation B-4 expressed in the form

$$g(r) = \epsilon + (1-\epsilon) A$$

where A represents the value of the definite integral.

An error in emittance ($\Delta\epsilon$) is related to an error in $g(r)$ (Δg) by

$$\Delta g = (1-A) (\Delta\epsilon).$$

The cavity geometry is such that $A \geq .9$ for $\epsilon \geq .8$, thus $|\Delta\epsilon| \leq 1 |\Delta g|$

A ten percent error in ϵ causes less than a one percent error in $g(r)$.

TABLE VIII
CAVITY ANALYSIS PROGRAM FOR PDP-5

```

DIMENSION G(5),H(20)
ACCEPT 50,WL,S,EM,REF,A,R,HD
50;FORMAT(E)
DR=R/5.
DZ=HD/20
DO 1 I=1,20
ACCEPT 50, H(I)
1;CONTINUE
2;C2L=14386.8/WL
T0=S+A*HD
RJS=EM*(EXPF(C2L/S)-1.)/(EXPF(C2L/T0)-1.)
DO 5 J=1,5
P=J-1
Y=DR*(P+.5)
SUM=0.
DO 4 K=1,20
P=K-1
X=DZ*(P+.5)
F2=R*R+Y*Y+X*X
F2=F2*F2
F2=F2-4.*Y*Y*R*R
F2=1.5*LOGF(F2)
F2=EXPF(F2)
F1=2.*R*R*X*(R*R*X-X-Y*Y)/F2
SUM=SUM+F1*H(K)*DZ
4;CONTINUE
G(J)=RJS+REF*SUM
5;CONTINUE
DO 20 I=1,20
P=I-1
Z=DZ*(P+.5)
SUM=0.
DO 10 J=1,5
P=J-1
Y=DR*(P+.5)
F1=R*R+Y*Y+Z*Z
F1=F1*F1
F1=F1-4.*Y*Y*R*R
F1=1.5*LOGF(F1)
F1=EXPF(F1)
F2=2.*R*Y*Z*(R*R+Z*Z-Y*Y)/F1
SUM=SUM+F2*G(J)*DR
10;CONTINUE
SUM1=0.
DO 15 K=1,20
P=K-1
X=DZ*(P+.5)
Z1=SOTF((X-Z)*(X-Z))

```

TABLE VIII - PAGE 2

```
IF(ZL) 11,15,11
11;F1=4.*R*R ZL*ZL
F1=1.5*LOGF(F1)
F1=EXPF(F1)
F3=(F1-ZL*(6.*R*R+ZL*ZL))/(2.*R*F1)
SU1=SU1+F3*H(K)*DZ
15;CONTINUE
T0=S+A*(HD-Z)
RJS=EM*(EXPF(C2L/S)-1.)/(EXPF(C2L/T0)-1.)
H(I)=RJS+REF*(SUM SU1)
20;CONTINUE
DO 25 J=1,5
TYPE 51,G(J)
51;FORMAT(E,/)
25;CONTINUE
DO 26 I=1,20
TYPE 51,H(I)
26;CONTINUE
PAUSE
GO TO 2
END
```

F

$\epsilon = .4$ $\lambda = .5$ microns

$dT/dz = 0$ $T_s = 2000$ deg C

GRAPH A - Convergence

$\epsilon = .8$ $\lambda = .5$ microns

$dT/dz = 0$ $T_s = 2000$ deg C

GRAPH B - Convergence

$\epsilon = .85$ $T_s = 2000$ deg C

$dT/dz = 49$ deg/inch

GRAPH C - TYPICAL SOLUTIONS

FIGURE 19 - SOLUTIONS OF INTEGRAL EQUATIONS

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