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THERMAL EMITTANCE MEASUREMENTS

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With the advent of satellites, space vehicles, and space probes, our attention is directed toward thermal protection of structures in a somewhat new environment. The term "spacecraft" will be used in this paper to include satellites, manned or unmanned space vehicles and space probes. With these spacecraft in an environment of ambient pressures less than 10^{-8} mm of mercury, heat transfer to and from the craft will be limited to radiative modes. With this limitation the emittance, reflectance, and absorptance of materials are the important factors determining the ultimate heat rejection or heat acceptance ability of the exterior surfaces of a spacecraft.

Of equal importance is the problem of thermal protection of these vehicles upon re-entry into the earth's atmosphere. Because of the severe frictional heating encountered during re-entry by a vehicle, such as the Dyna-Soar, an efficient radiating skin surface is most important for keeping vehicle temperature within safe limits.

For the more common materials there is a wealth of information, including emittance values. Unfortunately, there are many instances where there are wide discrepancies between data from different investigators, presumably, for the same materials. In the case of emittance measurements, there are cases when it was not specified whether the measurement was total normal emittance or total hemispherical emittance. Surface conditions are factors that require more than just casual attention.

There is a dearth of information for the newer materials. The Air Force is interested in this type of information for a variety of materials; in order to provide this much needed information, this Directorate has initiated several programs with commercial research laboratories and universities. In some cases, these programs are for the generation of data for materials of interest; in other cases, the emphasis is on the development of improved techniques of measurements or for the extension of temperature capabilities. Therefore, most measurements are made on a spectral basis using suitable integrating techniques to derive the total normal emittance or spectral normal emittance data needed by the vehicle designers. Total hemispherical emittance measurement techniques often use the method of heating a sample by its own electrical resistance (Joulian heating), measuring the power input and specimen temperature, then calculating the total hemispherical emittance. Such techniques do not lend themselves readily for nonelectrically conducting materials. Measurements of total normal emittance seem to be somewhat simpler to make and the equipment can be used for electrical conductors as well as for electrical insulating materials.

Although there has been some laxity in the past about distinguishing between emittance and emissivity, Prof. A. C. Worthing has emphasized (1) the distinction, and investigators have been more concerned recently with properly identifying the properties they have been measuring. Worthing states, "That in accord with the usage that an 'ivity' ending shall denote a characteristic of a material, the term 'emissivity' is limited to a comparison with a blackbody under conditions where the individual characteristics of bodies composed of the material under consideration are eliminated. Since the radiation characteristics of a body depend in part upon its opaqueness and the roughness of its surface, these factors must be considered in forming an acceptable definition of emissivity.

Accordingly, the emissivity of a material is defined as the ratio of a rate of emission of radiant energy by an opaque body with a polished surface composed of that material as a consequence of its temperature only, to the corresponding rate for a blackbody at the same temperature."

"In accord with the usage that an 'ance' ending shall denote a characteristic of a body or a portion of a body rather than of the material composing it, an emittance for a body at some constant temperature is defined as the ratio of the rate of emission of radiant energy by the body in consequence of its temperature only to the corresponding rate for a blackbody at the same temperature."

According to Kirchhoff's law: At a given temperature, the total emissive power for any body is equal to its absorptivity multiplied by the total emissive power of a perfect blackbody at that temperature. This may be expressed as:

$$E = \alpha E_B \tag{1}$$

where E is the emissive power of a material

E_B is the emissive power of a blackbody

α is the absorptivity of a material

This may be written as:

$$\frac{E}{E_B} = \alpha = \epsilon \tag{2}$$

since ϵ, the emissivity is numerically equal to the absorptivity.

Radiation properties usually are defined with respect to a theoretical material or standard that is completely absorbing. Known as a blackbody, it is a perfect radiator in that it will emit the maximum amount of radiation per unit area that is possible to be emitted by a body at that particular temperature. The Stefan-Boltzman Law shows how the total radiant flux from a unit area of a blackbody varies with temperature:

$$W = \sigma T^4 \tag{3}$$

where W is the total radiant flux from a unit surface, σ is the Stefan-Boltzman constant, and T is the absolute temperature. In practice, the true blackbody is never realized and a measure of the success in approaching true blackbody conditions may be the term $\epsilon_{(T_h)}$, the total hemispherical emittance.

A few more definitions are required at this point. The transmittance of a material may be defined as the ratio of the radiation transmitted through the material to the radiation incident upon the material. The absorptance and the reflectance can be defined, likewise, as the ratios of the radiation absorbed by the material and the radiation reflected by the material to the radiation incident upon the material, respectively. The interrelation of absorption, transmission, and reflection of radiant energy is illustrated in figure 1. Figure 1 is for a general case where a transparent material is being irradiated. From this figure and following the concepts of the conservation of energy, it is seen that reflected energy (ρ), transmitted energy (τ) and the absorbed energy (α) may be combined to equal the total incident energy. This may be stated as:

$$\rho + \alpha + \tau = 1 \quad (4)$$

For opaque materials where the transmitted energy is zero, ($\tau = 0$) the reflectance and the absorptance are complementary:

$$\rho + \alpha = 1 \quad (5)$$

Therefore emittance was defined as the ratio of radiation from a particular specimen to the radiation of a blackbody operating at the same temperature; and emissivity is defined as the ratio of the radiation from a material with an optically smooth surface which is thick enough to be opaqued to the radiation from a blackbody.

On this basis, several relations similar to those shown for absorptance, reflectance, and emittance may be written for absorptivity (A), reflectivity (R), and emissivity (E):

$$A + R = 1 \quad (6)$$

or

$$R = 1 - A \quad (7)$$

and

$$A_{t1} = E_{t1} \quad (8)$$

where the subscripts t1 indicate a certain temperature.

Materials at temperatures in excess of absolute zero will radiate energy. The rate of radiation from a blackbody is a function of temperature alone and is proportional to the fourth power of the absolute temperature. The blackbody radiation is the maximum radiation possible from a material at a specific temperature and wavelength; therefore, it is reasonable to compare radiation from all other materials (non-blackbodies) with the radiation from a blackbody at the same temperature for a basis of comparison. The radiation from a non-blackbody depends upon the material, its temperature, and the condition of its surface.

A blackbody will emit or absorb the maximum radiation possible at a specific temperature. Obviously for maximum heat transfer, one would choose a blackbody radiating to another blackbody at a lower temperature. Since a true blackbody is only approached, never realized, it is necessary to know how near to true blackbody conditions a particular material really comes. This indicates that a blackbody (under ideal conditions) should be chosen as a reference or a standard, and all other materials or bodies compared with it determine their radiation properties. This has been borne out by the definitions of several terms with which we are working.

Blackbodies have received close attention with the possibility of constructing cavities that approach very closely to true blackbody conditions. It is not unreasonable to expect the radiation from so-called blackbody cavities to be 0.995 the radiation from a true blackbody. Careful design and precise temperature control have permitted very good blackbodies to become available. As a result, much radiation work at the present time depends upon a blackbody reference when comparing specimens. Figures 2 and 3 show two types of apparatus using a blackbody reference. (2) In other cases, the blackbody has been used to calibrate a particular detector as that the signals from this detector may be converted directly into specific radiation data, whether it be emittance, reflectance, or absorptance data. Figure 4 represents such a technique whereby a calibrated detector is used for the measurement of total normal emittance. (2)

Some general comments concerning radiation are necessary in order to provide a common basis for further definitions or concepts. The thermal radiation being radiated from a unit area of an opaque solid (grey body) is a function of its temperature and of its emissivity. Emissivity is the ratio of the radiation from a certain material to the radiation from a blackbody at the same temperature.

This may be measured on a spectral basis or on a total basis. For the former, measurements would be made over a narrow wavelength increment at one time. Total emissivity would consist of the measurement of radiation over the entire wavelength region in which radiation would be present. The directional detection factor of emissivity is described by the terms normal and hemispherical where normal emissivity refers to only that radiation being emitted normal to the surface of the specimen while hemispherical emissivity would mean a measure of all radiation being emitted into the hemisphere bounded by the plane of the specimen.

The type of environment a particular spacecraft will encounter will determine the type of test conditions that may prevail. The usual protection for materials under test is a good vacuum (10^{-6} mm Hg). However, when the vehicle is not at consistently extreme high altitudes, it seems reasonable to assume that the test can be run in an air atmosphere. Likewise, where a material will be used in a vacuum, then testing in similar vacuum environments would be indicated. Inert atmospheres may be used when required. Most emittance measurements have been made either in air or in a vacuum. At present, the Aeronautical Systems Division is supporting programs in various laboratories for emittance measurements in an air atmosphere at temperatures up to 3000°F, in vacuum at temperatures up to the 4000° - 5000°F region, and in some cases, an inert atmosphere is used for specimen protection because of the endless variety of end requirements for such data.

Inherent to most experimental measurement programs is the problem of errors. An important probable source of error in emittance measurements is the uncertainty of specimen temperature. Although thermocouple contamination could result in a change of the calibration, the usual trouble is thermocouple location or thermocouple attachment including the problems of unpredictable temperature gradients. Some methods call for the thermocouple to be pressed against the front or rear surface of the specimen. Should the facility utilize an air atmosphere, the specimen could oxidize to such an extent that the thermocouple actually would be separated from the specimen indicating the temperature of the oxide layer. With a pressure type thermocouple in a protective atmosphere, changes in contact pressure caused by differential thermal expansion or spring failure may permit the thermocouple to move away from the specimen's surface. For metallic specimens where the thermocouple is welded directly to the specimen, care must be exercised to use the smallest wire feasible in order to minimize conductive heat losses. Larger thermocouple beads and wires can cause considerable cooling by conduction in the area of the bead. In this case, the true specimen temperature would be higher than indicated by the thermocouple output. The location of the thermocouple should be considered carefully. For thick specimens heated from the rear surface, it is natural that a temperature gradient from the rear to the front surface will be present. A thermocouple on the rear surface could indicate an erroneously high temperature because of the inherently higher temperature of the rear surface and because it could receive direct radiation from the heat source. A possible gradient from the middle to the edge of the specimen must be considered when locating the thermocouple on the front surface of the specimen. However, the furnace design would influence this type of a gradient. A related area of temperature measurement occurs in systems where the radiation from a specimen is compared directly with the

radiation from a blackbody. In such cases, it is essential that both furnaces (blackbody furnace and specimen furnace) be operating at the same temperature during the measurements.

Thus far, only opaque specimens have been considered. Many materials such as ceramics and ceramic coatings are translucent to infrared radiation from the heat source. Special precautions must be exercised, for should a cooling plate be moved into position between the heat source and the specimen just before emittance measurements are made, spurious radiation would reach the detector giving inaccurate readings.

Various techniques in use at this time provide for total normal emittance, total hemispherical emittance, and normal spectral emittance measurements in air, inert gas, or vacuum at temperatures up to the 4500°F region. With the various techniques or modifications thereof, many combinations of errors, both known and unknown, are encountered. In order to provide a firm basis for all emittance measurements of interest to the Air Force, this Directorate is supporting a program at the National Bureau of Standards to develop standard techniques for emittance measurements providing several sets of emittance standards to cover the range from low to high emittance. To better cover the spectral and temperature ranges, the spectral region has been divided into two parts - 0.7 to 15 microns and 15 to 35 microns. The temperature range has been divided into three parts: room temperature to 1000°F, 1000° to 2000°F, and 2000° to 4000°F. As the temperature of a body increases, the wavelength below 98% of the energy emitted by a blackbody will fall toward the shorter wavelengths (table 1). This indicates that at a very high temperature, the long wavelength emission will contribute only a small part of the total emission and emittance measurements in the 2000° to 4000°F temperature range, 15 to 35 micron spectral range are of less importance than the similar measurements in the 0.7 to 15 micron range.

The National Bureau of Standard program calls for the development and characterization of three emittance standards: low, intermediate, and high, for the overall region from 0.7 and 35 microns, and from room temperature to 4000°F. The first region to be studied will be from 0.7 to 15 microns, 1000° to 2000°F.

It was considered desirable as far as possible, that commercially available standard components be used when developing the standard instrumentation for emittance measurements. With this in mind, the National Bureau of Standards chose a double beam ratio recording infrared spectrometer. In its original operation, this instrument used a beam splitting device to divide into two equal and separate beams the radiation from a Nernst glower. The two beams were chopped alternately, 180° out of phase, and then passed through combining optics so that the two beams were transmitted along the same path, but at alternate intervals, through the monochromator into the detector assembly. The signals, corresponding to the two beams, were separated, amplified and rectified, giving two signals, each proportional to the intensity of its respective beam, which could be handled as desired.

Basically, this instrument was designed for transmittance measurements where a sample would be placed in one of the chopped beams and the two resulting signals would be compared to indicate the transmittance of the sample for particular wavelengths.

Since emittance is the ratio of energy emitted from a material to the energy emitted from a blackbody at the same temperature, it would be desirable to compare directly the energies from similar areas of the sample and from a blackbody at the same temperature. To define further the emittance as spectral, it is necessary to compare their energies

for narrow wavelength intervals. By removing the Nernst glower and the associated beam-splitting optics, two independent signals can be introduced and compared by the infrared spectrometer as shown in figure 5. This means that a blackbody furnace can be located so that its radiation will be the source of one beam for the spectrometer. The specimen furnace can be located so the radiation from the specimen will be the source of the other beam. It is necessary to insure that the optical paths are the same length and that the apertures are the same for these two beams. A differential thermocouple was installed with one junction in the blackbody furnace and the other junction in the specimen furnace so that the thermocouple output would indicate the magnitude, and direction, of temperature differences between the specimen and the blackbody. By feeding this thermocouple output into a center-zero potentiometer-controller, the power to one furnace can be controlled to maintain a temperature equal to that of the other furnace. This technique requires a simple independent temperature measurement to determine the temperatures of the specimen and the blackbody. This arrangement insures that all measurements from the specimen are compared with the blackbody at the same temperature. The remainder of the system is as originally designed where the two beams are chopped alternately, then combined before their introduction into the monochromator and the detector. As previously indicated, the signals from the detector are separated with respect to source and are amplified and rectified. The result is two d.c. signals that are proportional respectively to the radiation intensities from the specimen and the blackbody.

Of equal importance to the development of the standard techniques, is the development of the emittance standards themselves. Considerable time has been spent in selecting candidate materials for standards. Some materials were eliminated rather quickly on the basis of their temperature limitations. Naturally, the materials for standards must have melting points considerably above the temperature range for which they are to be used. In addition, the surface must be mechanically stable and temperature stable so that the emittance will not change appreciably with time and with temperature cycling. The National Bureau of Standards will recalibrate these standards periodically. Once these standards have been completely calibrated, they will be available from the Physics Laboratory, Directorate of Materials and Processes, Aeronautical Systems Division, for short-term loan to those organizations having a bona fide need to calibrate their own emittance apparatus. These emittance standards will be prepared in an assortment of sizes and shapes to accomodate nearly all major laboratories making emittance measurements. However, changes in equipment design and the construction of new apparatus may result in size and shape requirements that will not be met by the standards now being prepared. In these cases, arrangements will be made with NBS to determine the feasibility of preparing a special set of standards.

Since the National Bureau of Standards is responsible, primarily, for the development of standards and techniques of measurement, straight-forward emittance measurements on a wide variety of materials must be accomplished at commercial or university laboratories. In view of present technological developments, it is very important that emittance measurement capabilities for higher temperatures be available. NBS has been asked to continue their work on the higher temperature regions as previously indicated so that suitable standards will be available for laboratories making measurements in these extended temperature regions. Figure 6 shows (replotted on the same scale) the normal spectral emittance curves for oxidized Inconel and platinum at 2061°F (1400°K). These data were reported by National Bureau of Standards in WADD Technical Report 59-510. (3)

Thus far, greatest emphasis has been on emittance measurements, per se, of opaque solids. Recently a program has been initiated for the study of emittance for transparent and translucent materials. Although this program is relatively new, it is expected to yield information necessary for the thorough understanding of the general area of thermal radiation. Additional work is required to resolve the problem of total normal versus total hemispherical emittance data. Somewhat related to this area is the further investigation of emittance versus angle of emittance. Indications are that the Lambert Cosine Law does not apply for all types of surfaces and more information is needed before reliable predictions can be made regarding the angular emittances of a particular surface profile. At the present time, this Directorate is supporting a program to consider this problem; however; it is too early for conclusive results. Whenever the surface of a material is mentioned, the accurate description of this same surface comes to mind immediately. Earlier, it was stated that one problem in comparing earlier emittance data was the lack of a good uniform description of the surface. As in the humanities, what may be considered polished by one person may not be considered as qualifying for a "polished" label by another person. The effect of continued exposure at high temperatures or of surface conditions, on the emittance properties of specimens has been encountered. It now remains to evaluate these effects so that they may be dealt with effectively for the solution of continually arising technological problems.

In addition to the preceding outline of technological goals in this area, effort will be devoted to extending these measurements into the very high temperature regions and into the cryogenic regions as well.

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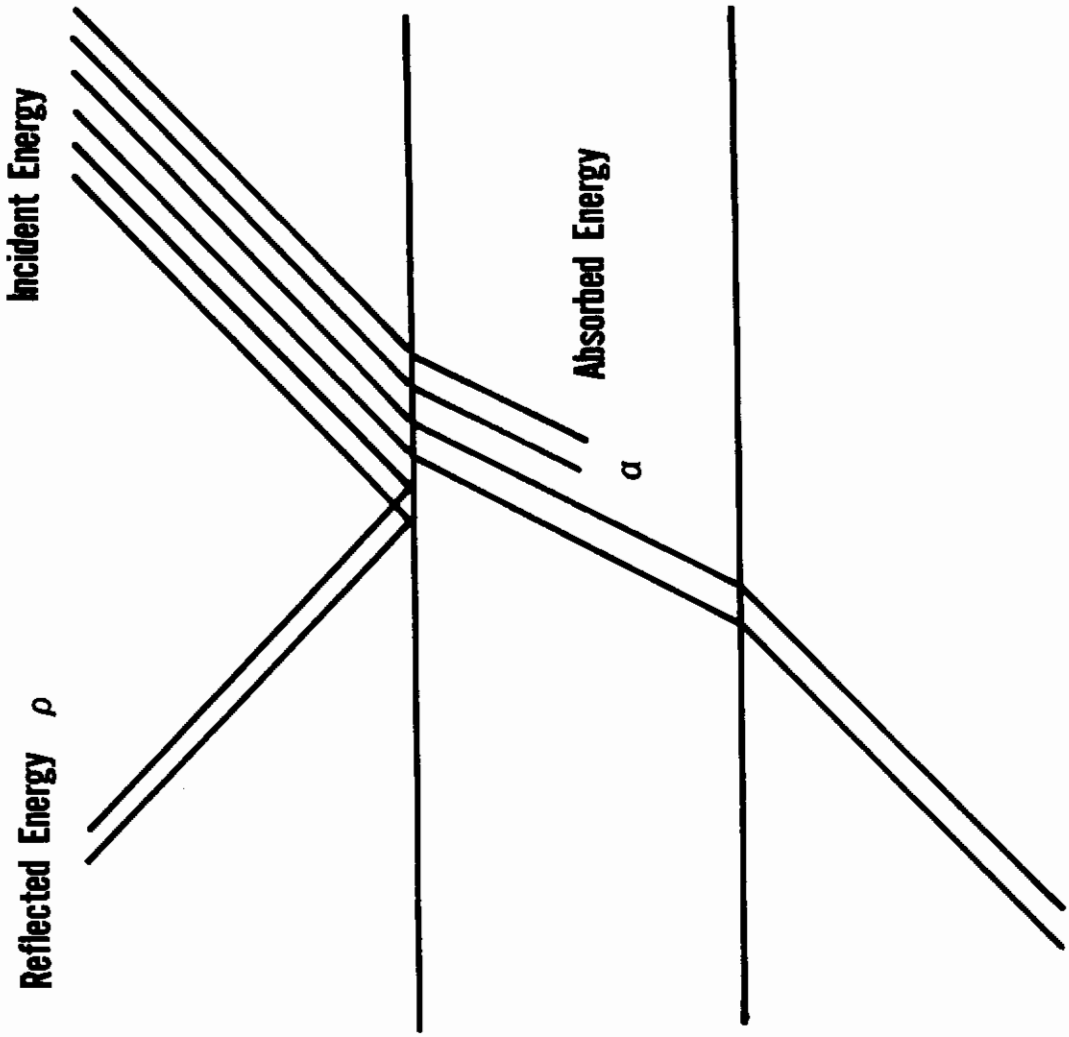
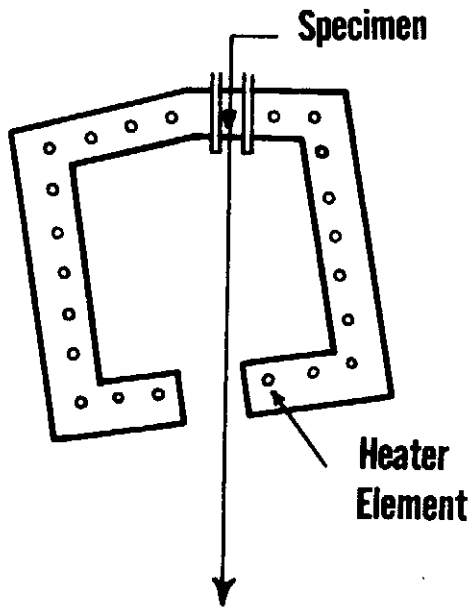


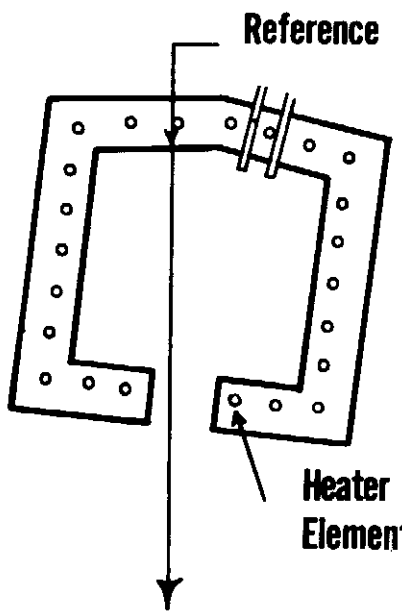
GENERAL CASE FOR ENERGY TRANSFER

Figure 1.

U OF CALIFORNIA GIER - DUNKLE TYPE CAVITY



Cavity Tilted For Measurement
Of Specimen Reflectance



Cavity Tilted For Measurement
Of Blackbody Radiation

Figure 2.

APPARATUS FOR DETERMINING NORMAL SPECTRAL EMITTANCE

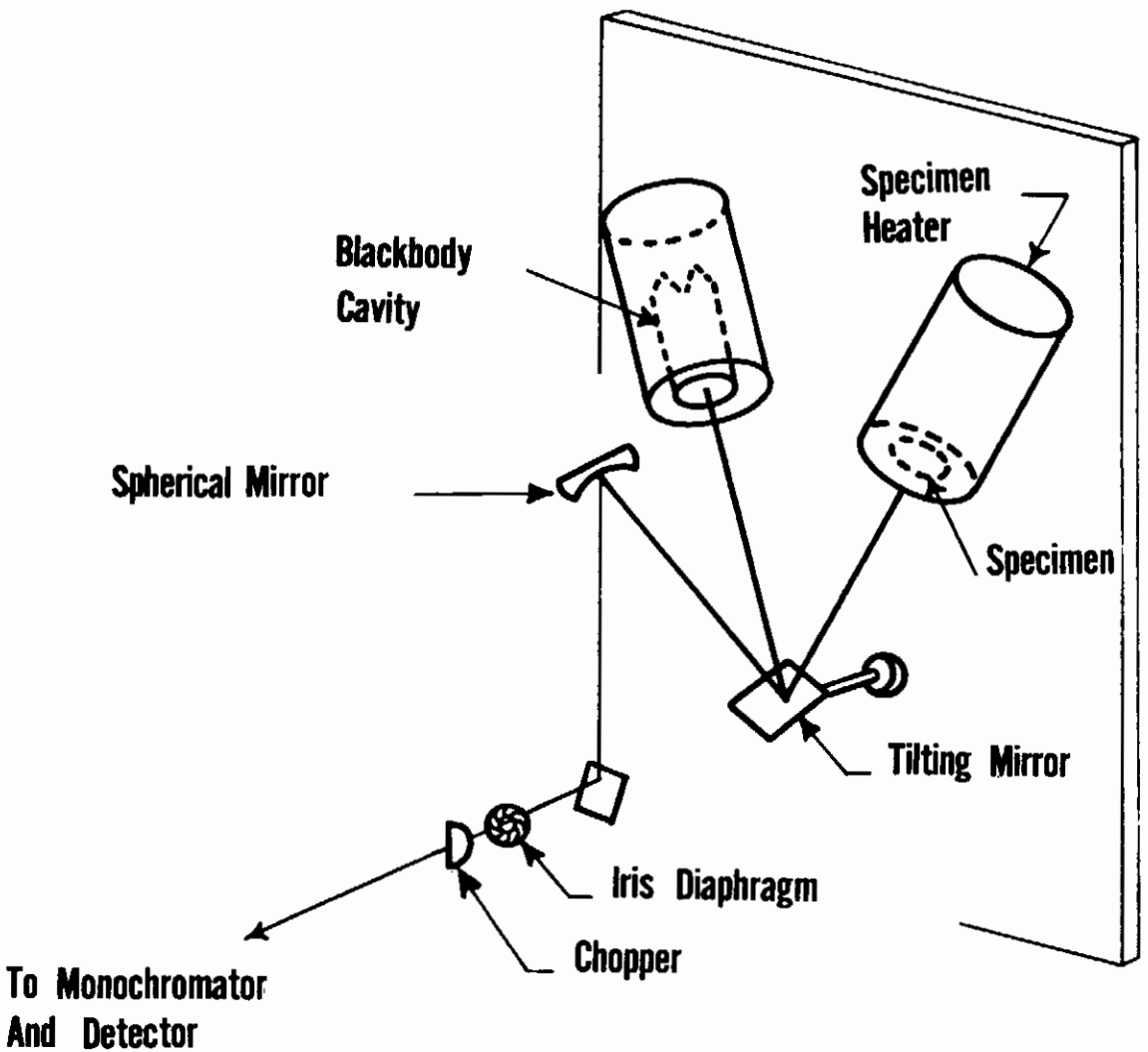


Figure 3.

APPARATUS FOR DETERMINING TOTAL NORMAL EMITTANCE (GAS-FIRED UNIT)

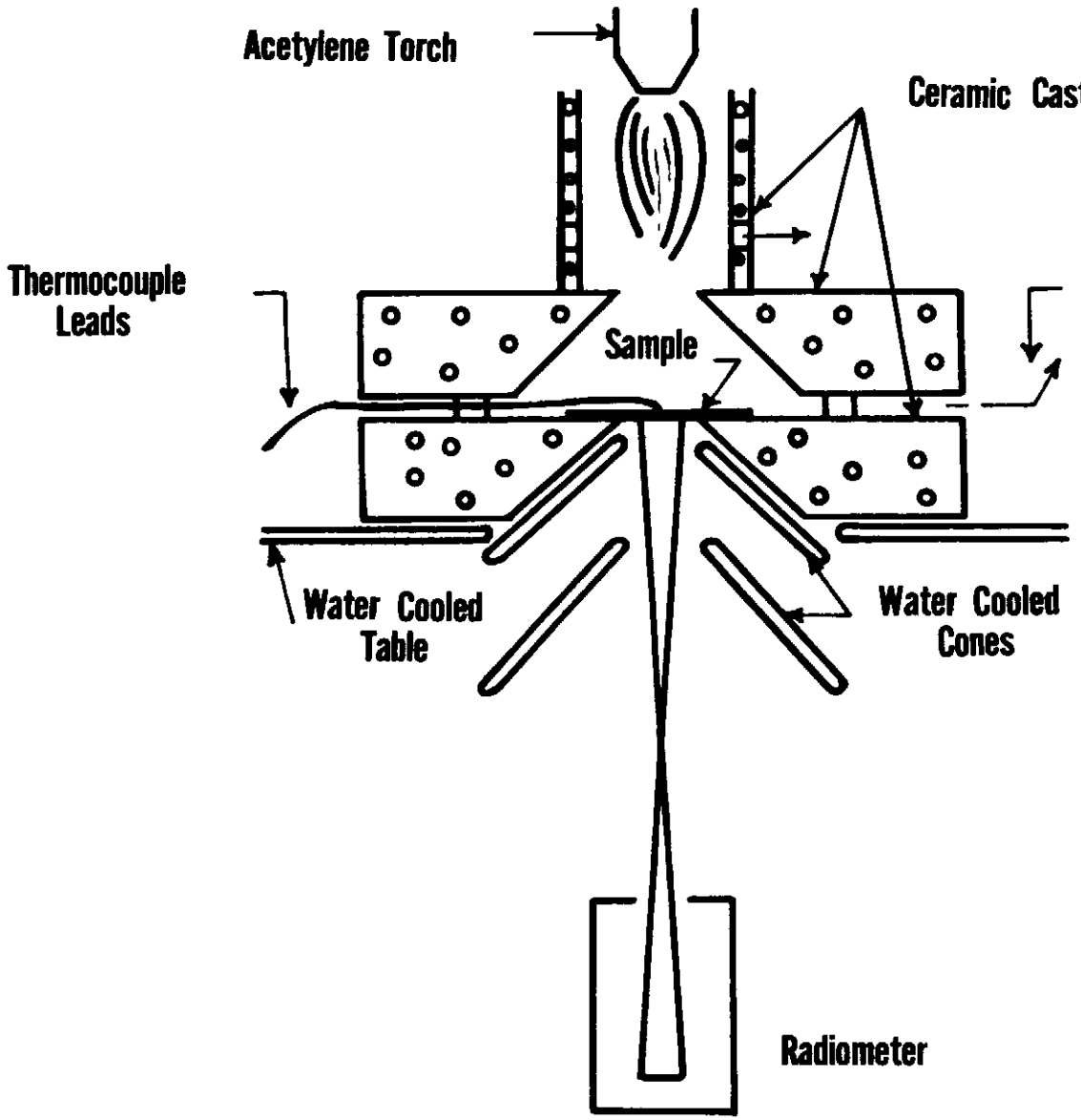


Figure 4.

SCHEMATIC DIAGRAM OF NBS APPARATUS TO DETERMINE SPECTRAL NORMAL EMITTANCE

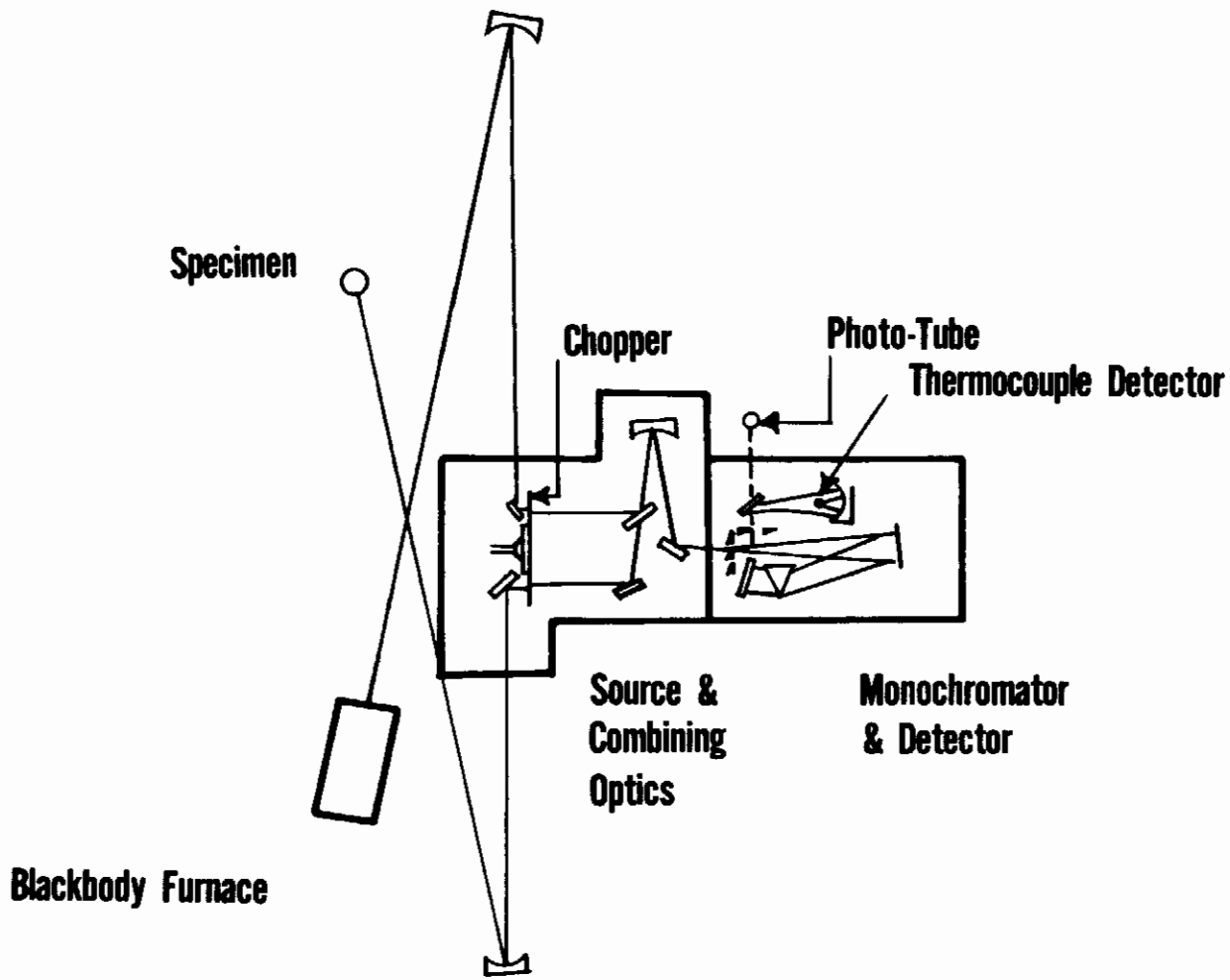


Figure 5.

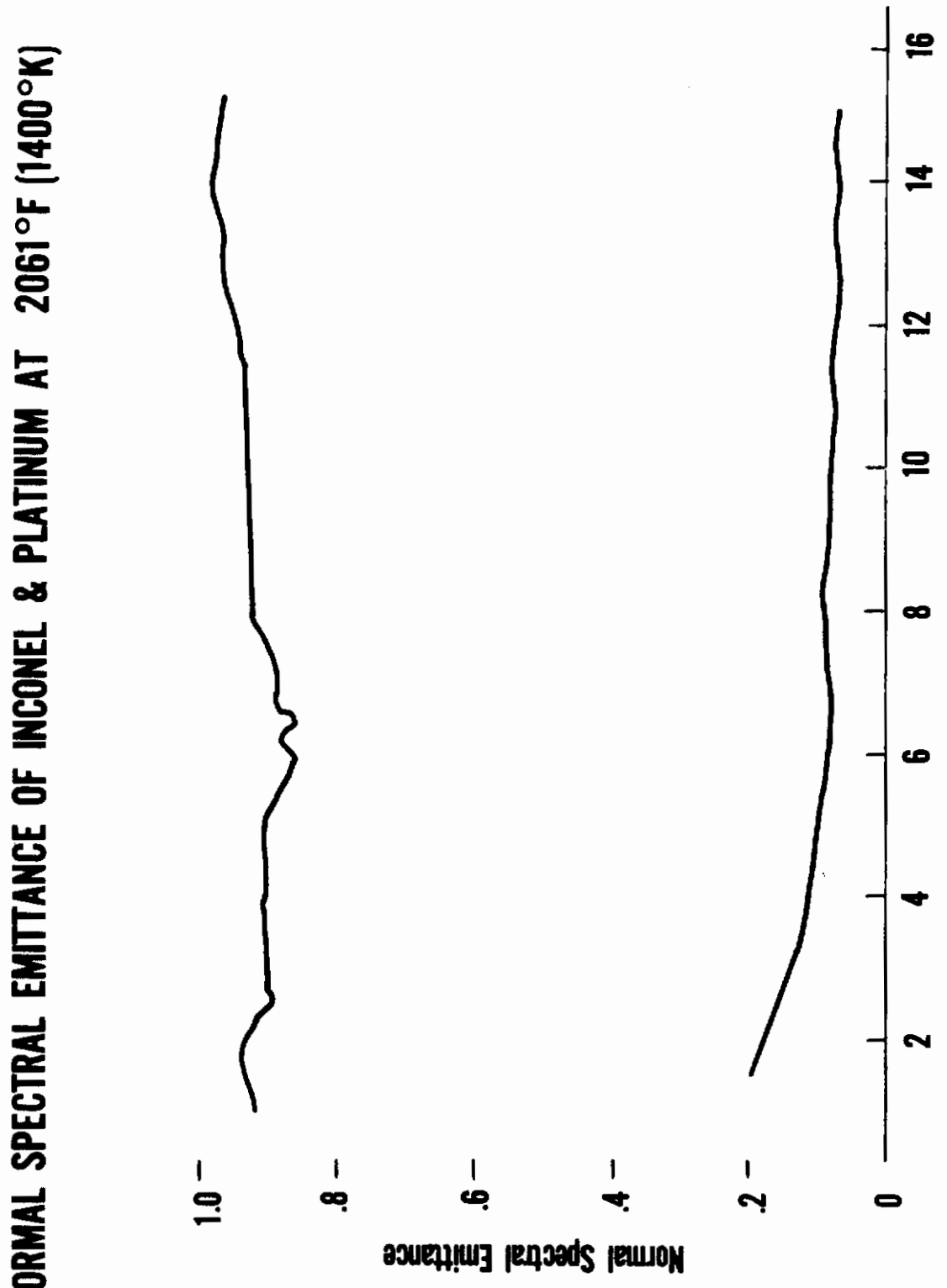


Figure 6.