A COMPARISON OF TWO
EMITTANCE MEASUREMENT TECHNIQUES

James B. Heaney

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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

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ABSTRACT

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A technique used to measure total normal emittance that employs a Gier-Dunkle Portable Emissivity Inspection System is explained in detail. This is then compared with the familiar heated cavity hohlraum type measurement which gives a value of total normal emittance by summing spectral data. Emittance values obtained from samples measured on both systems are compared and an analysis of some of the errors inherent in each measuring technique is given.

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INTRODUCTION

The two measurement techniques described here are commonly used to determine emittances of paints, metals or dielectric films that are used as satellite temperature control coatings or skin materials. The emittance of a given material is an important parameter in determining its thermal control properties in an environment where radiation is the primary mechanism of energy exchange.[1] Most measurement systems require the preparation of a sample that duplicates the conditions under which the material is to be used. However, the Gier-Dunkle Portable Emissivity Inspection System is one of the type that can make on-site measurements of satellite surfaces or other irregularly shaped surfaces. The instrument measures total normal emittance, as opposed to the heated cavity (hohlraum) type system which employs a monochromator to give sample emittance as a function of wavelength. Total normal emittance can then be obtained by summing the spectral values, with an additional weighting factor, over all wavelengths. Thus we have two means of obtaining the same value and they serve as a convenient relative check of instrument accuracy. Since the techniques of measurement are different, they have different sources of error and data obtained from one instrument can be used to point out inaccuracies in the other.

DESCRIPTION

A. Total Normal Emittance

We will first consider our technique of obtaining total normal emittance (as opposed to spectral emittance). The measurement is made with a portable emissivity inspection system manufactured by Gier-Dunkle Instruments, Inc. This emissivity inspection system is designed to measure the emittance of an opaque surface at room temperature. Refer to Figure 1. The system is composed of a radiometer head which is connected by means of a flexible conduit to its power supply and electronic read-out. Once the instrument has been electronically balanced, all we need do is place the opening in the radiometer head over the surface we wish to measure and immediately obtain a potentiometer reading which is converted to emittance. The entire process takes only a few seconds. Although the instrument can make a measurement on just about any opaque

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surface that can be put in contact with the sensing head, we normally measure prepared samples. One of these is shown in Figure 1 leaning against the radiometer head. It consists of the paint, whose emittance is to be determined, on an aluminum substrate three inches long, by one inch wide by one-sixteenth of an inch thick. The substrate size is determined by the sample opening of the radiometer head.

The principles of operation can best be explained by analyzing the radiometer head which is depicted in Figure 2. It is a cylindrically shaped container whose walls are black and are kept isothermal by circulating steam at 100°C through a conducting shroud. At the base of the head is an evaporated gold spherical mirror that focuses all near-normal radiation coming
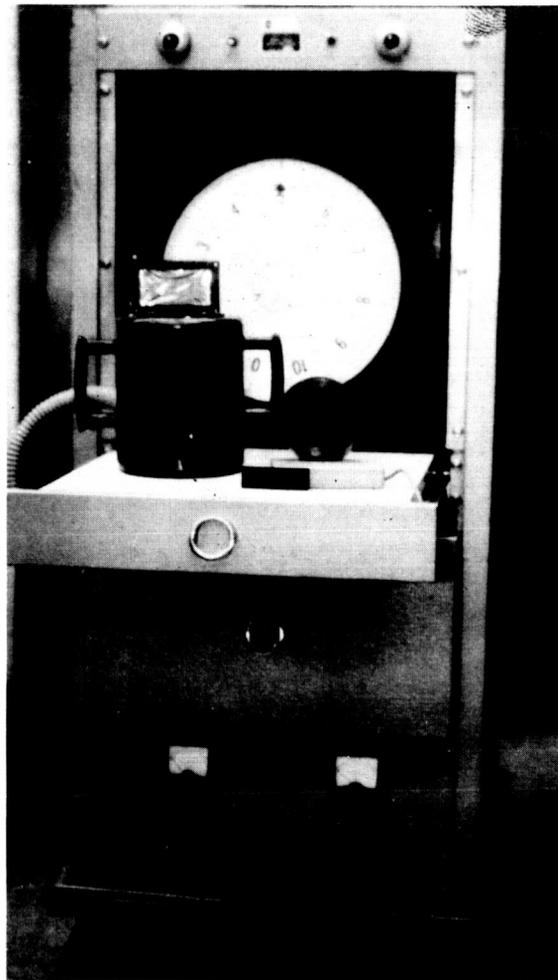
Figure 1—Portable Emissivity Inspection System
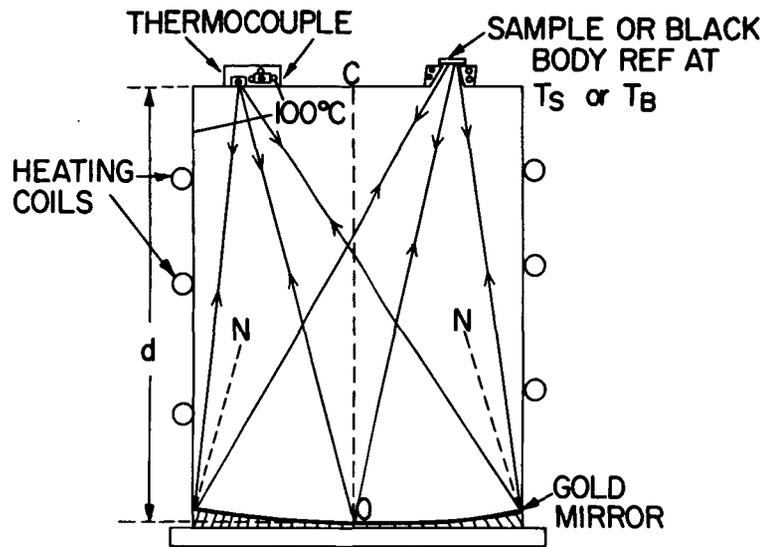
Figure 2—Diagram of Radiometer Head

from the sample opening onto the sensing junction of a thermopile. The reference junction of the thermopile is kept at 100°C and it is the hotter junction. Energy lost by the sensing junction through radiation accounts for the ΔT across the thermopile. This energy loss is proportional to the infrared emittance of whatever covers the sample opening and it is indicated on a self-balancing potentiometer.

Three things may cover the sample port:

1. The "zero ϵ" reference which is a highly reflecting, well insulated piece of aluminum overcoated with mylar;

2. the "maximum ϵ" or blackbody reference - a cylindrical cavity at room temperature whose absorptivity = emissivity = 1;

3. the sample itself.

The near-normal sample emittance may be obtained from the heat balance equations that describe what happens when something covers the sample port.

First consider the radiometer head with the zero ϵ reference covering the sample port. Whatever energy is radiated away by the sensing thermopile junction is reflected back by the aluminum which is itself at 100°C. The mathematical relation describing this is shown on the following page as Expression (1).

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$$\epsilon_\tau \sigma T_B^4 - R_\rho \epsilon_\tau \sigma T_B^4 - \epsilon_\rho \sigma T_B^4 \propto V_o \quad . \quad . \quad . \quad . \tag{1}$$

where

$\epsilon_\tau \rightarrow$ emittance of the blackened thermopile $\simeq 1$.

$\epsilon_\rho \rightarrow$ emittance of the reference $\simeq 0$.

$R_\rho \rightarrow$ reflectance of the reference $\simeq 1$.

$T_B \rightarrow$ temperature of the thermopile junction and also of the reference $\simeq 100°C$.

$\sigma \rightarrow$ Stefan-Boltzmann constant.

Expression (1) becomes:

$$0 \propto V_o \quad . \quad . \quad . \quad . \tag{1a}$$

and this becomes our zero level which is then adjusted on the potentiometer recorder.

Next, consider what happens when the blackbody reference is placed over the port. The heat balance relation is:

$$\epsilon_\tau \sigma T_B^4 - R_R \epsilon_\tau \sigma T_B^4 - \epsilon_R \sigma T_R^4 \propto V_R \quad . \quad . \quad . \quad . \tag{2}$$

where terms not previously defined are:

$\epsilon_R \rightarrow$ emittance of blackbody reference $\simeq 1$.

$R_R \rightarrow$ reflectance of blackbody reference $\simeq 0$.

$T_R \rightarrow$ temperature of blackbody reference $\simeq 20°C$.

Expression (2) is then:

$$\sigma T_B^4 - \sigma T_R^4 \propto \cdot V_R \quad . \quad . \quad . \quad . \tag{2a}$$

and this becomes our 100% level on the potentiometer.

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Now, consider what happens when a typical sample covers the port. The net energy lost by the thermopile sensing junction is given by:

$$\epsilon_\tau \sigma T_B^4 - R_S \epsilon_\tau \sigma T_B^4 - \epsilon_S \sigma T_S^4 \propto V_S \cdot \cdot \cdot \cdot \tag{3}$$

where, terms not previously defined are:

$R_S \rightarrow$ reflectance of the sample

$\epsilon_S \rightarrow$ emittance of the sample

$T_S \rightarrow$ temperature of the sample.

Expression (3) then becomes:

$$\epsilon_\tau \sigma T_B^4 - (1 - \epsilon_S)\, \epsilon_\tau \sigma T_B^4 - \epsilon_S \sigma T_S^4 \propto V_S \cdot \cdot \cdot \cdot \tag{3a}$$

since the sample is opaque $R_S = 1 - \epsilon_S$, and since $\epsilon_\tau = 1$, we get

$$\epsilon_S \left(\sigma T_B^4 - \sigma T_S^4 \right) \propto V_S \cdot \cdot \cdot \cdot \tag{4}$$

V_S then becomes the sample reading on the recorder. To find the sample emittance relative to the blackbody reference we take the ratio of the sample and 100% readings:

$$\frac{V_S}{V_R} = \frac{\epsilon_S \left(\sigma T_B^4 - \sigma T_S^4 \right)}{\sigma T_B^4 - \sigma T_R^4}$$

Sample emittance is then given by

$$\epsilon_S = \frac{V_S \left[\sigma T_B^4 - \sigma T_R^4 \right]}{V_R \left[\sigma T_B^4 - \sigma T_S^4 \right]} \tag{5}$$

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T_S and T_R are actually measured during the testing procedure by placing a thermocouple in contact with the sample or blackbody reference. The temperature is then read off the potentiometer using a calibration chart. T_B is $100°C$. V_S and V_R are the respective recorder readings when either the sample or blackbody reference covers the port.

Some emittance values that have been obtained using this system are given in Figure 3.

Sample Description	Total Emittance
1. Aℓ leafing paint	.22
2. Aℓ_2O$_3$ paint, potassium silicate vehicle	.89
3. Carbon black, methyl silicone vehicle	.86
4. Catalac Black	.89
5. Parson's Black	.91
6. 3M Black	.92
7. TiO$_2$, potassium silicate vehicle	.87
8. TiO$_2$, potassium silicate, Boron treated	.90
9. Z$_N$O, potassium silicate vehicle	.89

Figure 3—Table of Total Emittance Values

From Equation (5) we can see that our determination of ϵ_S is based on four independent measurements, each of which uses the system's electronics. If all components are correctly balanced and operating properly, the most probable error should be less than $\pm 2\%$ of the full scale value. This means that it is impossible to measure an ϵ_S of .02 or less with any precision.

This error resides in the electronics of the instrument (including thermopile sensitivity) and can be effectively minimized by proper calibration procedures. But there are other sources of inaccuracy which are inherent in the measuring technique itself.

Consider the quantity ϵ_S as determined by Equation (5). We can see from Expression (4) that ϵ_S is a function of T_S^4 and T_B^4, i.e., $\epsilon_S = \epsilon_S(T_S, T_B)$. If we express this in terms of spectral quantities, we get:

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$$\epsilon_S(T_S, T_B) = \frac{\int_0^\infty \epsilon_S(\lambda, T_S) [J(\lambda, T_B) - J(\lambda, T_S)] Q d\lambda}{\int_0^\infty J(\lambda, T_B) d\lambda - \int_0^\infty J(\lambda, T_S) d\lambda}$$

or simply:

$$\epsilon_S(T_S, T_B) = \frac{\int_0^\infty \epsilon_S(\lambda, T_S) [J(\lambda, T_B) - J(\lambda, T_S)] Q d\lambda}{\sigma T_B^4 - \sigma T_S^4} \qquad (6)$$

where

$\epsilon_S(\lambda, T_S)$ is the spectral emittance of the sample for wavelength λ and temperature T_S at near-normal direction.

$J(\lambda, T)$ is the Planckian spectral radiance function at temperature T and near-normal direction.

Q is a quantity determined by such things as the transmittance of the air in the radiometer, the reflectance of the gold mirror and the absorptance of the Parson's optical black on the detector. We assume $Q = 1$.

The true normal emittance of a sample at temperature T_S is given by

$$\epsilon_T(T_S) = \frac{\int_0^\infty \epsilon_T(\lambda, T_S) J(\lambda, T_S) d\lambda}{\sigma T_S^4} \quad \cdots \qquad (7)$$

The quantity given by Equation (6) is what the instrument actually measures. From Equation (6) we see that the measured ϵ_S is the near-normal spectral emittance weighted by:

$$\frac{J(\lambda, T_B) - J(\lambda, T_S)}{\sigma T_B^4 - \sigma T_S^4} \qquad \text{(since } Q = 1\text{)}.$$

Likewise, from Equation (7), the true near-normal emittance is seen to be the true spectral emittance weighted by:

$$\frac{J(\lambda, T_S)}{\sigma T_S^4}.$$

Now, if we choose as typical working temperatures $T_S = 300°K$ and $T_B = 373°K$ (steam), we see that the first weighting factor emphasizes the 8-10 micron region more heavily than the second. This means that the measured ϵ_S, as obtained from Equation (5), only equals the true emittance ϵ_T, when we are dealing with a gray sample, i.e., $\epsilon_S(T_S) = \epsilon_S(\lambda, T_S)$. In this case both weighting factors approach unity in a uniform way. However, if the sample is non-gray, the wavelength shift in the weighting factors may cause an increase or decrease in the true emittance, depending on how much and at what wavelengths the sample reflectance increases or decreases (since $\epsilon = 1 - R$ for an opaque sample).

B. Spectral Emittance

If we knew the emittance as a function of wavelength, we could use Equation (6) to determine the inaccuracy involved in assuming that our sample is gray. $\epsilon_S(\lambda, T_S)$ can be measured in a variety of ways and the difference between the true emittance $\epsilon_T(T_S)$ and the measured emittance $\epsilon_S(T_S)$ can be calculated using the above expressions. The technique we use to determine $\epsilon_S(\lambda, T_S)$ is a fairly common one that has been fully analysed by various people.[2,3,4] It consists of a heated hohlraum reflectometer used in conjunction with a Perkin-Elmer 13-u spectrophotometer (see Figure 4). The hohlraum is maintained at a temperature of 800°C. There are some problems with temperature gradients along the walls of the oven and for this reason the oven itself is not used as an absolute reference when making measurements. Instead, we use an evaporated Au reference disc as our full scale (100%) level. The hohlraum is used merely as a source of diffuse radiant energy to cover the wavelength region from 4 to 30 microns. A sample of the material to be measured is attached to an aluminum substrate 15/16 in. in diameter. (Usually the sample is a paint and it is just painted on the substrates. Strong, conducting solids can sometimes be measured without a substrate). The sample is then placed in a water cooled sample holder which is shown together with the total reflectance retaining nut in Figure 5. The sample holder is then inserted into the oven so that the sample is nearly flush with the oven roof and it is then rotated about an axis normal to the sample (and roof) until a maximum reading is indicated on the recorder. This means that the sample is looking at a spot on the oven wall from which the radiant energy is a maximum. The same procedure is followed for the Au reference.

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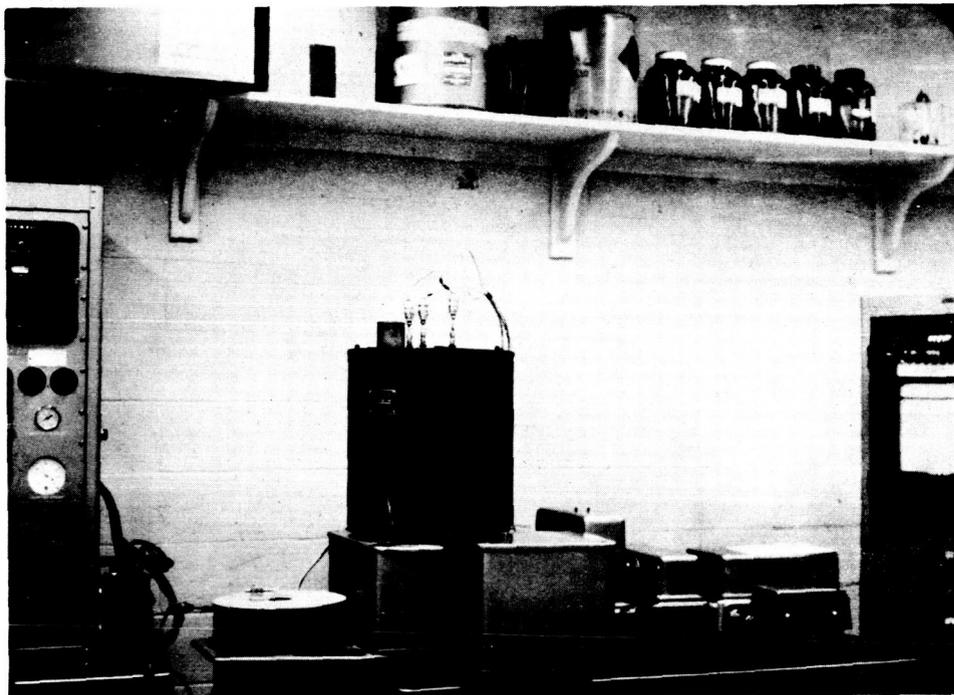
Figure 4—Hohlraum and 13-U Spectrophotometer
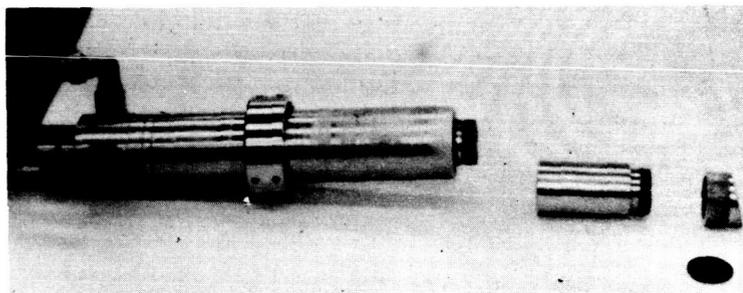
Figure 5—Sample Holder and Black Paint Sample

Since the 13 u is a dual beam system, one half of the chopped signal is coming from a portion of the oven roof and the other half comes from the sample (or reference) which is being diffusely irradiated by the oven and is specularly viewing a portion of the wall near the bottom. By rotating both sample and reference until a maximum is reached we are certain that they are both viewing the same spot on the wall. This is important for specular samples. Consider this simple explanation of what is happening. We first insert our Au reference

into the oven and make a measurement, scanning through a specified wavelength interval. This would give us on the recorder, at any wavelength λ, a 100% level, L_R. We then remove the Au reference and make a similar scan with a sample which gives a corresponding measurement level, L_S. That is:

$$L_R = \frac{E(\lambda,\ T_1) \cdot R_{AU}(\lambda)}{E(\lambda,\ T_2)}$$

$$L_S = \frac{E(\lambda,\ T_1)\ R_S(\lambda)}{E(\lambda,\ T_2)}$$

where

$R_{AU}(\lambda)$ → reflectance of Au reference at λ

$R_S(\lambda)$ → reflectance of sample at λ

$E(\lambda,\ T_1)$ → is the radiant energy of wavelength λ coming from the point on the wall viewed by both sample and reference

$E(\lambda,\ T_2)$ → is the radiant energy coming from the point on the oven roof viewed by the detector during the other half of the chopped cycle

T_1 and T_2 refer to the temperatures of the respective portions of the oven wall. (In an ideal case $T_1 = T_2$).

Now, assuming that our zero level is at zero, we can obtain the ratio:

$$\frac{L_S}{L_R} = \frac{R_S(\lambda)}{R_{AU}(\lambda)} \quad \ldots \ldots \tag{8}$$

Multiplying by the reflectance of Au at λ gives us $R_S(\lambda)$. The water cooled sample holder keeps the sample at room temperature. Hence, for our opaque sample:

$$\epsilon_S(\lambda) = 1 - R_S(\lambda).$$

This is a brief description of our method of obtaining $\epsilon_S(\lambda)$ at near-normal incidence and at room temperature in the wavelength region from 4 to 30 microns. However, we must now use this data to calculate the total emittance which is the

parameter we wish to evaluate. There are several ways to do this.[5,6,7] We use a computer technique that employs a Hoffman Calibrator system programmed to operate in conjunction with our Perkin-Elmer 13-u spectrophotometer. A picture of this setup is shown in Figure 6.
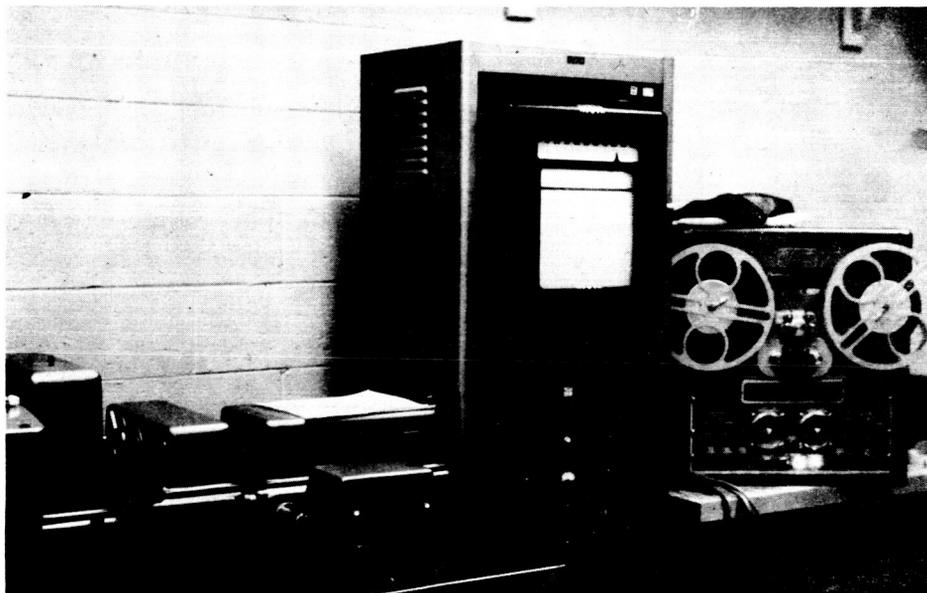
Figure 6—Hoffman Calibrator System

To evaluate a total emittance from spectral data we use the so-called selected ordinate method described in reference 6. The instrument actually measures reflectance which we then convert to emittance. By definition, total sample reflectance is:

$$R_S = \frac{\displaystyle\int_0^\infty R_S(\lambda)\, E_B(\lambda)\, d\lambda}{\displaystyle\int_0^\infty E_B(\lambda)\, d\lambda} \quad \cdots \cdots \tag{9}$$

where

$R_S(\lambda)$ is the spectral sample reflectance (at near-normal incidence and room temperature).

$E_B(\lambda)$ is the spectral energy function for a blackbody at room temperature (300°K).

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But, as was mentioned previously, we use evaporated gold as a reference and not the oven wall, so Equation (9) should be adjusted to give:

$$R_S = \frac{\int_0^\infty R_S(\lambda)\, R_{AU}(\lambda)\, E_B(\lambda)\, d\lambda}{\int_0^\infty R_{AU}(\lambda)\, E_B(\lambda)\, d\lambda} \quad \ldots\ldots \quad (10)$$

where $R_{AU}(\lambda)$ is the spectral reflectance of evaporated Au. The product $R_{AU}(\lambda)\, E_B(\lambda)$ gives the reflected energy and it is the quantity that is actually used as our reference. Now, in the selected ordinate data reduction method we work with values of $R_{AU}(\lambda)\, E_B(\lambda)$ that give 1% of the total reflected energy in our wavelength region of interest. (NOTE: The limits of integration are actually from 4.0 to 30 microns and a correction factor is included to account for the reflected energy from 0 to ∞ which lies outside the above range and which is about 10% of the total value. This can be avoided by normalizing the reflected energy over the working wavelength region. This has not as yet been done, so for simplicity we will continue to use the 0 to ∞ notation.) This is done by choosing unequal values of $\Delta\lambda$ as the working wavelength intervals that will give us our equal reflected energy increments. Equation (10) now becomes:

$$R_S = \frac{\sum_{n=1}^{100} \bar{R}_S(\Delta\lambda_N)\, \bar{R}_{AU}(\Delta\lambda_N)\, E_B(\Delta\lambda_N)\, \Delta\lambda_N}{\int_0^\infty R_{AU}(\lambda)\, E_B(\lambda)\, d\lambda} \quad (11)$$

where

$\bar{R}_S(\Delta\lambda_N)$ is the average monochromatic reflectivity in the wavelength interval $\Delta\lambda_N$.

The same is true of $\bar{R}_{AU}(\Delta\lambda_N)$.

$E_B(\Delta\lambda_N)$ is the total radiant energy contained in the interval $\Delta\lambda_N$.

Here we can see a possible source of inaccuracy creeping in by choosing our $\Delta\lambda_N$ too large. It may be too difficult to get an average value of $R_S(\Delta\lambda_N)$ and still maintain our accuracy. This can be avoided by choosing a sufficient number of intervals that are close enough together so as to include any variation in $R_S(\lambda)$. We have chosen 100 intervals but with some paints this may be inadequate and we intend to go to 1000 in the near future. Thus, while our data reduction time is decreasing, our accuracy is increasing as a direct result of

using a computer. There is a practical limit to the number of points that can be chosen for manual or graphical techniques of data reduction and your overall accuracy is correspondingly limited.

If we return to Equation (11) we can define the following quantity:

$$P_N = \frac{R_{AU}(\Delta\lambda_N)\, E_B(\Delta\lambda_N)\, \Delta\lambda_N}{\int_0^\infty R_{AU}(\lambda)\, E_B(\lambda)\, d\lambda} \quad \cdots \quad (12)$$

This gives us a fraction of the total reflected energy that can be found in any interval $\Delta\lambda_N$. Our total sample reflectance now becomes:

$$R_S = \sum_{n=1}^{100} \overline{R}_S(\Delta\lambda_N)\, P_N \qquad (13)$$

In two successive scans on the instrument, once with the Au reference in and once with the sample in, the computer obtains the ratio given by Equation (8). Then, because this ratio has been stored at pre-selected wavelengths and simultaneously accumulated, we get the value of total reflectance given by Equation (13). From this we get our value of total emittance.

There are several factors which can influence the overall accuracy of our final value. By using a gold reference we need not worry too much about minor variations in oven wall temperature. However, we cannot measure any sample whose ϵ_S is less than .02 (gold). Sample emission becomes a problem in the region around 10 microns. This can be minimized by efficient cooling of the sample. But, for materials with high infrared emittances, such as most black or white paints, a sample temperature of only 60° or 70°C can cause a significant error. In addition to this, the paints must be made thick enough to guarantee that they are opaque and this increases both the difficulty of cooling the sample surface and the likelihood of sample emission. If we keep the sample too cool, we are more likely to disturb the temperature uniformity of the oven wall. These sources of error and others are discussed in references 2 through 4. In general, the data determined using this system are accurate to ±.02.

RESULTS

The data obtained using the hohlraum system are presented in Figure 7 where they are compared with values obtained from the total measurement

Sample Description	Total Emittance Measured Directly	Total Emittance Measured Spectrally
1. Aℓ leafing paint	.22	.20
2. Aℓ$_2$O$_3$ paint, potassium silicate vehicle	.89	.91
3. Carbon black, methyl silicone vehicle	.86	.88
4. Catalac black	.89	.89
5. Parson's black	.91	.92
6. 3M Black	.92	.92
7. TiO$_2$, potassium silicate vehicle	.87	.89
8. TiO$_2$, potassium silicate, Boron treated	.90	.88
9. Z$_N$O, potassium silicate vehicle	.89	.89

Figure 7–Table of Compared Emittances

technique. Although the samples were different, they were prepared so as to be as nearly identical as possible. However, if the samples differ slightly in surface smoothness or thickness, etc., they may have slightly different emittance values. This is especially true of paints.

Using the spectral emittance values we have obtained from the hohlraum measurements, we can now go back and evaluate the weighting factors. This should give us an idea as to how our determination of total emittance depends on wavelength and temperature. This was done for the three paints shown in Figure 8. The hohlraum measurement actually gives us:

$$\epsilon_s = \frac{\int_0^\infty \epsilon_s(\lambda, T_s) \, J(\lambda, T_s) \, d\lambda}{\sigma T_s^4}$$

Theoretically, the Portable Emissivity Inspection System (P.E.I.S.) gives:

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Sample	(Hohlraum)	(P.E.I.S.) Meas.	(P.E.I.S.) Theor.
1. $A\ell_2O_3$, potassium silicate	.91	.89	.94
2. Z_NO, potassium silicate	.89	.90	.93
3. Z_NO, methyl silicone	.89	.86	.89

Figure 8—Evaluation of Weighting Factors

$$\epsilon_S = \frac{\int_0^\infty \epsilon_S(\lambda, T_S) \, [J(\lambda, T_B) - J(\lambda, T_S)] \, d\lambda}{\sigma T_B^4 - \sigma T_S^4}$$

where all the terms are the same as Equation (6). In Figure 8 the theoretical values are compared with those determined experimentally. The theoretical values seem somewhat high for samples 1 and 2. This may be due to the fact that the weighting function:

$$\frac{J(\lambda, T_B) - J(\lambda, T_S)}{\sigma T_B^4 - \sigma T_S^4}$$

was evaluated for each sample without the aid of a computer and the wavelength intervals chosen may have been too large to give any real accuracy. Also, more data will have to be evaluated in this way before any trend will be noticed. In addition to this, the factor Q which was defined for Equation (6) and assumed to be unity may actually have another value. If, for example, Q equaled .95 it would easily account for the difference between the measured and calculated value of ϵ_S.

CONCLUSIONS

The Portable Emissivity Inspection System gives a quick and accurate check of sample emittance. Most materials can be considered gray unless their reflectance is known to vary radically with wavelength and this can be determined from the spectral measurement. Metallic surfaces are gray in the infrared portion of the spectrum.

In regard to the spectral measurements, we intend to increase by a factor of ten the number of intervals over which we integrate to obtain a value of total emittance. This should improve our accuracy, in this respect only, to its practical limit. The accuracy of the spectral measurement can be further improved by more efficient sample cooling and hohlraum heating. Modifications along these lines will be made when time becomes available.

Also, a hohlraum type system, capable of measuring infrared emittance as a function of incidence angle, will soon be in operation and this will increase our ability to measure and monitor changes in satellite temperature control coatings.[8]

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