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**BLACKBODY REFERENCE FOR
TEMPERATURES ABOVE 1200 K:
STUDY FOR
DESIGN REQUIREMENTS**

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TECHNICAL REPORT

by

ALBERT F. GRENIS

and

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JANUARY 1965

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**MATERIALS ENGINEERING DIVISION
U. S. ARMY MATERIALS RESEARCH AGENCY
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Blackbody reference
Temperature reference
Infrared radiation

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Technical Report AMRA TR 65-02

by
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January 1965

D/A Project 1C024401A110
AMCMS Code 5025.11.842
Materials for Army Weapons and Combat Mobility
Subtask 35232

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ABSTRACT

Studies were made in the design of a temperature reference unit, incorporating a vacuum system with a sighting window, for temperatures ranging from 1200 K to 2100 K. In view of the many variables present, the design study was supplemented with analytical and experimental data. Included in this work were transmittance studies of different sighting windows for blackbody radiation, the study of thermal shielding, and experimental studies of blackbody radiation. The window materials available included fused silica, calcium fluoride, and sodium chloride. Recommendations are made in regard to structural materials, sighting windows, and thermal shielding.

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INTRODUCTION

The calibration of temperature-measuring instruments, such as total radiation detectors or silicon photovoltaic detectors, at high temperatures requires the use of a blackbody temperature reference. Although a number of blackbody temperature references are commercially available, most are suitable only for temperatures below 1400 K. The availability of temperature references for higher temperatures (above 1400 K) becomes further limited when these are to include blackbody reference areas of moderate dimensions. In order to fulfill the above requirements, design studies were initiated relative to a temperature reference unit for temperatures beginning at 1200 K and extending beyond 2000 K. The main points emphasized were the design of a suitable high temperature reference unit containing a sighting window, and the determination of appropriate transmittance or correction factors for the particular window.

TECHNICAL CONSIDERATIONS

General

In reviewing the basic ideas for the design of a high temperature reference unit, various ideas were considered. The temperature reference unit should function as a blackbody, that is, follow a Planckian intensity distribution for the entire temperature range covered. The geometric configuration of the heating element should be that of a uniform temperature enclosure with an opening for temperature or radiation sightings only.

High temperature generation can be accomplished by many means including induction heating, dielectric heating, and resistance heating. The use of resistance heating, however, is desirable because electrical power outlets are usually available in laboratory areas, and many high-temperature materials are conductors of electricity so that these can be heated by direct or alternating current. The use of tantalum, tungsten, columbium, and graphite merit particular consideration in this respect. All are suitable for high-temperature operation in an appropriate atmosphere and all can be fabricated with varying degrees of difficulty. The use of an oxide as a material, such as zirconium oxide, can also be considered in combination with dielectric and resistance heating. Zirconium oxide, however, is poor in thermal-shock resistance and would not remain intact after short periods of use. In general, the selection of a refractory metal or graphite for the heating element is preferable.

Many devices, when heated, can be considered as temperature references in themselves. The most common is the tungsten-filament lamp used as a standard for the calibration of optical pyrometers. Here basic limitations are present which affect calibration measurements. The width

of the filament is usually narrow which makes it impractical to use with many total radiation-type instruments. Furthermore, technical data relative to the infrared spectrum of the tungsten filament, together with transmission corrections for the curved glass enclosure surrounding it, are not generally available.

The problem of high-temperature oxidation of the structural materials for the temperature reference unit can be resolved by excluding the oxidizing atmosphere and using a vacuum system with appropriate sighting windows. The use of windows, unfortunately, complicates the problem of infrared radiation since all window materials reduce, by reflection and absorption, the infrared radiation emanating from a source. Consequently, a satisfactory technical design must allow for an adjustment of such losses under all temperature conditions; and the design considerations must include the use of appropriate correction factors in conjunction with the temperature reference equipment.

To obtain the required correction factors, additional studies had to be performed. These included blackbody radiation studies on a theoretical and experimental basis; and transmission studies of the window materials on an analytical and experimental basis.

To increase operational efficiency, supplementary studies were also needed relative to temperature reference components. These included thermal shielding studies on a theoretical basis; and electrical studies of current and voltage on an experimental basis.

Radiation Theory

When initiating the design of a blackbody temperature reference unit, the basic laws and associated principles of thermal radiation should be considered. A blackbody differs physically from conventional materials in that it is both an ideal thermal absorber and an ideal thermal emitter. No known substance is a perfect blackbody radiator as such, but blackbody radiation can be nearly simulated from a small hole made in the wall of a uniformly heated enclosure.

An important law describing an ideal thermal emitter is that originally proposed by Planck.¹⁻⁴ This can be written simply as

$$J_{BB,\lambda}(\lambda, T) = C_1 \lambda^{-5} (e^{C_2 / \lambda T} - 1)^{-1} \quad (1)$$

where $J_{BB,\lambda}(\lambda, T)$ is the intensity of radiation of the ideal emitter per unit area per unit wavelength interval at a particular wavelength, C_1 and C_2 are two radiation constants, λ is the wavelength, and T is the absolute

temperature. This equation gives the intensity of radiation of an ideal emitter at a particular wavelength in terms of wave length, temperature, and two basic constants. Equation 1 can be integrated for all wavelengths to obtain the total intensity of radiation.

$$W_{BB}(T) = \int_{\lambda=0}^{\lambda=\infty} C_1 \lambda^{-5} (e^{C_2/\lambda T} - 1)^{-1} \cdot d\lambda \quad (2)$$

Upon integration of Equation 2 within a prescribed limits, the Stefan-Boltzmann equation is then obtained:¹⁻⁴

$$W_{BB}(T) = \sigma T^4 \quad (3)$$

where $W_{BB}(T)$ is the total intensity of radiation per unit area, σ is the Stefan-Boltzmann constant, and T is the absolute temperature.

Equation 3 shows that the intensity of thermal radiation of an ideal thermal emitter is related to the fourth power of the absolute temperature. Many temperature-measuring devices, such as total radiation detectors, can be designed and constructed in accordance with this known relationship. Of course, one could use a thermal emitter which is not a blackbody radiator as a reference, but here it is found that additional terms have to be included in Equations 2 and 3 to describe adequately the thermal radiation phenomena. These additional terms are known as the emittances of a material and are usually a function of temperature, wavelength, and surface condition. It can be seen then that the design of a temperature or radiation standard would be preferable when based on Equations 2 and 3. The principal reason for this is that the emittance of a blackbody, whether spectral or total, is a constant and equal to unity.

Now, the amount of spectral radiant energy received by a temperature-sensitive detector is dependent on the effect of the geometry and optics, g , of the detector together with the spectral transmittance $\tau_\lambda(\lambda)$ of the window. The resultant energy per unit time received by a detector can be written as

$$J'_{BB,\lambda}(\lambda,T) = g \cdot \tau_\lambda(\lambda) \cdot J_{BB,\lambda}(\lambda,T) \quad (4)$$

where g is a constant which includes the area of the blackbody source and the distance between the detector and the blackbody source. It also includes the characteristics of the optical system contained within the detector. The spectral transmittance $\tau_\lambda(\lambda)$ represents the fraction of the incident radiation which is transmitted by the window at a particular wavelength. It is a function of the window material and wavelength of the impinging radiation.

The total amount of blackbody radiation received by a temperature-sensitive detector can be written as

$$W'_{BB}(T) = g \cdot \tau(T) \cdot W_{BB}(T) \quad (5)$$

where $\tau(T)$ is the total transmittance. Here the total transmittance depends on the spectral distribution of the blackbody reference and, therefore, on the temperature of the blackbody reference.

The total transmittance $\tau(T)$ can be mathematically interpreted as being composed of two parts, that is

$$\tau(T) = \tau_{co}(T) \cdot \tau_{RA}(T) \quad (6)$$

where $\tau_{co}(T)$ represents that fraction of the blackbody radiation allowed to pass, considering only the cut-off wavelength of the window; and $\tau_{RA}(T)$ represents that fraction of the blackbody radiation allowed to pass, considering both the reflection and absorption losses of the window, up to the cut-off wavelength. The cut-off wavelength is taken to mean that wavelength beyond which the transmitted radiation is undetectable with the equipment used.

In the case of a fused silica window which has a cut-off wavelength at 4.66μ , Equation 6 can be written in detail as

$$\tau(T) = \frac{\left[\int_0^{4.66\mu} J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]}{\left[\int_0^{\infty} J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]} \cdot \frac{\left[\int_0^{4.66\mu} \tau_{RA}(\lambda) \cdot J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]}{\left[\int_0^{4.66\mu} J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]} \quad (7)$$

or as

$$\tau(T) = \frac{\left[\int_0^{4.66\mu} \tau_{RA}(\lambda) \cdot J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]}{\left[\int_0^{4.66\mu} J_{BB,\lambda}(\lambda, T) \cdot d\lambda \right]} \quad (8)$$

Using Equations 5 and 8, the total amount of blackbody radiation received by a temperature-sensitive detector with a fused silica window can now be written in detail as

$$\epsilon_{BB}(T) = \epsilon \left[\frac{4.66 \times 10^{-12} \int_0^\infty \lambda^{-5} J_{EB,\lambda}(\lambda, T) \cdot d\lambda}{\int_0^\infty J_{BB,\lambda}(\lambda, T) \cdot d\lambda} \right] \cdot \int_0^\infty J_{BB,\lambda}(\lambda, T) \cdot d\lambda. \quad (9)$$

In this study, Equations 6, 7, 8, and 9 were used.

Thermal Shielding Theory

In one phase of the experimental work a single tantalum shield was needed and used to reduce power losses by thermal radiation. It was realized, however, that a multi-element thermal shielding unit, particularly in a vacuum environment, would be greatly superior. Some of the advantages of a multi-element thermal shielding unit, therefore, were briefly reviewed.

In the case where a cylindrical configuration is used, it can be shown that the equation below satisfactorily describes the heat transfer characteristics for a multi-element shield.* For mathematical simplicity it is assumed that concentric infinitely long cylinders are employed as shields and that the emissivity of all surfaces, including the hot surface and the sink, are equal. The equation, then, can be written as

$$\frac{q}{A_0} = \frac{\sigma(T_0^4 - T_{n+1}^4)}{\left[\frac{1}{\epsilon} + \left(\frac{1}{1 + (n+1) \frac{\Delta r}{r_0}} \right) \left(\frac{1}{\epsilon} - 1 \right) + \left(\frac{2}{\epsilon} - 1 \right) \sum_{n=1}^n \left(\frac{1}{1 + n \frac{\Delta r}{r_0}} \right) \right]} \quad (10)$$

where

- q/A_0 = rate of heat transfer per unit area from the hot surface
- σ = the Stefan-Boltzmann constant
- T_0 = temperature of the hot surface
- T_{n+1} = temperature of the cold surface (sink)
- ϵ = total emissivity (assumed to be the same for all surfaces)
- n = number of thermal radiation shields
- Δr = change in radius between consecutive cylindrical shields
- r_0 = radius of the hot surface

If the ratio $\Delta r/r_0$ becomes very small (r_0 large relative to Δr), Equation 10 reduces to the form

*GOTTS, S. V., Jr., and BROWN, J. J. U. S. Army Materials Research Agency, Private communication.

$$\frac{q}{A_0} = \frac{\sigma(T_0^4 - T_{n+1}^4)}{(n+1)} \cdot \frac{\epsilon}{2-\epsilon}. \quad (11)$$

This equation describes the heat transfer by radiation from a source to a sink where all surfaces, including the shields, are infinite parallel planes.

If $n = 0$, that is, there are no cylindrical thermal shields present, an equation of the form below can be used:

$$\frac{q}{A_0} = \frac{\sigma(T_0^4 - T_1^4)}{\frac{1}{\epsilon} + \frac{r_0}{r_1}(\frac{1}{\epsilon} - 1)}. \quad (12)$$

This equation describes the heat transfer by radiation from one cylindrical surface to another cylindrical surface which surrounds it.

The effects of shielding on power loss by radiation can be explored by first studying the least desirable condition and then studying the more favorable conditions. In all cases, it will be assumed that $T_0 \gg T_{n+1}$, A_0 is a constant, Δr is a small constant increment, and the ratio $\Delta r/r_0 = 1/10$.

The least desirable condition exists when there are no thermal shields present and when the total emissivity for the remaining cylindrical source and the sink is a maximum, that is, $\epsilon = 1$ (assuming the same spacing between source and sink as will later be present between shields). The ratio q/A_0 would be large and, for the sake of discussion, let it be assumed to have a magnitude of 10,000 on a relative scale.

If tantalum is used, where $\epsilon = 0.3$ approximately, then the ratio q/A_0 is reduced to 1833. This value is considerably smaller than the first. If thermal shields are progressively added, the ratio q/A_0 becomes progressively smaller. For example, if six cylindrical shields are used, the ratio q/A_0 is reduced to 330. Figure 1 illustrates this condition. It shows various magnitudes of q/A_0 as a function of the number of shields employed. Therefore, if one uses a certain number of shields, the thermal efficiency can be greatly increased.

EQUIPMENT AND PROCEDURE

Based on the principles reviewed, a simplified blackbody reference unit was assembled for study and experimentation. Figure 2 shows a diagram of the blackbody reference unit with pertinent dimensions. The tubular graphite element shown was 11 inches in length; the outside diameter was 0.75 inch; and the wall thickness was 0.03 inch. Graphite end-plugs, together with water-cooled copper electrodes, were used to complete a direct-

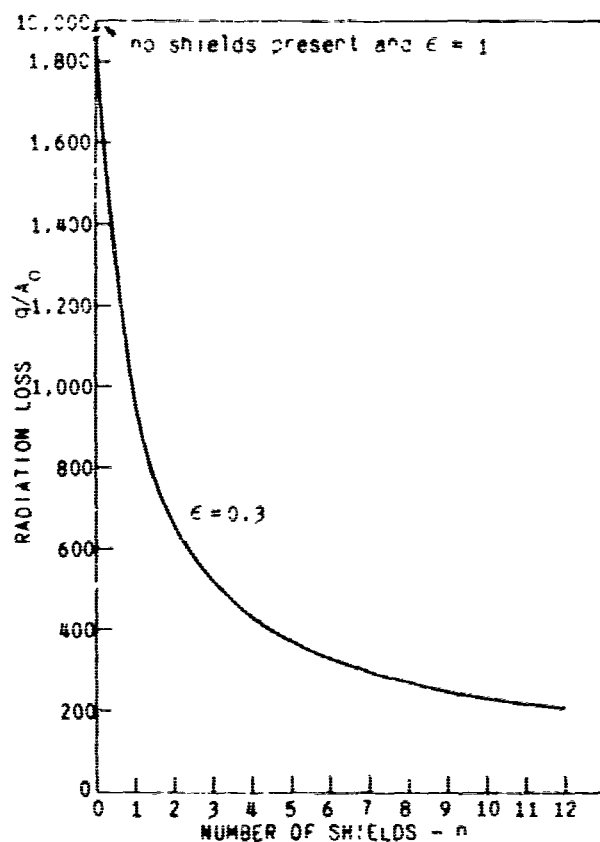


Figure 1. RADIATION LOSS VERSUS NUMBER OF CYLINDRICAL SHIELDS

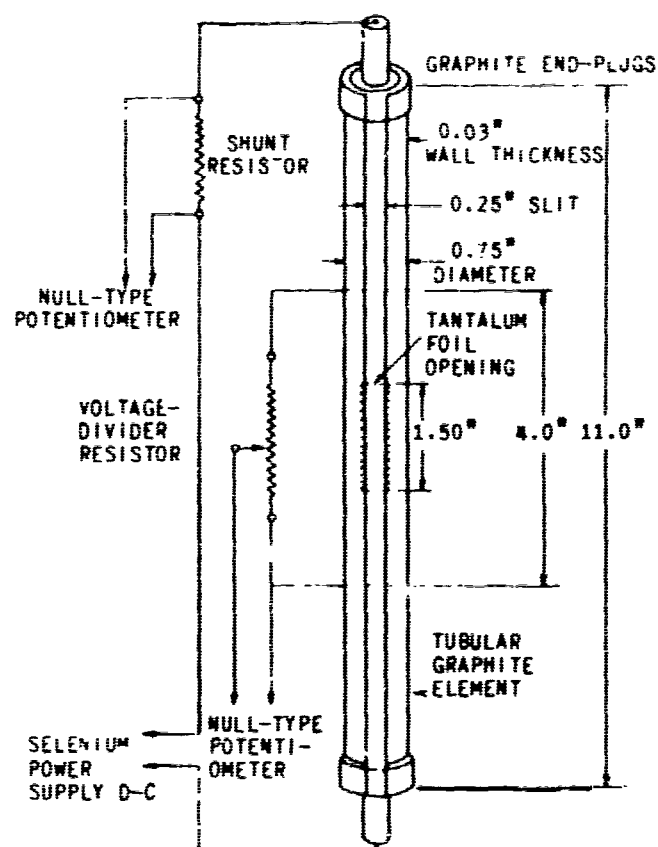


Figure 2. DIAGRAM OF BLACKBODY REFERENCE UNIT

current circuit. A shunt resistor was added to the circuit in series with the graphite cylinder. Since the resistance of the shunt was a known quantity, the current could be determined when voltage measurements across the shunt resistor were made. Similarly, the voltage across a 4-inch length of the cylinder could also be determined by the use of tungsten-wire probes embedded through the wall of the graphite cylinder. The power input for this length of cylinder could then be determined; in addition, an analysis could be made of the current stability and power requirements at a particular temperature. Figure 3 shows a schematic diagram of the assembled blackbody reference equipment.

The temperature-measuring instruments available were a micro-optical pyrometer and a total radiation detector. The pyrometer was one which could be used at different focal distances and on small target areas. Temperature sightings and measurements with the pyrometer were made visually at an effective wavelength of 0.65 micron. The total radiation detector operated on the principle that the total infrared radiation received was converted to an electrical output signal. The detector contained a calcium fluoride window and two mirrors in its optical system which focused the infrared radiation from the source onto a heat-sensitive element. This element, a thermocouple, produced an electromotive force which varied as the temperature of the source varied.

Another radiation-measuring instrument available for this study was an infrared spectrometer having a monochromator with single-beam, double-pass

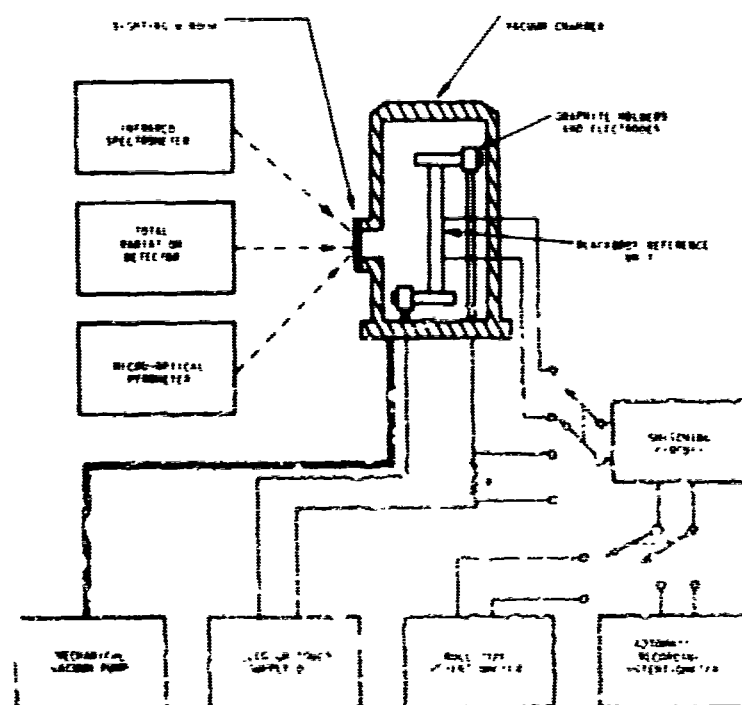


Figure 3. SCHEMATIC DIAGRAM OF BLACKBODY REFERENCE EQUIPMENT

capabilities. This instrument was able to reproduce the radiation intensity from the temperature reference unit as a function of the wavelength.

Current and voltage measurements were recorded with an automatic-recording potentiometer (and with a null-type potentiometer) using the tungsten probes for voltage measurements and current shunt resistor for current measurements at an initial temperature of about 1200 K. As this temperature was increased, current and voltage measurements were again recorded. This procedure was continued over a wide range of temperatures.

The millivolt output of the total radiation detector was determined with the aid of a null-type potentiometer while measured temperatures were made with a micro-optical pyrometer. In this manner, the response of the total radiation detector, with a fused silica sighting window was measured (although as yet uncorrected for transmittance). Similar procedures were followed after the window on the vacuum chamber was replaced with a calcium fluoride window and later with a sodium chloride window. Correction factors were then applied to this data to obtain the final results.

RESULTS AND DISCUSSION

Although the transmittance data of the selected window materials have been obtained previously by other investigators, these properties, particularly near the region of the cut-off wavelength, were again reviewed and determined. Figure 4 shows the transmittance curves of a fused silica window (SiO_2); a calcium fluoride window (CaF_2); and a sodium chloride window (NaCl). The data ranging from 1.0 micron to the cut-off wavelengths shown were obtained experimentally with an infrared spectrometer. The data in the wavelength region below 1.0 micron were calculated from known values of the refractive index⁵⁻⁸ together with Fresnel's reflection formula for normal incidence. The curves show that at a wavelength of 1.0 micron the

calculated values are in agreement with the experimental values. The data for the calcium fluoride window extending from 0.12 micron to 0.29 micron is based on experimental work performed with ultraviolet and calcium fluoride crystals.⁸

All windows were approximately 2.0 inches in diameter; the various thicknesses are noted with the

transmittance curves. These windows are representative of others made of the same material, provided that the window thickness was not differ appreciably from the value shown.

For illustrative purposes, theoretical blackbody radiation curves at different temperatures are shown in Figure 5. These curves are based on Planck's work and can be represented at different temperatures by Equation 1. Here radiation intensities are shown as a function of wavelength and temperature. The temperature range extends from 1000 K to 3000 K. It can be seen that the radiation intensities are very small near 0.2 micron even at the higher temperatures, and that the peak intensities shift toward the shorter wavelengths as the temperature is increased.

In order to determine the total transmittance of the different windows for blackbody radiation at different temperatures, the data and equations presented in previous sections were required. The data shown in Figure 4, in turn, were used with the data of Figure 5. The results were interpreted in accordance with Equations 6, 7, and 8.

As previously mentioned, $\tau_{co}(T)$ represents that fraction of the blackbody radiation allowed to pass considering only the cut-off wavelength of the fused silica window at 4.66 microns. It was determined analytically using theoretical blackbody radiation values (Figure 5) together with the known value of the cut-off point. A mathematical description can be found in Reference 5. The fraction $\tau_{RA}(T)$ represents the blackbody radiation allowed to pass considering both reflection and absorption losses of the fused silica window, up to the cut-off wavelength. It was obtained by using theoretical blackbody radiation values (Figure 5) together with the transmittance data of the window (Figure 4) and then applying the methods of numerical integration. The mathematical principles are based on the summing up of individual transmitted radiation magnitudes for selected wavelength increments. The total transmittance (expressed as percent transmittance) $\tau(T)$ for blackbody radiation is the correction factor needed.

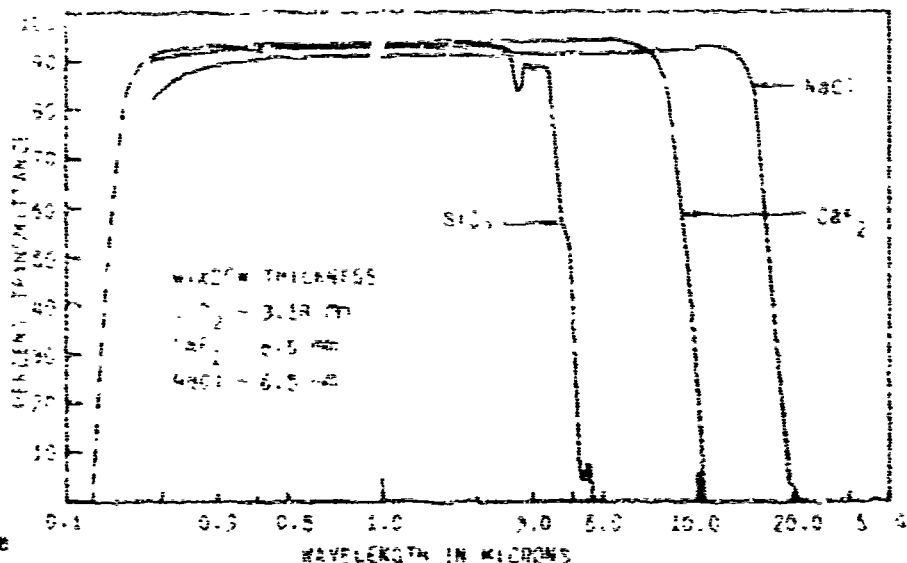


Figure 4. TRANSMITTANCE DATA OF SELECTED WINDOW MATERIALS

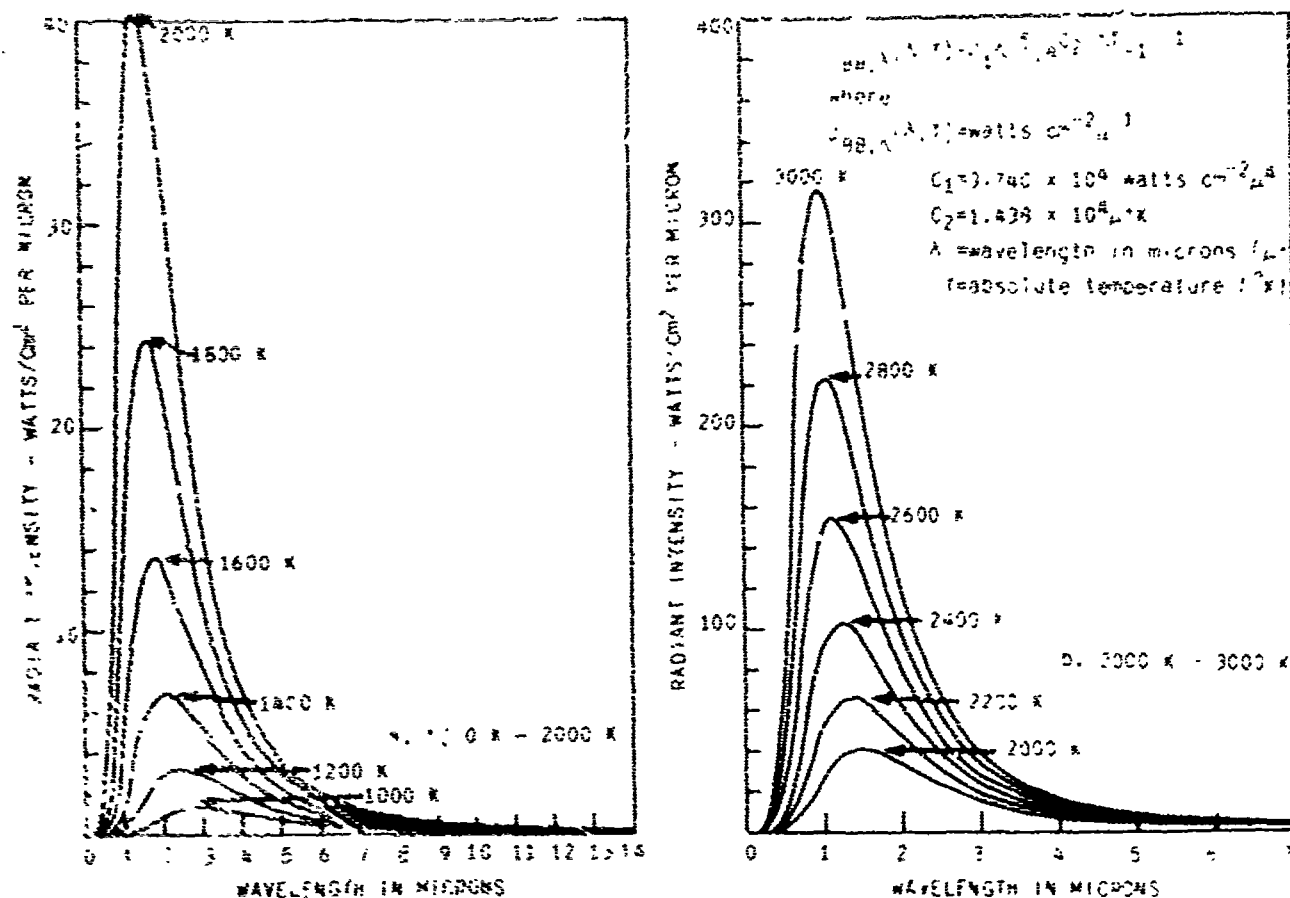


Figure 5. BLACKBODY RADIATION. THEORETICAL

The total transmittance of the calcium fluoride and sodium chloride windows for blackbody radiation was also separately determined in the same manner. Here the upper limit for the pertinent integrals had to be replaced by the cut-off wavelengths of 10.5 μ and 20.0 μ . All the required data is shown in Figure 6.

The various transmittance data indicate that the sodium chloride window would be the most desirable from the point of view of infrared transmission. However, the principal disadvantage of this window is that it fogs gradually when exposed to atmosphere in relative humidities above 40% and fogs rapidly at levels above 80%. The window then becomes limited in infrared transmission. Although the window surfaces can be repolished, this added inconvenience is present.

The infrared radiation output characteristics of the temperature reference unit were then reviewed by comparing the theoretical radiation curves with the experimental radiation curves. Figure 5 shows that the radiation amplitudes greatly increase with temperature and that definite intensity ratios exist between any two temperature curves at each wavelength. For example, at a wavelength of 2.0 microns, intensity ratios of 1.50, 1.66, 1.91 and 2.35 are obtained. These intensity ratios are associated with the temperature curves of 2000 K/1800 K, 1800 K/1600 K, 1600 K/1400 K, and 1400 K/1200 K, respectively. Similar ratios can be extended to include other

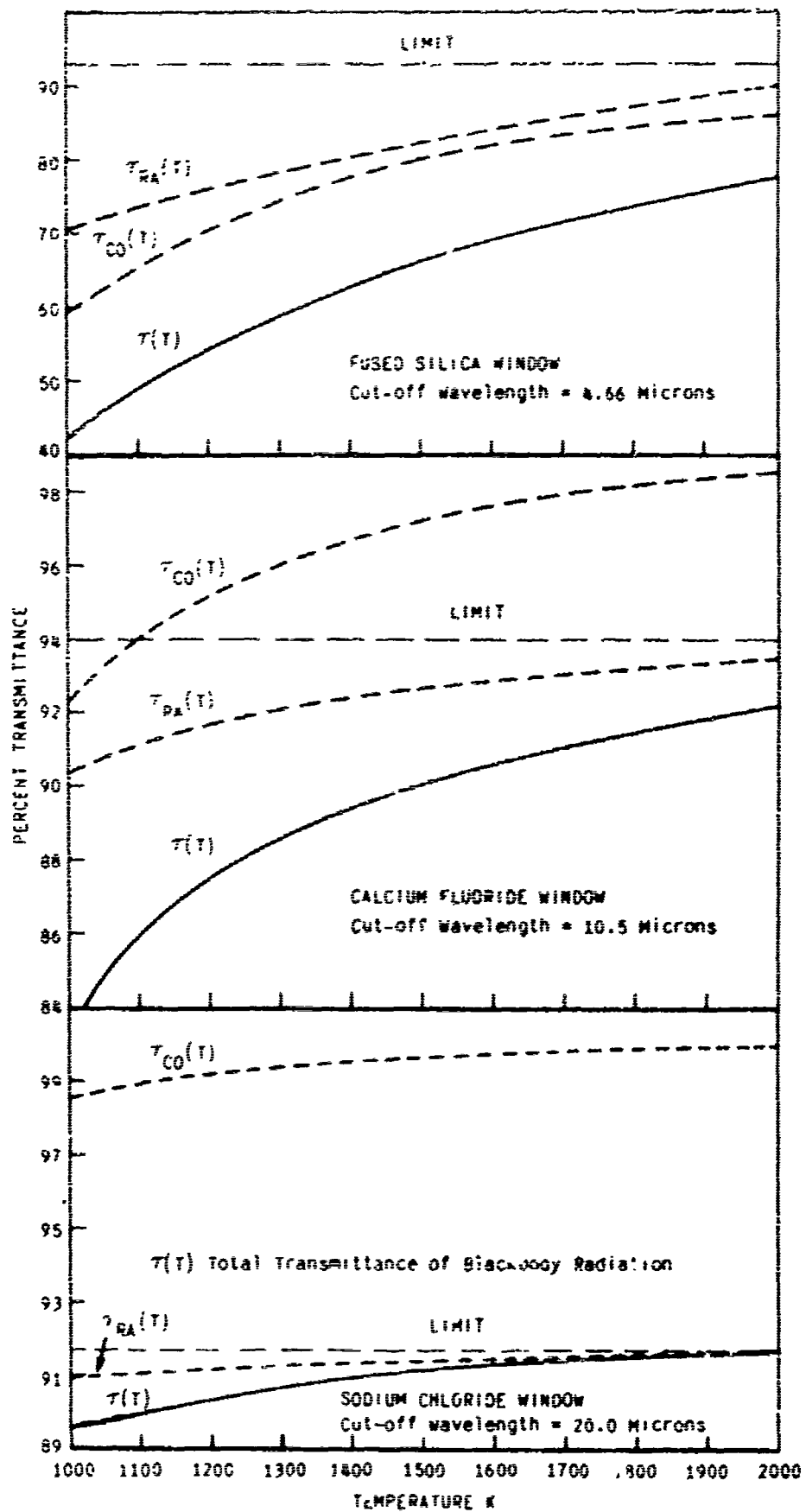


Figure 6. TRANSMITTANCE OF BLACKBODY RADIATION

wavelengths. Figure 7 shows a group of experimental curves which have been obtained with the aid of an infrared spectrometer. These curves are of blackbody radiation which has been attenuated by the calcium fluoride window and the air environment present in the room. They are similar in form to the theoretical blackbody curves and characterize the radiation reaching a temperature-sensitive detector. The wavelength, indicated on the abscissa axis, is nonlinear and is appropriately marked; the temperatures shown have been obtained with a micro-optical pyrometer. Of significance are the large H_2O and CO_2 absorption bands near 2.7μ and 4.3μ .

Now, if the experimental curves of Figure 7 are blackbody radiation curves, the same ratios should be obtained at the same wavelengths as with the theoretical curves, since that attenuation, due to all the factors mentioned above, has been held constant. Table I contains the magnitudes of the ratios of blackbody radiation, both for the theoretical and experimental curves. Some of the temperatures for the experimental curves are slightly higher than those shown for the theoretical curves, but when all the ratios are reviewed with this in mind, the data is in good agreement. One still should consider the possibility that these curves could also be representative of a graybody, since unpolished graphite does have radiation characteristics of a graybody with an emittance constant near 0.90.¹⁰

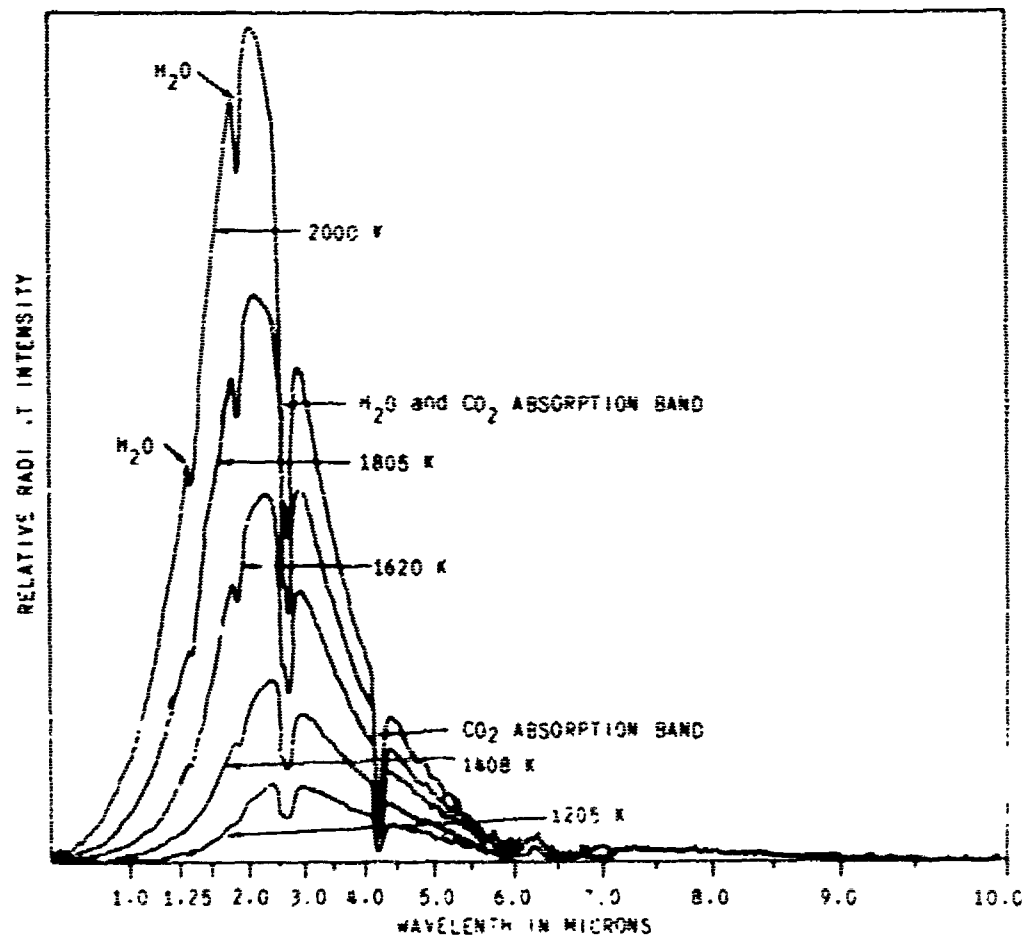


Figure 7. BLACKBODY RADIATION, EXPERIMENTAL
(CALCIUM FLUORIDE WINDOW AND AIR ENVIRONMENT)

This would undoubtedly be the case if the radiation was from a flat graphite piece alone, but the geometric configuration of this material has been chosen to approximate blackbody conditions and it is believed, therefore, that the behavior tends to be that of a blackbody.

Figure 8 shows another group of experimental curves obtained with an infrared spectrometer. These are the blackbody radiation curves which have been attenuated by the fused silica window and the air environment in the room. Of significance is the region near the cut-off wavelength of 4.66μ . The radiation intensities here have been drastically reduced in magnitude and the CO_2 absorption band near 4.3μ no longer can be recognized. Table I also shows the magnitudes of the ratios of blackbody radiation both for the theoretical and experimental curves up to a wavelength of 3.5μ . Although these curves are repetitions of the data obtained with the calcium fluoride window, they do illustrate the effects of a sharper cut-off.

The study of blackbody radiation was continued using a total radiation detector in conjunction with a micro-optical pyrometer. Figure 9 shows the total radiation detector output in millivolts (both uncorrected and corrected) for a fused silica window, a calcium fluoride window, and a

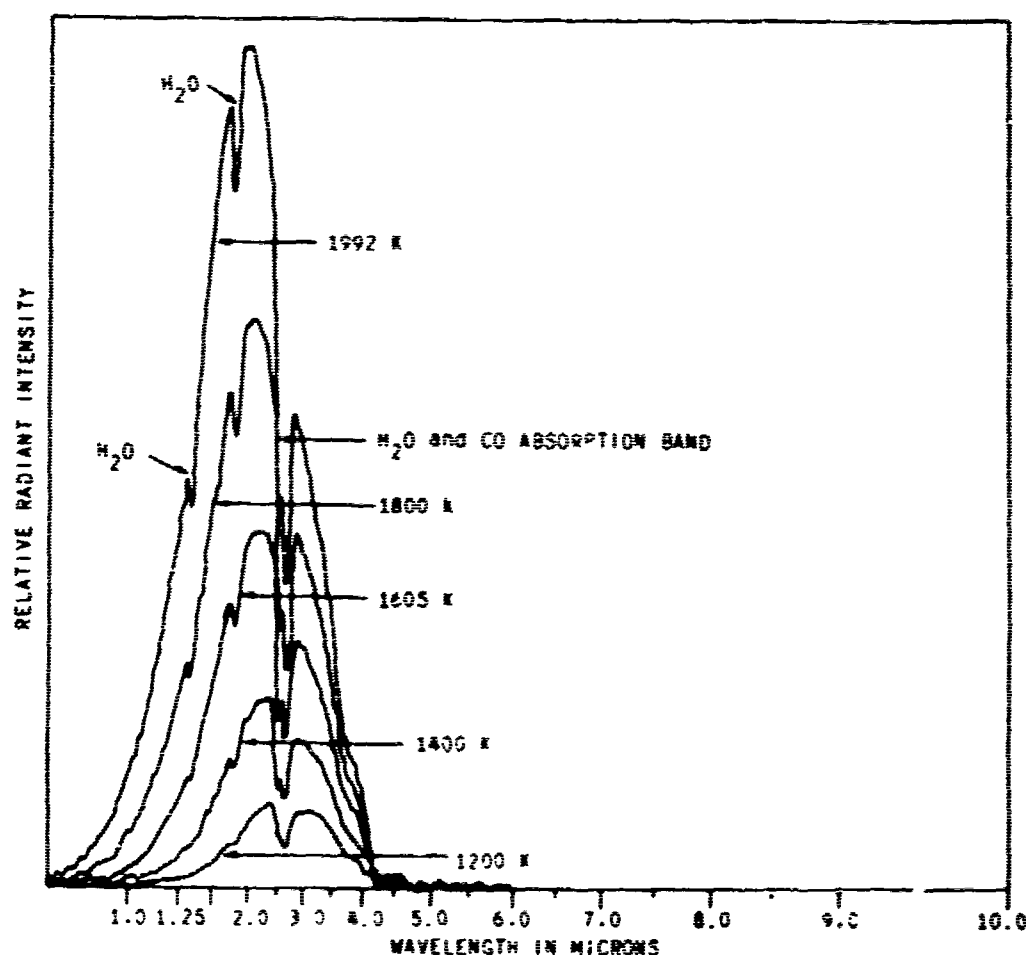


Figure 8. BLACKBODY RADIATION, EXPERIMENTAL
(FUSED SILICA WINDOW AND AIR ENVIRONMENT)

Table 1. RATIOS OF BLACKBODY RADIATION

Microns	Theoretical				Experimental (CaF ₂)				Experimental (SiO ₂)			
	Deg K				Deg K				Deg K			
	2000 1800	1800 1600	1600 1400	1400 1200	2000 1805	1805 1620	1620 1408	1408 1205	1992 1800	1800 1605	1605 1400	1400 1200
1.00	2.21	2.71	3.59		2.16	2.66	3.46		2.21	2.55		
1.25	1.89	2.22	2.78	4.14	1.82	2.19	3.07	3.50	1.92	2.17	3.00	
1.50	1.70	1.95	2.19	3.16	1.65	1.95	2.67	3.27	1.78	1.93	2.38	3.23
2.00	1.50	1.66	1.91	2.35	1.50	1.64	2.17	2.48	1.46	1.63	2.04	2.47
3.00	1.33	1.42	1.56	1.79	1.30	1.39	1.81	1.54	1.31	1.43	1.64	1.86
3.50	1.13	1.37	1.48	1.66	1.24	1.33	1.68	1.47	1.21	1.43	1.62	1.71
4.00	1.24	1.33	1.42	1.58	1.23	1.29	1.63	1.73				
4.50	1.20	1.39	1.35	1.50	1.21	1.23	1.65	1.62				
5.00	1.23	1.28	1.35	1.47	1.21	1.22	1.59	1.70				

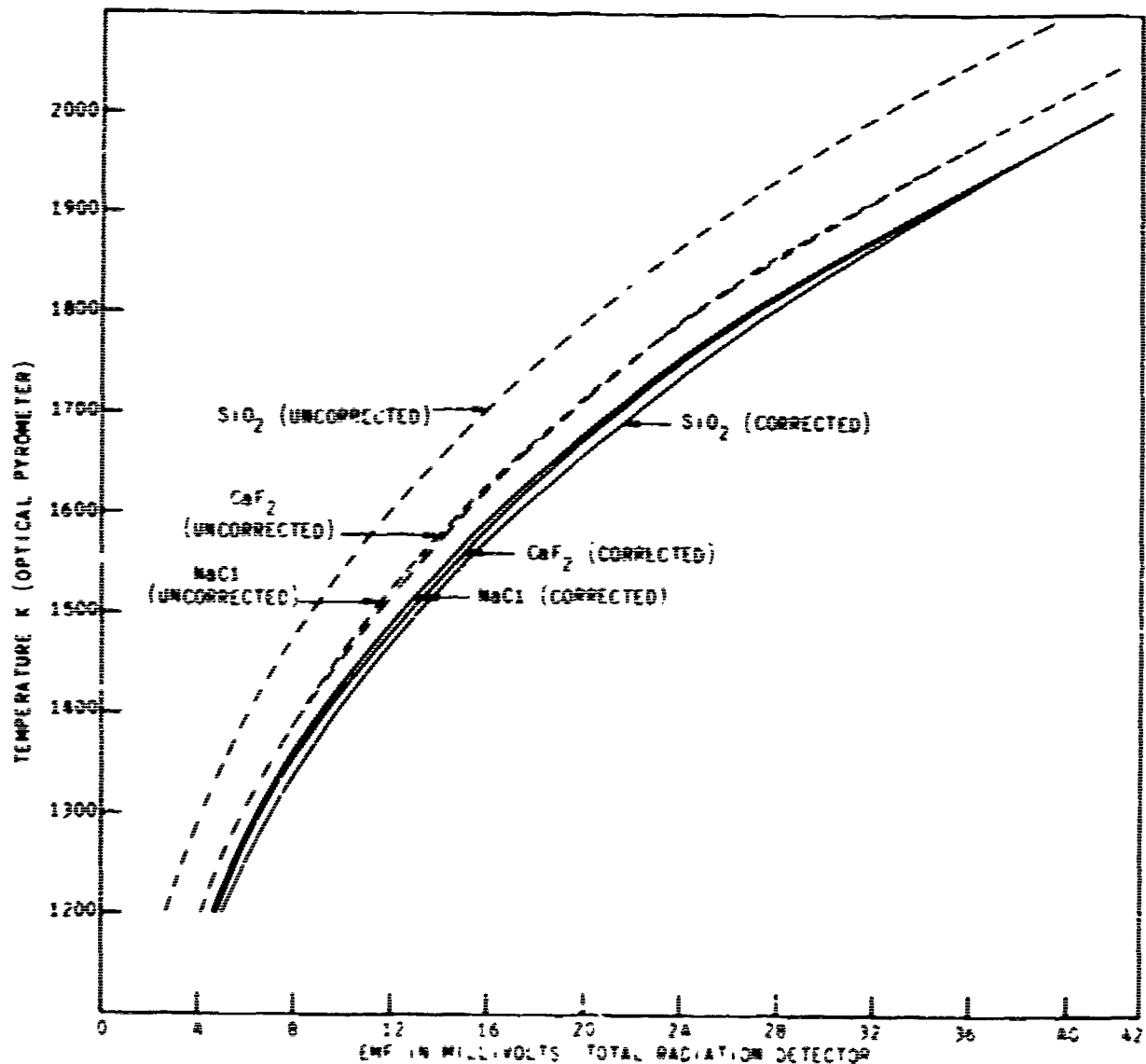


Figure 9. TOTAL RADIATION DETECTOR OUTPUT FOR ALL WINDOWS

sodium chloride window. The uncorrected data indicates that the attenuation of the fused silica window is much greater than for the other windows. This was anticipated from the known transmittances of the pertinent window materials. The corrected data was determined by applying the correction factors $\tau(T)$ found in Figure 6. At 0.10 millivolt the corrected temperature readings are 1410 K, 1423 K, and 1430 K; at 0.24 millivolt the corrected temperature readings are 1736 K, 1750 K and 1755 K; and at 0.38 millivolt all of the corrected temperature readings are 1953 K. The temperature differences range from 1.4 percent approximately to zero percent with the largest difference occurring near 1400 K. Ideally, all the resultant curves should overlap, that is, the data should be represented by one curve after the correction factors are applied.

Since temperature stability of the temperature reference unit was a function of current and voltage stability, it was important that these magnitudes did not fluctuate or change appreciably during the periods of radiation measurement. For this reason, current and voltage magnitudes were reviewed at the different temperatures. For example, at a temperature of 1188 K, the current was 105 amperes and the voltage (along a 4-inch length) was 1.08 volts; at a temperature of 2218 K, the current was 332 amperes and the voltage was 4.95 volts. It was noted that both current and voltage remained stable during all periods of radiation data acquisition.

During the various tests, there was a slow deterioration of the tantalum heat shield with corresponding changes in surface emittance; in time these changes affected the power input requirements. This deterioration was probably due to two basic causes: the oxidation of tantalum in a vacuum environment of 35 microns of pressure and the reaction of tantalum with graphite at the higher temperatures.¹¹ One solution is the use of a higher vacuum and an all-tantalum temperature reference unit. Normally, this slow deterioration is not a severe problem since simultaneous temperature measurements can be made quickly with the different instruments. This could be a problem if one wishes to calibrate the temperature reference unit (temperature versus power input) or if one is limited in the maximum current available from the power supply.

One other point which can be mentioned is that although total radiation detectors are designed in accordance with the Stefan-Boltzmann law (Equation 3), the physical situation as it exists in the atmosphere differs slightly from this law. This is due in part to the absorption bands present in the atmosphere and shown in Figures 7 and 8. Here, again, the effects of the large absorption bands occurring near 2.7μ (H_2O and CO_2) and 4.3μ (CO_2) can be seen together with the smaller absorption bands occurring near 1.3μ (H_2O) and 1.9μ (H_2O). The radiation detector then sees something less than it would in a vacuum environment alone. The response of the radiation detector does not conform to the Stefan-Boltzmann equation, which contains a parameter of absolute temperature to the fourth power but actually conforms to something less than the fourth power. Of course, most temperature measurements are performed with the respective instruments located in an air atmosphere. Temperature calibrations are also performed in an air atmosphere by comparing

one instrument against a standard instrument and the above absorption bands are not required in detail.

Although the correction factors shown in Figure 6 have been evaluated to 2000 K, these values could be extrapolated to 3000 K without substantial error. The reason for this is that all the curves representing the required correction factor are nearly linear beyond 2000 K. In addition, the characteristic slopes of the respective curves are known together with the upper limits of the percent transmittance (dotted straight lines). As the temperature increases, the percent transmittance increases together with an increase in the magnitude of the correction factor.

CONCLUSIONS

The results of this study show that a simple, economical, blackbody reference unit can be constructed for operation at temperatures ranging from 1200 K to 2100 K. At these high temperatures, a vacuum system capable of operation well below 35 microns of pressure is necessary principally to reduce the effects of oxidation. After steady-state conditions have been attained relative to oxidation, out-gassing, and reaction of the component materials, it may be possible to remove the vacuum equipment after first sealing off the evacuated vessel containing the high-temperature components and sighting window. This arrangement would not require the vacuum-pumping equipment as a permanent fixture but only during this initial phase.

A sighting window is required with the blackbody reference equipment to provide access to the radiation source as well as to exclude the external atmosphere. However, a correction factor, $\tau(T)$, dependent on the transmittance of the sighting window, needs to be known when using this equipment for the calibration of new instruments. Any of the windows previously described can be used since the correction factors are known. These remain constant at a particular temperature and for sustained periods of use.

Provisions should also be made for the continuous measurement of current and/or voltage. The initial selection of the power supply is dependent on the magnitude of the current needed and used; in addition, any current and voltage fluctuations would be an indication of temperature instability of the blackbody temperature reference unit. Depending on the power supply chosen, it may be possible to operate the unit without the need of a temperature-controlling device.

With appropriate selection of materials, a blackbody reference unit can be constructed for calibration purposes at even higher temperatures. Although graphite was used in this analysis as the principal structural material, a refractory metal^{12,13} such as tantalum or tungsten can be substituted. Tantalum is preferable because of its ductility and strength; but additional experimental tests are required to study factors such as loss of strength as a function of high temperature for the particular design configuration employed. The use of an all-tantalum blackbody reference unit

would probably necessitate the addition of a high-emittance ceramic oxide (dielectric) within its interior for favorable blackbody radiation characteristics. The basic heating element would be thin-walled and the unit could be enclosed by a multi-element tantalum heat shield. The use of tungsten sheet can also be considered as another building material although it may become limited because of brittleness associated with crystal growth at high temperatures. Such a temperature reference unit should prove to be satisfactory for operation at temperatures up to at least 2500 K.

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