NATIONAL BUREAU OF STANDARDS REPORT

9094

The New Tungsten-Filament Lamp Standards of Total Irradiance

by

Ralph Stair, William E. Schneider and William B. Fussell
Metrology Division
National Bureau of Standards
Washington, D.C.

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U. S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS

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I. Introduction

The accurate measurement of thermal radiation requires the use of either a standard source or a standard detector. Most of the early work in this area was centered around meteorological problems and was based upon two independent approaches initiated by K. Ångstrom [1] of Sweden and C. G. Abbot[2] of America. Emphasis was placed upon the development of a detector which could be calibrated in an absolute manner directly into response as a function of the radiant flux incident upon its surface. Prior to 1900 K. Ångstrom of Sweden began work on an electrical compensation instrument later known as the Angstrom Pyrheliometer. This instrument became the basis of most European work, not only in meteorology but in other fields as well. Meanwhile in the Smithsonian Institute under the direction of the pioneer astrophysicist Langley, C. G. Abbot and his co-workers developed the silver disk and the water-flow pyrheliometers. The water-flow instrument was the primary or absolute standard, but the silver-disk instrument became the working standard because of its greater simplicity in operation and use.

Most of the meteorological measurements throughout the world are still based upon either the Ångstrom type pyrheliometer or the Abbot silver-disk instrument. Since neither of these instruments can be considered truly absolute it is not surprising that through the years differences in results through the use of the two instrumentations have occurred. These differences between the two scales of about 1 to 2 percent have not been completely resolved [3], thereby emphasizing the need for a new standard in this area.

For other than meteorological measurements, a standard of total irradiance originally set up by Coblentz [4] in 1913 in the form of a 50-watt carbon filament lamp and operating at a color temperature of around 1800 to 2000°K has been employed to the present time. This standard has served well for more than 50 years in many laboratories not only in America but throughout the world.

This standard is based upon the Stefan-Boltzmann Law of Radiation which relates the flux per unit area (M) from a blackbody to its absolute temperature T:

$$M = \sigma T^4$$

In the original measurements by Coblentz the value of σ was taken as 5.7×10^{-12} watt cm^{-2} deg^{-4}. The blackbody was usually operated near 1400°K and usually set at a distance of approximately 70 cm. (Other distances and temperatures were also employed.) No correction was made for water vapor absorption for either the blackbody or the lamp. While the value of σ employed by Coblentz, namely 5.7×10^{-12} watt cm^{-2} $deg^{-4}K$, represented the best information at that time; it may be noted that later experimental values are much higher.

These data [5/], (see Table I) obtained between 1916 and 1933 scatter around a mean of 5.767. In addition to the values of Table I, a recently unpublished value of 5.77 was obtained by E. J. Gillham [6/]. On the other hand, the theoretical value of σ based upon

$$\sigma = \frac{2\pi^5 c^2 h}{15 c_2^4} \quad \text{or} \quad \frac{2\pi^5 k^4}{15 c^2 h^3}$$

results in a value of 5.669, about one-half percent below the value employed by Coblentz in 1913. Thus the proper value of σ still remains to be determined.

Nevertheless, since recent needs for higher accuracy and wider ranges of total irradiance have arisen, we have proceeded to set up lamp standards of total irradiance in the form of tungsten-filament lamps of three sizes (100-, 500-, and 1000-watt) operated at color temperatures between 2700 and 2850°K, and based upon the spectral radiance, L_λ, of a blackbody.

$$L_\lambda = c_1/\lambda^5 \,(e^{c_2/\lambda T} - 1), \text{ where}$$

$$c_1 = 1.191 \times 10^{-12} \text{ watt cm}^2/\text{ster, and}$$

$$c_2 = 1.4380 \text{ cm deg K (by definition, IPTS),}$$

$$\lambda = \text{wavelength in cm, and}$$

$$T = \text{temperature in degrees K.}$$

II. Instrumentation and Methods.

In order to eliminate problems which arise because of significant water vapor and CO_2 absorption beyond 4 microns, a quartz plate calibrated for spectral transmittance was interposed between the blackbody and the receiver. Atmospheric absorption of the energy from the lamp standard is almost insignificant, first because of the operation of the lamp at a relatively high temperature and second because the glass envelope is shielded except for a narrow area (1 inch) of the bulb in front of the filament. In figure 1 is shown the experimental set up employed in comparing the irradiance from the blackbody with that from a tungsten-filament lamp. In this case for the 100-watt lamp, the blackbody is set at a distance of about 33 cm - the lamp at about 1.3 meters. Calibrated, water-cooled apertures* determine the blackbody irradiances at the set temperatures which are controlled to ± .2 degree C over extended periods of time. The thermopile (or thermocouple) is rotated to alternately face the blackbody and the lamp under study. The thermoelectric

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* See footnote on page 3.

outputs are evaluated through the use of a nanovoltmeter and strip chart recorder. To keep the two thermoelectric voltages comparable when calibrating the 100-, 500-, and 1000-watt lamps, the blackbody temperature is altered, the distance of the lamp is varied, or an attenuating chopper is set up between the lamp and detector as required. Extensive shielding is incorporated into the setup to eliminate any effects from extraneous irradiation reaching the thermoelectric detector. The blackbody furnace (and blackbody) is shielded by a double water-cooled shield. The detector is covered by a shield limiting its view to a small angle. A triple (aluminum) metal shield (also triple shutter) each piece blackened on the side facing the detector, and placed about 25 cm from the standard lamp, insures a near-room temperature condition on all surfaces visible to the detector. A supplementary shield placed midway between the multiple shields and the detector further reduces stray irradiances and air currents in the vicinity of the detector.

Although several thermoelectric detectors were set up and employed in the early measurements in this investigation the final results are based primarily upon the use of two conical cavity detectors of the type previously described [7] and illustrated in figure 2. This detector is constructed in the form of a cone of small angle and coated with carbon or other black on the inside surface. To reduce heat capacity and thereby increase response rate, the cone is made of the thinnest gold foil having sufficient strength to insure adequate support under laboratory conditions. It is the nearest approach to a blackbody detector of any studied in this laboratory. Certainly over the narrow spectral range of about 0.3 to about 5.0 microns, which includes above 99 percent of the irradiance from both the blackbody and the standard tungsten-filament lamps, the spectral response of this detector may be considered to be neutral.

The blackbody, which was operated up to 1400°K, is constructed of a casting of an alloy of 80 percent nickel and 20 percent chromium and has a 3-inch outside diameter, 6-inch length and a wall thickness of 1/2 inch. The low reflectivity of this oxidized metal coupled with the small aperture (3/8" diam.) as compared with the internal surface area results in a blackbody effective emissivity (when applying the DeVos method of determining cavity emissivity) of 0.999. The high heat capacity of the associated furnace gives the blackbody a very high thermal stability. The temperature of the blackbody was both measured and controlled by the voltage generated by a platinum-platinum (10% rhodium) thermocouple previously calibrated by the NBS Temperature Physics Section of this Bureau to an accuracy of 0.5 degree C. To correct for thermocouple depreciation at the temperatures of operation (1300 to 1400°K) replacement or recalibration of this element was required from time to time. The thermocouple ice point was maintained at 0.0 ± 0.05 degree C by means of a commercial thermoelectric ice point. Lead wires without soldered connections carried the thermocouple voltage to copper knife

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*(See fourth to last line page 2) Three apertures having diameters of approximately 2, 3, and 4 mm were carefully calibrated by David Spangenberg of the Engineering Metrology Section of this Bureau. Most of our measurements were made with the 4 mm aperture.

switches by which it could be directed, alternately or simultaneously, to the temperature measuring or temperature controlling equipment.

The measuring equipment consisted of a Leeds & Northrup K-3 potentiometer with accessory equipment. The standard cell had previously been calibrated by the NBS Electrochemistry Section of this Bureau.

The temperature controlling equipment consisted of a Leeds & Northrup 10877 control system, plus an FAG3 magnetic amplifier. The 10877 control system consists of a No. 10810 set point unit, a No. 9834-2 null detector, and a No. 10877 C.A.T. (current adjusting type) control unit.

The mode of operation was as follows:

A. The desired blackbody temperature was selected, and the corresponding thermocouple voltage was set into the set point unit by means of a 0 to 50 millivolt coarse adjustment with 5 millivolt steps, and a ten-turn "helipot" fine adjustment which divided each 5 millivolt interval into one thousand 5 microvolt divisions. The output of the set point unit was the difference: thermocouple voltage minus set point voltage. This output formed the input for the null detector, which amplified it; the output of the null detector was the input for the C.A.T. unit, which transformed it to a current source; finally, the output of the C.A.T. unit was the input for the FAG3 magnetic amplifier. The magnetic amplifier provided up to 20 amperes current, at up to 90 volts, to heat the blackbody oven.

B. To operate the blackbody at, say 1400°K, the oven current was set manually at about 15 amperes when the oven was started from room temperature. When the null detector indicated the blackbody temperature was roughly 50 deg. C. below the desired temperature, the C.A.T. unit was switched from manual to automatic control. As the blackbody temperature approached nearer to the desired value, the sensitivity of the null detector was slowly increased to a level sufficient to maintain the equilibrium temperature.

C. If the equilibrium temperature differed from the set point, it could be corrected by a minor adjustment of the set point.

Figure 3 illustrates the spectral irradiance of a blackbody operated at 1300°K, the temperature employed in some of the work. Also there is indicated on the same scale the spectral irradiance from a 300°K blackbody - the temperature of the water-cooled shutter - which may be considered zero on this scale. The spectral transmittance of the quartz plate determines the long-wave cutoff of the blackbody irradiance. Hence, the effects of the water vapor absorption at 6 microns and longer wavelengths are eliminated as is the case with much of the CO_2 absorption at 4.2 microns. Only the H_2O bands at shorter wavelengths need be considered. On this chart the water vapor absorption for the 33-cm path length between the blackbody aperture and thermopile is indicated on the basis of an amount equivalent to 0.0001 precipitable cm ntp. This amount of absorption by water vapor is based upon data recently published by Wyatt and associates [8], while the CO_2 values are based upon the data by Stull and co-workers [9]. The combined absorptions amount to approximately 0.5 percent.

The water vapor content of the atmosphere was determined from measurements of the temperature and relative humidity of the laboratory during the course of the measurements which ranged (a few degrees, or percent) around 75°F and 70%. And from the curves of Figure 4, which were prepared from the Smithsonian meteorological tables [10] giving the density of water vapor at saturation as a function of temperature, the moisture content (the absolute humidity of the atmosphere) was determined in grams per cubic meter.

III. Results.

In Table II are shown data obtained on the three original carbon filament lamp standards set up by Coblentz in 1913. As noted earlier his data, shown in column 5, were obtained by using the Stefan-Boltzmann Law and making no corrections for water vapor absorption. Our data were based upon the Planck Law of Radiation with a correction of +0.5% being made for water vapor absorption. His data incorporated a value for σ of 5.7 while a value of about 5.67 as pointed our above, is consistent with the constants which we used in Planck's equation.

In Table III data on total irradiance are given for three groups of tungsten filament lamps (100-watt, 500-watt, and 1000-watt) when operated at 0.75, 3.60, and 7.70 amperes, respectively. These data were not corrected for any absorption of radiant flux by water vapor between the lamp and radiometer. Any correction in the original data is small. However, it is possible that some correction should be made if the lamps are used in a very humid atmosphere [13] (e.g. at relative humidities above 75 percent).

Since the new standards operate at much higher temperatures than the carbon filament lamps, the peak of the spectral energy curve is shifted toward the shorter wavelengths and consequently conforms more closely with the spectral curves of the NBS standards of luminous intensity, spectral radiance, and spectral irradiance. The lamps employed are commercial projection-type tubular-bulb lamps having C-13 type coiled filaments and may be operated on either ac or dc. The useful calibration life for the 100-watt lamps (at least 50 hours for 1% change) falls somewhat short of that previously available through the use of the carbon filament lamps. A similar lamp life may be expected in the case of the 500-watt and 1000-watt lamp standards since their operating color temperature (when operated at 3.60 and 7.70 amperes respectively) lies between 2800 and 2850°K. Otherwise, their characteristics are similar, with outputs being about 5.5 and 13 times that for the 100-watt lamp standards.

An estimate of the accuracy of the values assigned to the lamps is based on the following factors:

1. The temperature of the blackbody is known to within 1/2° at 1300°K thereby producing an uncertainty of ±0.2%.

2. The distance measurement is known to within 0.5 mm thereby producing an uncertainty of ±0.2%.

3. The transmittance of the quartz plate is known with an uncertainty of ±0.4%.

4. The area of the blackbody aperture produces an uncertainty of ±0.1%.

5. The precision of measurement contributes ±0.3% to the uncertainty.

6. The uncertainty of the blackbody emissivity is 0.1%.

When these factors are taken into consideration along with the uncertainty for the values of c_1 and c_2, an overall certainty of the order of ±1.0% should be attained, based upon a value of 1.4380 cm deg K for c_2.

IV. Operation of the Standards

The carbon-filament lamp was employed as a standard of total irradiance for half a century largely because of its proved stability [11/]. The requirements for higher irradiances at higher temperatures has necessitated the switch to the tungsten-filament type lamps. Considerable experience at this Bureau over many years with commercial projection lamps as standards of luminous intensity and color temperature has proved their adaptability for use as standards of total irradiance. Although their useful life may not equal that of the early carbon-filament lamps, proper care and handling should insure a life approximating at least 50 hours with change in total irradiance not exceeding about 1 percent.

These standards have been set up with operation on dc and with all current and voltage measurements made with potentiometric equipment. It is recommended that they be operated at the fixed current values listed with voltage measurements made as power input checks from time to time. They may be operated on ac or dc as desired. A change in the current-voltage relationship is a definite signal that the lamp standard requires recalibration or replacement but if it is necessary to use the standard in further measurements, operation at calibrated wattage would be preferable.

The lamps employed for use as standards are selected for absence of significant optical or mechanical defects, seasoned, marked for orientation and then calibrated for the density of radiant flux at 1 and 2 meters in the specified direction - indicated by a vertical line on the side of bulb toward radiometer and a vertical line through a circle on the opposite side.

In operation the lamp is screwed into any suitable socket which is held upright by some convenient support. The lamp bulb is plumbed in a vertical position with the center of the filament level with the radiometer and set directly back of a 1-inch high by 3-inch wide opening in a triple-plate metal shield blackened on the surface toward detector at a distance of 25 cm from the shield. A similar triple-plate blackened metal shutter is mounted near the 1-inch by 3-inch opening in the shield in such a manner that it can be easily moved by remote control a sufficient amount to clear the opening in the shield. The recommended setup is thus similar to that shown in figure 1 and employed in the original calibrations. Additional blackened shields should be placed at 1 meter back of the lamp, over the thermopile, and between the thermopile and principal shield as required. For best operation the entire setup may be placed in a large blackened chamber or small unlighted room.

To conserve the calibration, which always gradually changes with use, these lamps must be kept as reference standards only, and other lamps used as working standards in all cases where extensive radiometric comparisons are made.

These instructions and the use of these standards of total irradiance apply to radiometers having neutral responses with wavelength and used in air. Most thermal detectors are not neutral in response over wide spectral ranges [12/] and if a window is used on the radiometer, it's transmittance may not be uniform through the entire spectral range of wavelengths emitted by the standard lamp or the source under study, in which case correction will be required for the window absorption [13/] and the selective response of the detector. For example, a quartz window (or quartz glass) may be found to have a transmittance for the total standard lamp irradiance of about 90 percent while its spectral transmittance is near 92 percent through much of the ultraviolet, visible and infrared to near 3 microns. For another source, for example a low temperature heater or blackbody, the total transmittance of the quartz may be as low as 10 to 50 percent. Similar data on a CaF_2 or LiF_2 window having a spectral transmittance from the ultraviolet to near 7 microns (and for the standard lamp) of around 92 percent may be found to have a 50 to 80 percent transmittance for the irradiance of a very low temperature source. Or a KBr window having a high spectral transmittance from the ultraviolet to near 20 microns (total transmittance for the standard lamp of about 89 percent) may be found to have a 60 to 80 percent transmittance for the total irradiance from a low temperature source.

The thermal-radiation sensitivity of a thermopile varies with the degree of evacuation; when highly evacuated this sensitivity may be several times as great as in air. Because at low air pressures the sensitivity is variable with the pressure, great care must be taken to test the sensitivity of the thermopile under the exact conditions existing during its use. Generally, there is no further change in the sensitivity of the thermoelectric detector at pressures below 10^{-5} torr.

The identical area of the radiometer receiver should be exposed to the standard of radiation as is used in the measurements of the unknown source [14/] Likewise it is important that the irradiances from the two sources be of uniform intensity since all thermal detectors may vary significantly over their surfaces [12/].

The thermal-radiation sensitivity of a thermopile may vary with the temperature. Or in the case of a thermopile-galvanometer system wherein current measurements are made, the circuit resistance may vary appreciably with temperature. In any case temperature corrections should be made when and where required.

Calibration data are given at two distances, namely at 1 and at 2 meters. In general, the value at 1 meter is exactly 4 times that at 2 meters. In most work the inverse square law may be applied in the use of these lamps for all distances greater than about 25 to 50 cm. with a resultant precision of about 1 percent. Measurements with the lamps at two distances, for example at 1 and at 2 meters, will furnish a check on errors which may result because of scattered background irradiance or from non-linearity in electronic or other equipment which may be employed in the measurements.

Table I.

Experimental Values of the Stefan - Boltzmann Constant, 1916-1933

W. Gerlach	1916	$5.80 \times 10^{-12} Wcm^{-2} deg^{-4}$
W. W. Coblentz	1917	5.72
K. Hoffman	1923	5.76
A. Kussmann	1924	5.74
F. Hoare	1928, 1932	5.74
C. F. Mendenhall	1929	5.79
C. Müller	1929, 1933	5.77

Table II.

New and Original Calibrations on Three Primary Carbon-Filament Lamps, in $\mu W/cm^2$ at 1.00 meter

Lamp No.	1965 Values Trial 1	1965 Values Trial 2	1965 Values Mean	1913 Values	Difference %
C-1	358.0	360.5	359.25	359.6	-0.1
C-2	330.1	329.2	329.65	333.2	-0.99
C-3	367.0	366.6	366.8	368.0	-0.3
				Average	-0.46%

Table III

Total irradiances from three groups of tungsten-filament lamp reference standards.

100-watt lamp standards operated at 0.75 ampere

Lamp #	Volts	Irradiance at 1 meter, $\mu W/cm^2$
7741	97.57	568.8
7745	96.56	582.4
7746	94.94	548.1
7749	94.04	541.4

500-watt lamp standards operated at 3.60 amperes

Lamp #	Volts	Irradiance at 1 meter, $\mu W/cm^2$
1	90.18	2956
3	90.00	3000
4	89.51	3064
5	89.24	2960

1000-watt lamp standards operated at 7.70 amperes

Lamp #	Volts	Irradiance at 1 meter, $\mu W/cm^2$
1	100.94	7216
2	101.04	7380
3	101.16	7332
4	101.03	7220

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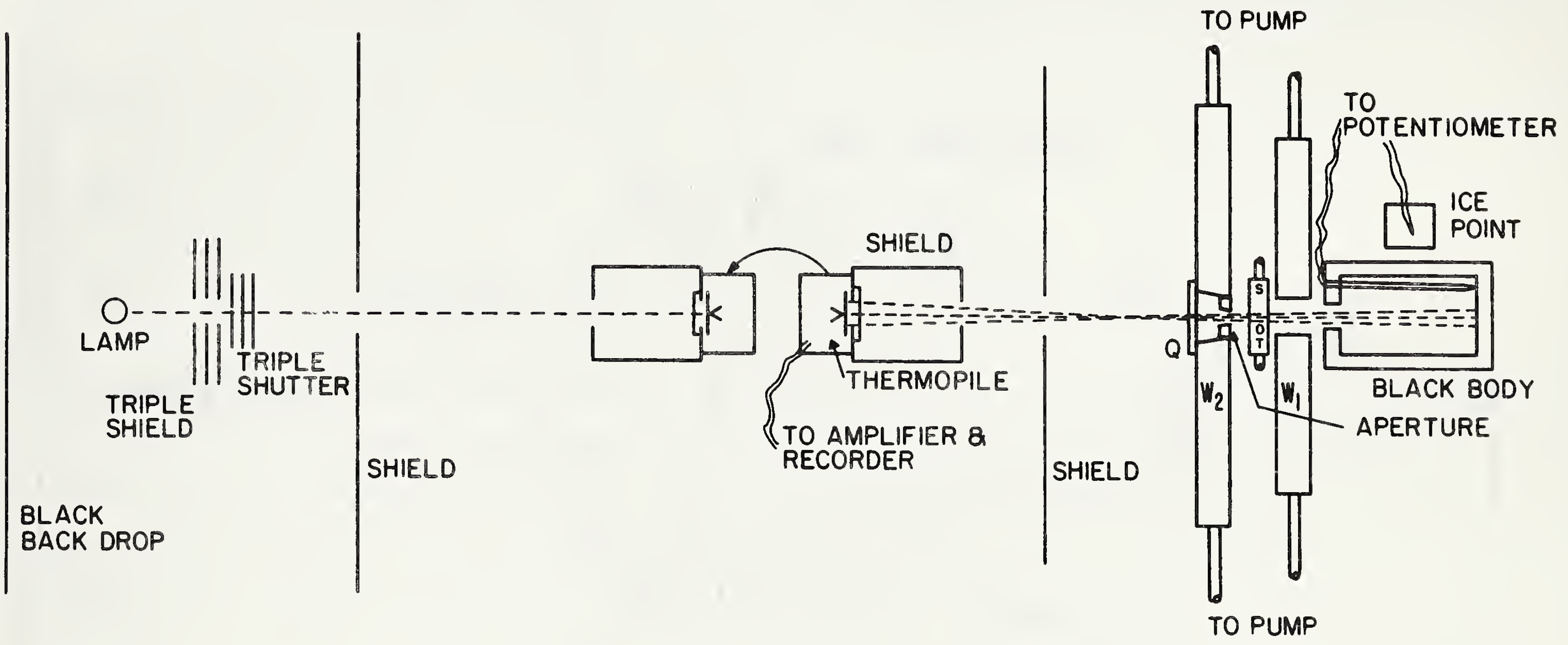

Figure 1. Layout of blackbody; water-cooled shields, shutter, and aperture; thermopile; lamp, and lamp shutter and shields; and auxiliary equipment employed in the comparison of lamps with blackbody.

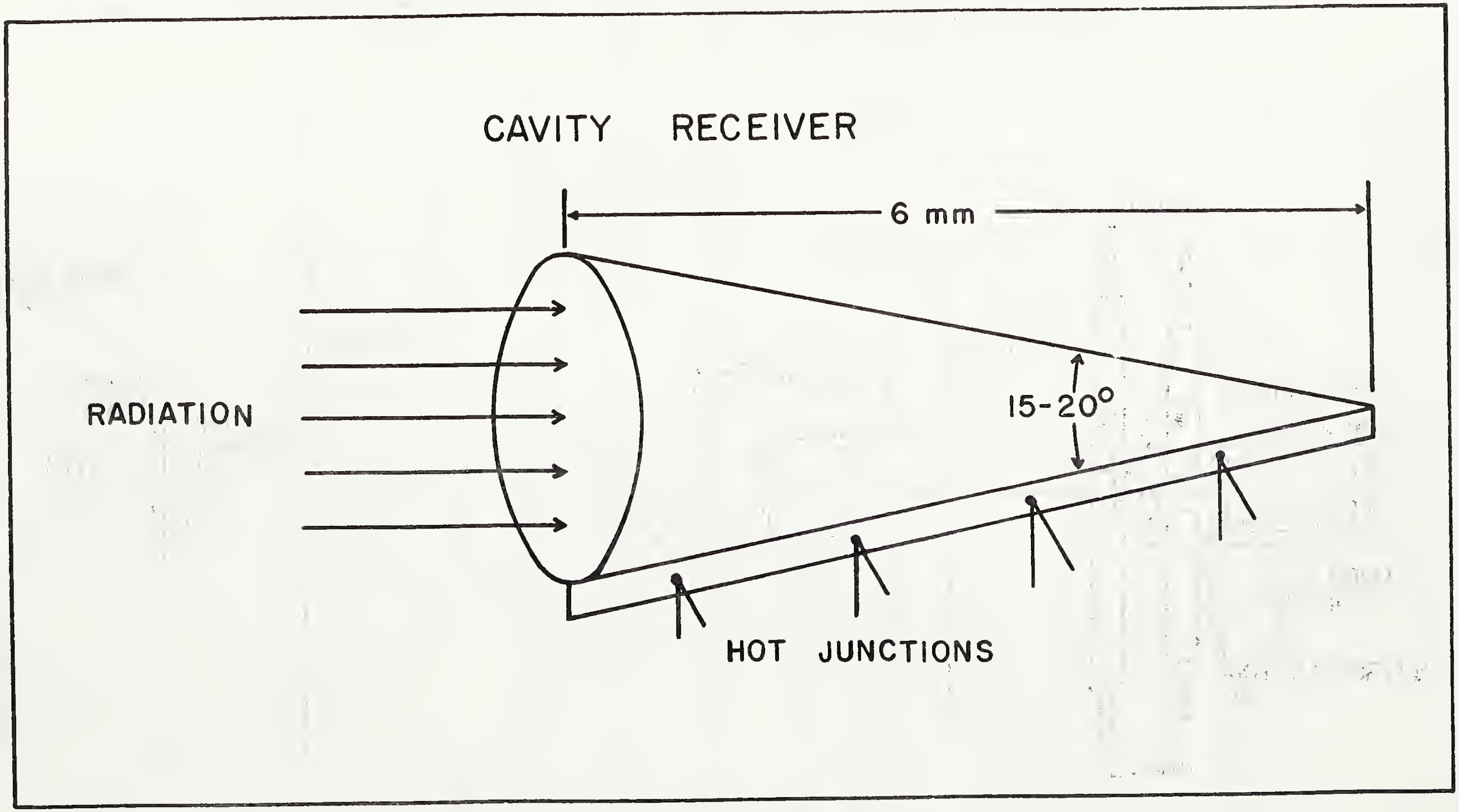

Figure 2. Conical blackbody detector consisting of a formed gold foil cone blackened inside and having several thermojunctions attached along a single fold.

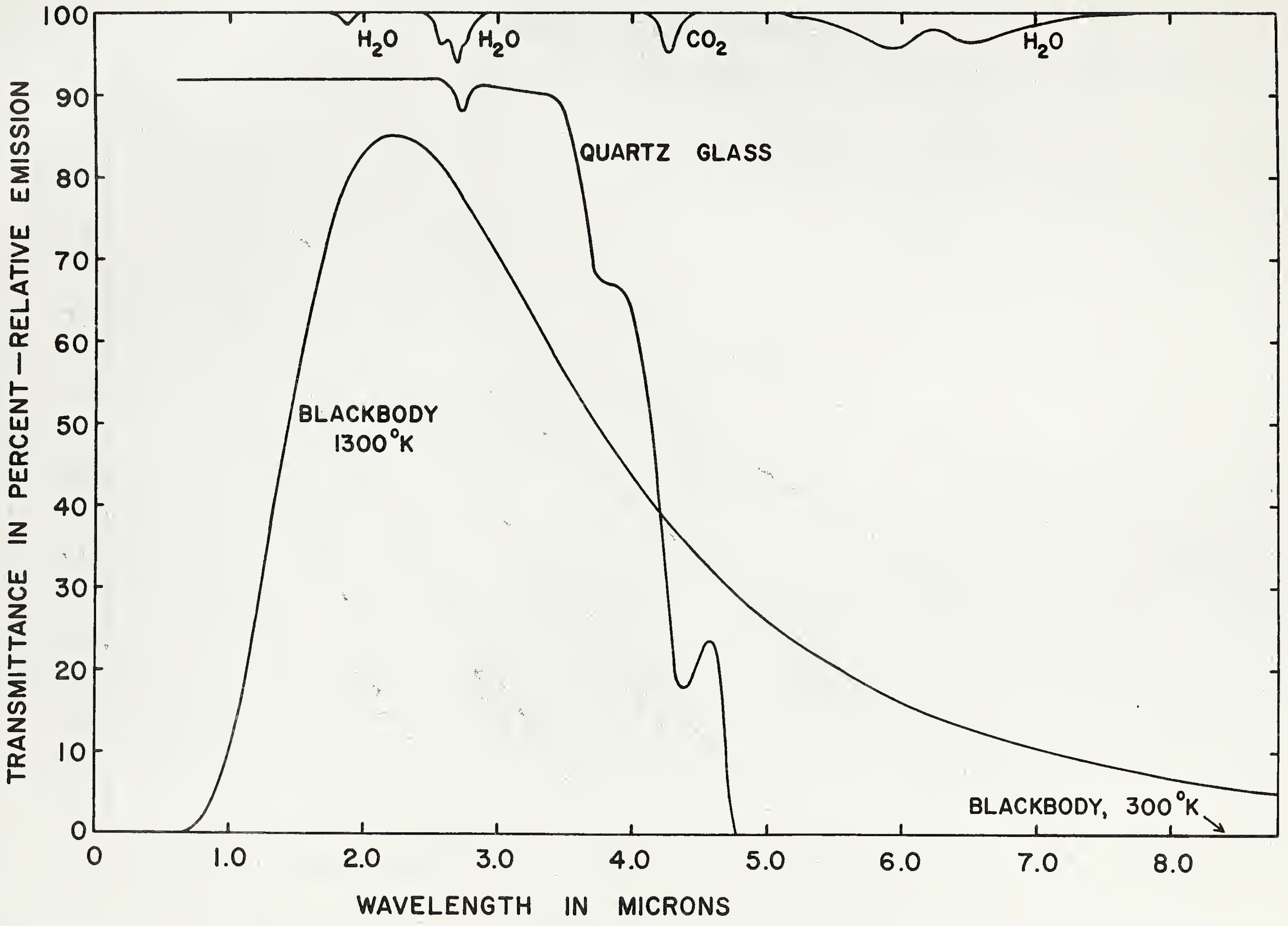

Figure 3. Spectral emission of a 1300°K blackbody, and a 300°K blackbody (negligible); transmittance of a quartz plate; and transmittance of a 33 cm path for water vapor and carbon-dioxide.

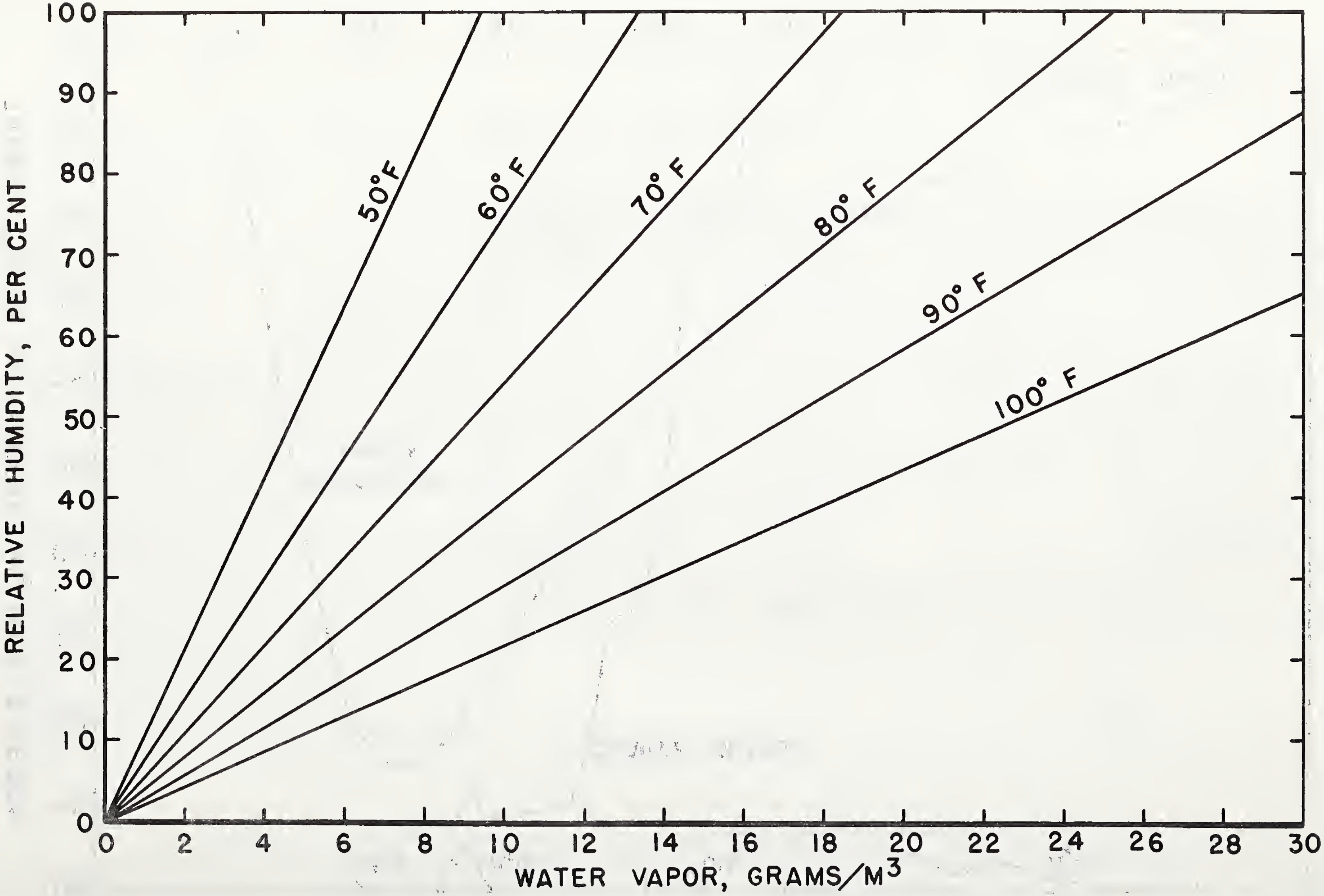

Figure 4. Total atmospheric humidity as a function of relative humidity and temperature. (From Smithsonian Meterological Tables.)

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