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Absolute Spectroradiometric Measurements

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There are two general methods for measuring a quantity of radiation emitted by a source. One can compare it with the radiation emitted by a standard source or one can measure the radiation with a detector calibrated in absolute units. When using the latter method, one must know the spectral transmittance factor of the optical components between source and detector.

In the present paper, a survey will be given of the standard sources available for spectroradiometry: cavity radiator, tungsten strip lamp, anode of the carbon arc, xenon arc and cascade arc. Several types of detectors such as the absolute bolometer and thermopile, with their properties, will be discussed.

Key words: Absolute spectroradiometry; absolute standard source of radiation; calibrated photodetector.

I. Introduction

If a physicist delivers a lecture for analytical chemists, he should take care that his language cannot lead to misunderstandings. From the Summary of Activities 1970/71 of the Analytical Coordination Chemistry Section (NBS Technical Note 584) it appears that the vocabulary used by physicists and chemists is not always the same. The main difference is in the use of the term *photometry*. For a physicist, particularly if he is engaged in the activities of the Commission Internationale de l'Eclairage (C.I.E.), photometry is the measurement of quantities referring to radiation evaluated according to the visual effect which it produces, as based on certain conventions [1].[1] These conventions require the evaluation to be done according to the international spectral luminous efficiency curve $V(\lambda)$, defined by C.I.E. in 1923. In *spectral* measurements of radiation, the $V(\lambda)$-curve does not play a part. Therefore, in my opinion, it is better to speak of *spectroradiometry* instead of photometry. In this terminology the main apparatus is a *spectroradiometer* instead of a photometer. Then the term *photometer* can be reserved for an apparatus, used to measure light (= visible radiation evaluated according to the $V(\lambda)$-curve) and the pleonasm in the expression "photometric scale in the visible region" can be avoided.

The following quantities will be used:

Spectral radiant intensity I_λ (in a given direction): Power emitted in that direction per unit of solid angle per unit of wavelength. Unit: W/m·sr,

Spectral radiance L_λ (of a source in a given direction): Power emitted in that direction per unit of projected area per unit of wavelength. Unit: $W/m^3 \cdot sr$,

Spectral irradiance E_λ: Radiant power received by a surface per unit area per unit of wavelength. Unit: W/m^3,

Spectral exitance M_λ: Quotient of the spectral radiant flux leaving an element of a surface by the area of that element. Unit: W/m^3.

It should be noted that the same definitions, without the adjective "spectral," can be used; then the units should be multiplied by m. Another point to be mentioned in the introduction is the usefulness of absolute measurements. Again referring to NBS Technical Note 584, the whole chapter on spectroradiometry is devoted to relative measurements, viz., the study of different color filters on behalf of radiometry. In these measurements, a constant radiation source and detector, reproducable samples and standard filters, and linearity of the detector in a wide range, are the most important requirements for the apparatus. However, there are other fields in which absolute measurements can give more information. For example, in line-reversal experiments, knowledge of the radiance of the background can give information on the radiance of a spectral line and therefore the number of transitions belonging to the line. Another example is the measurement of the spectral distribution of a radiation, emitted by an arbitrary source with either a continuous or a discontinuous spectrum. An example is the measurement of the radiance of a fluorescent surface.

By comparing the spectral distribution of the radiation with that of a standard source, an absolute measurement can be obtained if the geometry of the

*We have learned with sorrow during the publication of this paper of the death of Professor Rutgers on October 4, 1972.

[1] Figures in brackets indicate the literature references at the end of this paper.

measuring equipment is known.

From these examples, it will be clear that for absolute measurements sometimes a comparison is made with an absolutely calibrated source; in other cases, an absolute receiver will be used. In the latter case, the influence of the optical components between source and detector upon the measured quantities are often required.

In the following sections a survey will be given of:

(1) the standard sources available for spectroradiometry and their properties with respect to spectral radiance, accuracy and reproducibility,

(2) some detectors, used for absolute measurements, their calibration, reproducibility, accuracy and other properties, and

(3) some additional procedures used in absolute measurements.

Literature references will be far from complete; usually, references are given only to review articles and to special devices.

II. Spectroradiometric Standards

A. Black-Body Radiator

A radiator of which the spectral properties can be derived completely from theory is the *full radiator*, also called the *black-body radiator*. At a given temperature, T, the spectral distribution of the radiation emitted is only a function of the wavelength λ and is described by *Planck's law*. According to this law, the spectral *radiance*, L_λ, of a black-body as a function of λ is given by the relation:

$$L_\lambda = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda kT}} - 1} \qquad (1)$$

where h is the Planck's constant, c the velocity of light and k Boltzmann's constant. With $c_1 = 2\pi hc^2$ and $c_2 = hc/k$ (first and second radiation constant) eq (1) can be written[2]

$$L_\lambda = \frac{c_1}{\pi\lambda^5} \frac{1}{e^{hc/\lambda kT} - 1} \qquad (1a)$$

$c_1 = 3.7415 \times 10^{-16}$ W $\cdot$ m^2; $c_2 = 1.4388 \times 10^{-2}\ m \cdot K$.

The spectral distribution (on the λ-scale) has a maximum at λ_m, given by the equation

$$\lambda_m \cdot T = 2.8978 \times 10^{-3}\ m \cdot K. \qquad (2)$$

For temperatures between 1200 and 3000 K, λ_m is situated between 2.4 and 1 μm, respectively (infrared region). The ratio of the radiances at e.g., 300 nm to those in the top increases from 2.4×10^{-5} at 1000 K to 0.0055 at 3000 K. Generally, the black-body radiator is more practicable for use in the infrared region than in the ultraviolet.

[2] The same expression without π in the denominator holds for the exitance M_λ.

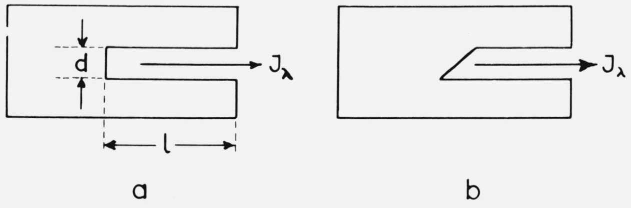

FIGURE 1. Simplified black-body radiators.

The most simple device is a hollow tube with a small hole in its (thin) wall, through which the radiation emerges. Another type is a rod with a hole drilled in its axis or a cavity of arbitrary shape (Hohlraumstrahler).

Deviations from ideal black-body conditions have been calculated, by Gouffé [2], De Vos [3] and recently by C. L. Sanders [4]. De Vos has shown that for a hole in a cylindrical rod (fig. 1a), the emissivity ϵ is between 0.978 and 0.997 if $l/d \sim 10$ and the inner wall has a reflection factor of 0.60. The lowest value of ϵ was found for a material with a specular reflection characteristic, the highest value for a material with perfectly diffuse reflection. For a cone-shape radiator, we measured a somewhat higher ϵ for a specularly reflecting wall. The first order approximation of ϵ in the general case (fig. 2) is, according to calculations by De Vos [3]:

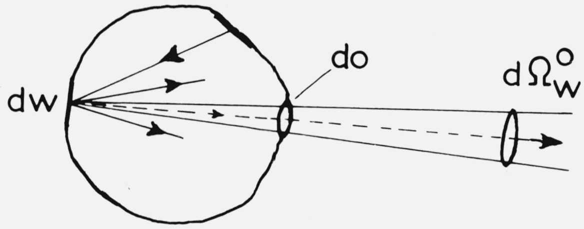

FIGURE 2. Cavity radiator to calculate the radiation loss through the hole $d0$.

$$\epsilon = 1 - r_w^{00} d\Omega_w^0$$

where r_w^{00} is the reflection factor of the element, dw, in the direction $d0 \leftrightarrow d0$ and $d\Omega_w^0$ the "loss" cone. In order to avoid specular reflection (large r_w^{00}), the element observed should not be perpendicular to the direction of observation (fig. 1b).

The temperature of the radiator must be measured according to the procedures described in the text of the International Practical Temperature Scale (IPTS 1968). For temperatures below the melting point of gold (1337.58 K = 1064.43 °C) down to 630.74 °C a thermocouple calibrated on three fixed points is used. Above the gold point, the temperature measurement is based on Planck's law. Here, the optical pyrometer can be used as a measuring instrument. Then, the radiation should be measured in a small wavelength region, usually at 650 nm, and the temperature is calculated from the ratio of the radiant intensities at the unknown temperature and at the gold point. The accuracy of radiation measurements with a black-body standard is related to the accuracy with which the temperature of the radiator can be measured. In order to obtain an accuracy of 1 percent in L_λ, the accuracy in the temperature required at some wavelengths and temperatures is mentioned in table 1.

TABLE 1

Accuracy needed in K for an error of 1 percent in L_λ

λ/T	1337	2000	2500	3800 K
300 nm	0.4	0.8	1.3	3.0
650 nm	0.8	1.8	2.8	6.5
2000 nm	2.5	5.4	8.2	17

The accuracy with which the gold point can be transferred to a visual pyrometer (650 nm) can be estimated to be 0.5 K and with a photoelectric pyrometer to 0.05 to 0.1 K (apart from inaccuracies in the gold point itself). A visual pyrometer calibrated at 650 nm with an accuracy of 0.5 K, has an inaccuracy of at least 3 K at 2500 K (ratio of radiances to be bridged about 2500). An accuracy of 1 percent in the visible region does not seem an excessive requirement for radiation measurements, but the figures in table 1 show that it is difficult to obtain this accuracy with a black-body radiator calibrated with a visual pyrometer. According to Gray and Finch [5], the accuracy of calibration of a visual optical pyrometer at 2500 K is about 7 K; for an automatic photoelectric pyrometer the accuracy is 0.6 K at 1337 K and 3 K at 2500 K. These authors conclude that "the accuracy attainable outside the standards lab is, at best, only moderate, even with the most careful work and frequent recalibration."

In conclusion, it can be stated that (1) the black-body radiator is, from a physical point of view, the best defined radiator, because its radiation does not depend upon the physical properties of the material of which it is made, (2) its calibration does not permit a higher accuracy than 1 to 2 percent in its radiance at $T \sim 2500$ K and $\lambda \sim 650$ nm. The use of the black-body radiator is restricted because of the auxiliary apparatus, such as a furnace of accurately adjustable temperature or a tube of high melting point. For laboratory purposes the tungsten strip lamp is perhaps less accurate but more practical. Nevertheless, black-body furnaces up to 2500 K have been constructed and successfully used for radiation measurements [4a].

B. Tungsten Strip Lamp

This section deals only with the tungsten strip lamp as a standard source for spectral radiance. In pyrometry, this source is also used as a secondary temperature standard, for instance for the calibration of commercial pyrometers.

The principal part of the strip lamp is a tungsten ribbon with a width of some millimeters and a length which varies for different types of lamp. The ribbon can be heated by an electric current up to a temperature of ~ 2360 K if the strip is mounted in an evacuated tube and to ~ 2800 K if the tube is filled with a noble gas. The spectral radiance L_λ is determined by the temperature of the strip and can be derived from Planck's law, multiplied by the spectral emissivity $\epsilon(\lambda, T)$ (Kirchhoff's law):

$$L_\lambda(\lambda, T) = \epsilon(\lambda, T) L_{b,\lambda}(\lambda, T). \tag{3}$$

In this formula $L_{b,\lambda}(\lambda, T)$ is the spectral radiance of a black-body at the same temperature, given by eq (1).

$\epsilon(\lambda, T)$ as a function of λ and T has been the subject of many investigations. A discussion of the measurements has been given elsewhere by Schurer [6] and the present author [7]. Since then, further results have been published [8]. For the visible region (at 660 nm) the new measurements are in agreement with the measurements by De Vos ([9] fig. 3), and the conclusion is, according to Schurer [6]: "The ϵ-values of De Vos, after correction with -0.5 percent ($\Delta\epsilon \sim 0.002$) for possible influences of stray light and diffraction offer in the u.v. and the visible up to 800 nm a set of data with the required accuracy and reliability" can still be maintained.

In the infrared at 2.6 μm (the largest wavelength in De Vos' measurements), the ϵ-values of Kovalev and Muchnik are about 5 percent higher than those of De Vos. According to Schurer [6], all previous measurements in the infrared at 2.6 μm have results which are from 5 to 10 percent lower than those of De Vos. It is difficult to explain why the differences between the results of different authors in the infrared are so much larger than in the visible region. They can be caused partly by different properties of the glass envelope of the lamps, partly by different properties of the tungsten strips themselves. More investigations in this spectral region seem to be needed to solve this problem.

At the shorter wavelengths, Buckley [10] has shown that a tungsten ribbon filament lamp with a sapphire window can also be used as a calibration source in the wavelength range 150 to 270 nm (ultraviolet). The ϵ-values, derived by Buckley from his measurements (at wavelengths between 150 and 200 nm), show a rather large uncertainty, but the relation to other measurements at 200 nm is very satisfactory.

The calibration of the lamp is usually performed by means of a pyrometer at one (650 nm) or two wavelengths. In this way the *luminance temperature* T_L [3] at that wavelength is measured and all uncertainties in the pyrometer calibration are transmitted to the ribbon calibration. The true temperature T is calculated from the relation (in Wien's approximation):

$$\tau(\lambda) \cdot \epsilon(\lambda, T) e^{-c_2/\lambda T} = e^{-c_2/\lambda T_L} \tag{4}$$

or

$$\frac{1}{T} - \frac{1}{T_L} = \frac{\lambda \ln \epsilon(\lambda, T) \cdot \tau(\lambda)}{c_2} \tag{5}$$

[3] Luminance temperature = temperature of the full radiator for which the spectral radiance at a specified wavelength is the same as for the radiator considered.

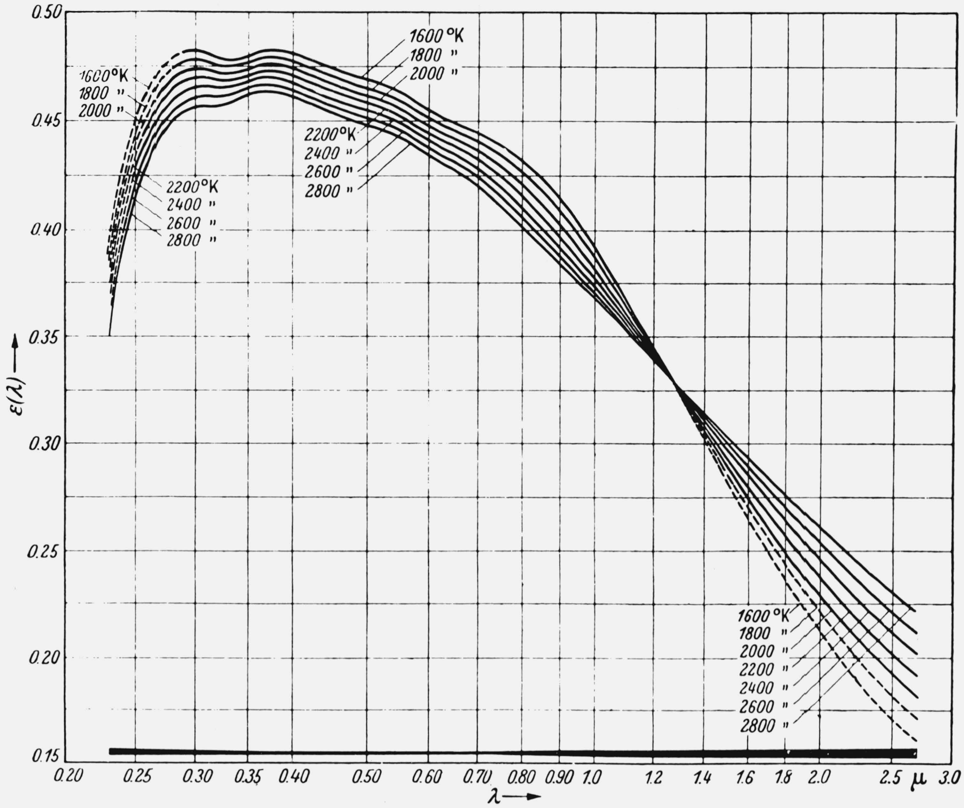

FIGURE 3. Spectral emissivity of tungsten as a function of wavelength and temperature after De Vos [9].

$\tau(\lambda)$ is the spectral transmission factor of the window. For $\lambda = 650$ nm and $c_2 = 1.4388 \times 10^{-2}$ m · K (5) can be written:

$$\frac{1}{T_L} - \frac{1}{T} = 1.041 \times 10^{-4} \lg \{\epsilon(\lambda, T) \cdot \tau(\lambda)\} \quad (5a)$$

Furthermore it should be kept in mind that there is a temperature gradient across and along the strip. The latter is smaller in the center part of the strip if the strip is longer and the end sections are folded back to the mounts. Detailed information for the use of the tungsten strip lamp is given, *a.o.* by Barber [11] and Kunz [12].

Usually, the current through the strip is supplied by a stabilized dc supply. A dc current can be measured with a great accuracy and electronically stabilized power supplies are commercially available. However, if a dc current is passed through the strip during a long time in the same direction, changes in the surface of the strip can be observed (De Vos [9], Quinn [13]). The grooves which are produced on the strip will have an influence upon its emissivity and therefore on the difference between true temperature and luminance temperature (Cf. eq (5a)). De Vos therefore recommended to reverse the current at regular time intervals.

One could also think on supplying the lamp with ac. Because of the finite heat capacity of the strip, it can be expected that the temperature of the strip changes periodically with the current and that a phase shift occurs between temperature and current. Measurements by Bezemer of our laboratory have shown that the temperature during a half-cycle of the 50 Hz supply changes between two values, T_{max} and T_{min}, which differ about 30 K at $T = 2000$ K for a tungsten strip of 20 x 2 mm and a thickness of 0.02 mm. If the temperature is measured with a visual pyrometer, no differences were found in the pyrometer readings for the same dc and ac (effective) current, because the eye is too slow to follow the 50-Hz fluctuations. If a chopping system is used, care should be taken that measurements are not made at a fixed point of the sine-wave.

The main reasons for nonreproducibilities in a particular strip lamp are:

(1) variations in the temperature because of changes in the position of the lamp (with respect to the vertical), typical for gas filled lamps [11],

(2) changes in the structure of the filament because of the direction of the current [9, 13],

(3) influence of the ambient temperature upon the calibration, particularly at low ribbon temperatures ($T < 1500$ K), and

(4) changes in the transmission factor of the window because of tungsten deposits. Evaporation of the tungsten has also an influence upon the ribbon itself.

Notwithstanding all these reasons for nonreproducibility, measurements of the spectral radiance of a number of lamps from different manufacture by Schurer [6] gave very satisfactory results. If all lamps were adjusted to the same luminance temperature at 650 nm, the spectral radiances at 280 nm did not deviate more than ±3 percent and at 2500 nm not more than ±2 percent.

For the user, the factors mentioned above mean that the lamp has to be recalibrated regularly. For absolute measurements, the accuracy is determined both by the accuracy of the calibration of the luminance temperature as a function of the lamp current and by the knowledge of the spectral emissivity of tungsten. In a review article such as this, the author cannot do much more than draw the user's attention to all the effects mentioned.

C. The Carbon Arc as a Standard for Spectroradiometry

A disadvantage of the tungsten strip lamp, inherent to the generation of the radiation, is the strong decrease in radiance with decreasing wavelength. At a temperature of 2800 K the maximum of the spectral radiance is at 950 nm; at 700 nm the radiance is still 74 percent of its maximum value, but at 300 nm it is only 0.3 percent of the maximum value. For a blackbody radiator, the relative slope of the radiance-wavelength curve in the visible and ultraviolet range of the spectrum decreases if the temperature increases. If $\epsilon(\lambda, T)$ does not change much with wavelength, a similar variation of radiance is found for other radiators. Therefore, one must look for a nearly grey radiator with a temperature as high as possible. In this respect, the anode of the carbon arc has favorable properties. Since the first measurements by Waidner and Burgess in 1904, the temperature and emissivity of the carbon and graphite anode have been subject of many investigations. A survey of these investigations has recently been given by Schurer [14]. The author drew attention to the remarkable differences in spectral reflectance of carbon, found by different investigators; they range from 1 to 30 percent, corresponding to emissivities of 99 to 70 percent.

First some words about the use of the carbon arc in practice. Generally, the arc is drawn between a horizontal anode (used as the radiance standard) and a vertical cathode. The electrodes must be mounted in a casing, which protects the arc from draught and the surroundings from radiation. Because of the rapid burning-off of the electrodes, their distance should be held constant, either manually or with an automatic device. It is often useful to make an enlarged image of the arc on a screen, on which the required position can be indicated. The arc is powered from a dc source, which should supply a current of about 10 A (for a low-current arc). To stabilize the arc, a ballast resistance is needed, which is usually chosen such that the voltage across the resistor is at least equal to that across the arc. Dependent on the quality of the supply, a ripple filter can be added to suppress a possible 50-Hz ripple of the supply source. Schurer did measurements on several electrodes from different manufacturers:[4]

Ringsdorff Werke G.m.b.H. (FRG), 6 different types, Ultra Carbon Corp. (USA), 5 different types, National Carbon Company (USA), 3 different types, Conradty (FRG), 3 different types. The data of these electrodes are collected in table 2. It can be seen that great variations in density and specific resistance exist in the different species. Much less variation was found in the current density at the overload point (current at which the arc starts hissing). Therefore, the variations in the temperature of the anode crater (the radiation source proper) are rather small. The lowest (true) temperature was found for Conradty-electrodes (3775 to 3785 K, ±15 K), the other temperatures range from 3790 K to 3865 K. The values of the spectral emissivity, found by Schurer for RWI anodes at arc temperature ranged from 96 percent in the ultraviolet, via 99 percent at 500 nm to about 96 percent at 1.5 μm. In some parts of the spectrum, the radiation from the arc itself can affect the observed anode radiance, particularly at

[4] In order to adequately describe materials and experimental procedures, it was occasionally necessary to identify commercial products by manufacturer's name or label. In no instances does such identification imply endorsement by the National Bureau of Standards, nor does it imply that the particular product or equipment is necessarily the best available for that purpose.

TABLE 2. Some data of the anodes, used by Schurer [14]

Manufacturer	Code	Kind of carbon	Density (10^3kg/m^3)	Resistivity ($10^{-6}\Omega$m)	Grain size	Overload A/mm^2
Ringsdorff	RWO	Graphite	1.79	7.7	Fine	1.12
	RWI	Graphite	1.59	7.5	Fine	1.07
	RWII	Lampblack	1.56	61	Fine	0.71
	RWIV	Graphite	1.78	7.2	Coarse	1.20
Ultra Carbon	U1	Graphite	1.75	7.2	Coarse	
	U2	Graphite	1.99	12.1	Fine	1.15
National Carbon	AGKSP	Graphite	1.66	6.4	Coarse	1.04
	SPK	Graphite	1.87	11.8	Fine	1.11
	L113SP	Lampblack	1.50	53	Fine	0.68
Conradty	Noris	Lampblack	1.20	96	Fine	0.6
	Noris vacuum	Coke	1.32	79	Coarse	0.75

those wavelengths where strong cyanogen bands are found and at wavelengths below 250 nm. Nevertheless, Schurer concluded "that the anode of a carbon arc in air offers a highly reproducible standard of spectral and total radiance." The total radiance, found for a RWO anode, appeared to be 3.84 W mm^{-2} $sr^{-1} \pm 1$ percent, of which 0.054 W $\cdot$ mm^{-2} sr^{-1} has its origin in the arc.

D. Some Other Standard Sources

Besides the standards, described in the foregoing sections, there are some radiation sources which, with certain restrictions, can also be used for absolute spectroradiometric measurements. Alternatives for the black-body radiator are the tungsten lamp, described by Magdenburg and Wende [15] and the black-body radiator after Quinn and Barber [16].

In the first case, a cylinder of tungsten foil is used with a slit in the surface. It can be used as a tungsten ribbon filament lamp, but with the possibility to measure $\epsilon(\lambda, T)$ of the tube by comparing the radiance of the tube and the slit. In the second case, a tungsten tube is used, which is observed end-on. Inside the tube is a bundle of tungsten wire, which is the proper source of radiation (fig. 4). It can be considered as a grey body with an emissivity as high as 0.95. The argon-filled lamp needs a current of 56 A at 12 V for a temperature of 2700 °C. Measurements by Jones [17] of the reproducibility of this lamp are promising and the Comité Consultatif de Photométrie of the Bureau International des Poids et Mesures, in its meeting of September 1971 has recommended to continue the study of this radiator.

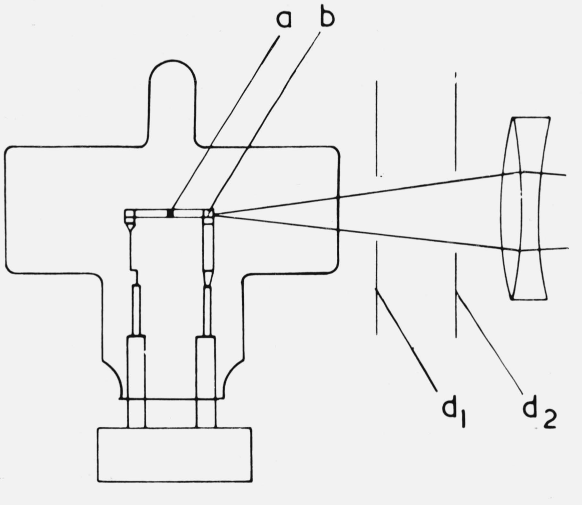

FIGURE 4. Quinn-Barber black-body radiator [16]. a, tungsten tube with tungsten wires; b, exit diaphragm, $\phi = 1$ mm; $d_1 d_2$ diaphragms for eliminating stray light.

For some spectroradiometric measurements, it would be worthwhile to have a background with a radiance still higher than that of the anode of the carbon arc. Attempts have been made to use the high-pressure xenon arc lamp for this purpose. Most investigations have been done for XBO–lamps of various wattage, made by Osram. For its use as a radiance standard one should take in mind that the discharge consists of two parts, the so-called "Plasmakugel," a small spot of high radiance situated just above the cathode and the column with a radiance which is about one quarter of that of the sphere. The spectral radiance of the sphere of XBO–900 lamp at 400 nm is about 1 $W/cm^2 \cdot sr \cdot nm$, that of the arc ~ 0.3 $W/cm^2 \cdot sr \cdot nm$. The latter value is by a factor of 3 to 4 larger than the radiance of the anode of the carbon arc and by a factor of 200 larger than the radiance of the strip lamp at 2800 K, both at the same wavelength. In our laboratory ter Heerdt has measured the spectral distribution of the radiation emitted by different parts of the arc and investigates whether the reproducibility of the xenon-arc lamp is good enough for the use as standard source.

Another stable source of high spectral radiance is the cascade-arc of Maecker [18], a stabilized high current arc with a current of about 1000 A and a temperature of about 12000 K (fig. 5).

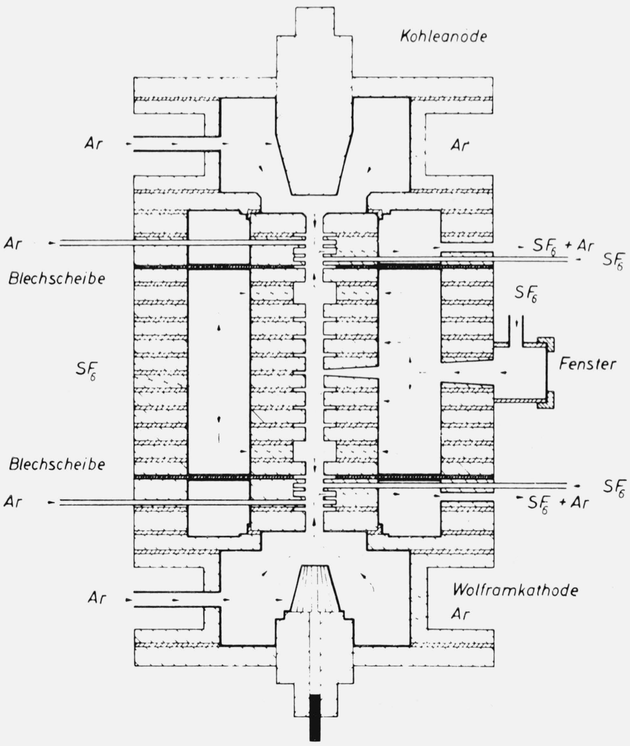

FIGURE 5. Maecker's cascade arc [18] between a carbon anode and a tungsten cathode. Around the arc the cooling discs. Argon is used here as protecting gas and SF_6 as the gas the properties of which are investigated.

The arc column burns within the bore of a stack of copper discs and has a diameter of about 5 mm. The spectrum consists of a strong continuous background on which spectral lines of the arc gas are superimposed. Most measurements up to now are related to the properties of the arc gas or gases at high temperatures, but it seems that this arc has also good properties for being used as radiation standard.

E. Irradiance Standards

All the standards mentioned in the foregoing sections are primarily meant for radiance standards. For absolute measurements of radiation, an irradiance standard can be required, that is to say a standard which causes a known spectral irradiance at the surface of a detector. If a black-body radiator is available, this can also be used as an irradiance standard if a diaphragm of known diameter is used. For the tungsten strip lamp this is more difficult to achieve, because the radiance is not constant along and across the strip. This makes it difficult to calculate the irradiance at a given distance from the lamp. More suitable standards for this purpose are the special tungsten filament lamps and quartz-iodine lamps, developed at the National Bureau of Standards [19].

An irradiance standard, which can also be used in the ultraviolet, is the UV-Normal by Krefft, Rössler and Rüttenauer [20], which consists of a high pressure mercury vapor lamp, run at dc, 2A, 200 W. An alternative is the Standard 75 lamp, 0.95 A, 80 W [21]. The spectrum consists of a weak continuum on which the mercury spectrum is superimposed. The spectral distribution has been measured *a.o.* by Rössler, van Stekelenburg [22], Coolidge and recently by Kok [21]. According to van Stekelenburg's measurements the differences between various lamps of a series are about 10 percent, the relative spectral distributions from different lamps are nearly equal. The UV-Normal gives an irradiance of 0.70 W/m^2 at a distance of 1 m at a wavelength of 365 nm (strongest line); at 296.7 nm this value is 0.10 W/m^2. The irradiance by the continuum at the same distance is 0.48 mW/m$^2 \cdot$ nm at 500 nm, 3.0 mW/m$^2 \cdot$ nm at 300 nm.

III. Absolute Radiometers

In the preceding section, standard sources have been described which can be used if absolute radiation measurements are required and a comparison of the unknown source with a standard source is possible. Another procedure for absolute measurements is to measure the radiation emitted by the unknown source directly with an absolute receiver, called also an *absolute radiometer*.

Most detectors used in optical measurements, such as the photomultiplier tube, the photoelectric cell etc., have a spectral responsivity which depends on the wavelength. Such a detector can be calibrated, either relatively or absolutely, with the help of a standard source, combined with a spectral apparatus or a series of interference filters. If the transmission characteristics of the spectral apparatus or the filters are known, the calibration can be made in absolute values. However, in many cases a relative spectral response curve is sufficient. We will come back to this procedure later on.

First we will pay attention to devices which offer the possibility of making an absolute measurement directly; that is to say, without using a standard source. In such a device the radiant energy or power absorbed must be compared with a quantity of energy or power of another form, usually a quantity of electric power. The apparatus, best suitable for this purpose and most thoroughly investigated is the *absolute radiometer*, belonging to the class of *thermal receptors*. Essentially, this type of receptor is independent of the wavelength of the incident radiation in the spectral region where the absorption factor (black surface) is independent of wavelength. The incident radiation is absorbed in, e.g., a metal foil which consequently increases in temperature. The increase in temperature can be measured in different ways, for instance with a thermopile or as a change in the resistance of the receiver, a *bolometer*.[5] Afterwards the metal foil can be heated by an electric current, which must be adjusted in such a way that an equal change in the detector element is caused.

One of the older instruments, based on this principle, is Wouda's bolometer [23], developed in the thirties in our laboratory. The radiation absorbing element in Wouda's bolometer is a manganin foil of 50 x 15 x 0.03 mm, blackened with carbon black on the front. On the back, a copper wire 50 μm in diameter is spread across the whole surface of the foil, as shown in figure 6.

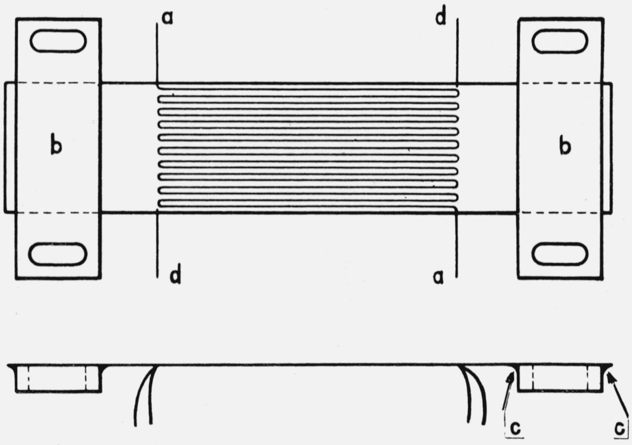

FIGURE 6. Wouda's absolute bolometer [23]. a,a = bolometer wire, $\phi = 50\ \mu$m; b,b, copper clamps on which the metal foil is soldered (at c,c); d,d, potential wires.

A change in temperature of the receiver element by absorption of the incident radiation causes a change in the resistance of the copper wire, which can be measured with a Wheatstone bridge. Local differences in the temperature are eliminated by the shape of the wire which operates as an integrating device. Afterwards the foil can be heated with a known electric current; its resistance (nearly independent of temperature) is also measured in a bridge circuit. A similar element in the opposite arm of the bridge compensates for a possible influence of the surroundings. The heat balance equation is:

[5] According to [1], a bolometer is a thermal receptor in which the heating of the part that absorbs the radiation gives rise to a change in its electrical resistance. Here, bolometer is also used as a device where the receiver heats a resistor which resistance changes because of the heating of the radiation receiver (see Wouda bolometer).

$$\alpha EA = i^2R \quad (6)$$

where E is the irradiance on the plane of the foil (W/m^2), α the absorption factor of the foil, A its surface (m^2), i the current which causes the same effect in the detector as the radiation and R the resistance of the foil. The accuracy is determined by the accuracy with which α, A, i, and R can be determined, the time constant by the heat capacity of the foil.

There is a difference between the heating of the copper wire by radiation or by the electric current through the foil, since in the first case the heat absorbed in the black layer has to pass this layer before it reaches the metal foil; in the second case the heat is produced inside the foil. Wouda has shown that the procentual error caused by this effect is $\sim \bar{\alpha}d/\lambda$ where $\bar{\alpha}$ is the heat loss per mm^2 and per °C of the frontside by radiation, convection and conduction of heat, d the thickness of the black layer and λ its heat conductivity. In the bolometer, used by Wouda, this correction was only 0.12 percent and was taken into account in the results of the measurements. Another point to be mentioned is the absorptance of the black layer. Carbon black has a reflection factor of 3–4 percent in the visible region; in the infrared beyond 4 μ the layer becomes more and more transparent. This can be avoided by the use of other layers, developed since then. Ultimately, Wouda claims an accuracy of 0.1 percent of his apparatus. Some years ago, we made a comparison between this bolometer and a thermopile, calibrated at the National Physical Laboratory, and found a difference of less than 1 percent. At that time, a more accurate comparison was not possible. An alternative device was designed by this author [24]. In this device the copper wire was replaced by a thin aluminum foil made by evaporation on the back of a mica foil. The receiver was a layer of evaporated manganin on the frontside of the mica foil. The accuracy was estimated to be better than 0.5 percent. Another alternative has been described by Bischoff of the Physikalisch-Technische Bundesanstalt [25] and by Gillham of the National Physical Laboratory [26].

In fact, Gillham developed three radiometers, of which the first one—an improvement of the older Guild radiometer—consisted of a circular metal disc, thermally insulated from its surroundings and provided with a number of thermocouples to measure its average temperature. The disc is heated either by the incident radiation or by an electrical heating element. Gillham made a new disc radiometer with a much smaller heat capacity and added a complete second receiver "identical to the first receiver, except that it looks in the opposite direction." The receiver and heating element are shown in figure 7. In his third radiometer, the *black-body radiometer*, the receiver is mounted in a cavity with an absorption factor sensibly equal to unity (fig. 8). This instrument has a sensitivity of 0.012 $V \cdot W^{-1}$ cm^{-2}, an area of the limiting aperture of 3.00 mm^2 and a time constant of 14 s. A comparison of the new instruments has shown that they agreed to within 0.2 percent.

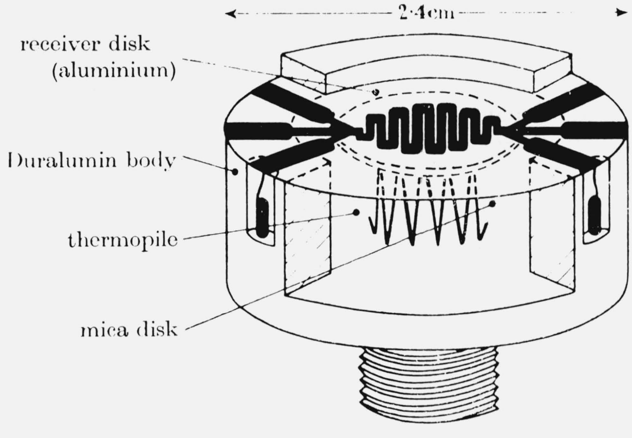

FIGURE 7. Gillham absolute radiometer [26].

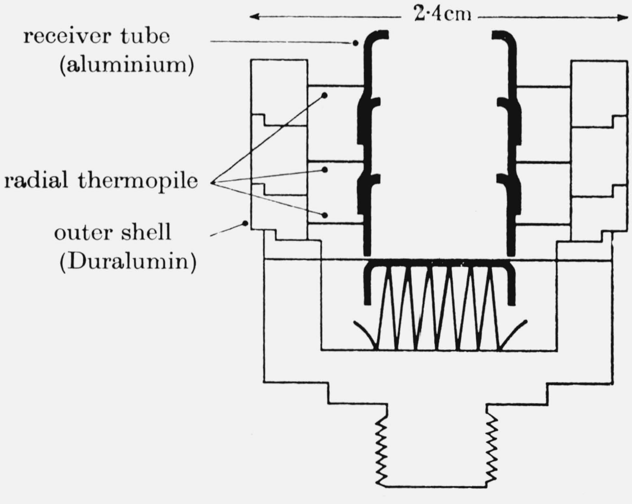

FIGURE 8. Gillham radiometer in a cavity [26].

At the National Standards Laboratory (Australia) a radiometer of the Gillham type has been used by Blevin et al. [27] for a new determination of the Stefan-Boltzmann constant. Preston [28] described a similar device, also intended for measuring the *energy* of radiation pulses. It had a rise time of $\frac{1}{4}$ s and a cooling time constant of 8 s.

An advantage of the black-body radiometer is that it is independent of the spectral characteristics of the black surface layer, used in the devices described above. It is often difficult to measure this absorption factor over a wide spectral region. Previously, Müller used a hemispherical mirror with the receiver in its center; the radiation is admitted through a hole in the mirror. The radiation which is reflected by the receiver impinges upon the mirror and is reflected back to the receiver. In this way the effective absorptance of the receiver can be increased.

Two other cavity-type radiometers have been developed and described in detail by Kendall and Berdahl [29]. One type is used in vacuum, the other either in vacuum or air. They are designed for measuring irradiances from about 0.10 mW/mm^2 to 8 W/mm^2 with an accuracy of 0.3 percent.

With all precautions taken, it seems possible to determine the total radiation on a certain plane with an accuracy of some tenths of a percent. For absolute spectral measurements the accuracy is much less. Intercomparisons by National Standardizing Laboratories of absolute spectral irradiance scales are carried out under the auspices of a committee on spectroradiometry of the Commission Internationale de l'Eclairage with C. L. Sanders as the chairman. All devices described above have a rather large area and time constant, and are generally not suited for measurements behind the exit slit of a monochromator. Therefore, the devices described must be considered as primary standard instruments, against which other radiation receivers, either nonselective or selective, can be calibrated.

IV. Additional Remarks Concerning Absolute Measurements

In the foregoing sections we have seen that for absolute measurements both absolute radiation standards and absolute receivers are available. For a proper use of these devices, several precautions have to be taken depending upon the aim of the measurements. The main problems in absolute radiometry are:

(1) the calibration of an arbitrary source in absolute units,

(2) the calibration of a selective receiver in absolute units.

In both cases the user is generally interested in the dependence of the quantities measured on the wavelength of the radiation emitted or received.

A. The Calibration of an Arbitrary Source

If an absolute standard source is available, both sources can be compared with the aid of a monochromator and an arbitrary receiver behind the exit slit. If the sources are comparable in size and spectral distribution, no special problems will be encountered. Both can sucessively be focused upon the entrance slit of the spectral apparatus and, if the receiver is a linear instrument, the ratio of the signals is a measure for the ratio in the radiances or radiant intensities. If the sizes or intensities of the sources differ considerably, a MgO- or $BaSO_4$-screen can be irradiated successively by the sources. Then, the radiances of the screen are compared. If the source to be calibrated has a spectrum composed of a continuous background and spectral lines superimposed upon the background (contrary to most standards described before, which have a rather smooth spectrum), the signal has to be separated into its component parts. This can be done in different ways:

(1) by variation of slit width. If for equal slit widths the width of the slits is changed, the intensity of the continuum leaving the monochromator is another function of this width than the intensity of the line radiation (intensity (:)$(\Delta\lambda)^2$ and $(\Delta\lambda)$ respectively under certain precautions [30]).

(2) with fixed (narrow) slits and continuous recording of the signal as a function of wavelength. The area between the total response and the interpolated continuum in the region of the line provides the radiant flux in the line. The slit width should be chosen in accordance with the dispersion and the slope of the spectral distribution curve. More about a similar method can be found in a paper by Bauer and Erb [31].

If an absolute receiver is available, one can either measure the radiant flux leaving the exit slit of the monochromator directly with the calibrated receiver or, if this receiver is not suited for this purpose (e.g., because his surface is too large and must be filled homogeneously), calibrate another receiver against the standard and use this one behind the exit slit (Cf. IV. B). In order to relate the signal of the receiver to the radiant intensity of the source to be calibrated, one must furthermore know the absorptance of the optical components between source and detector and the width of the spectral region transmitted by the monochromator. This last quantity is needed for the reduction of the measured signal to a quantity per unit of wavelength.

A method, which gives all the information needed, is schematically given in figure 9 (Krijgsman [32]). Two monochromators are required in crossed position. The source to be calibrated is focused on the entrance slit S_1 of the first monochromator (i.e., a double monochromator), which in its turn is successively focused on S_2 and S_3. S_3 is focused with lens L_3 in P. The spectral irradiance in P is measured with the absolutely calibrated receiver. Afterwards the image in P is replaced by the source K. The radiant intensity of K and its image (both in P) are compared with a second monochromator with arbitrary receiver or spectrograph but with a direction of dispersion which is perpendicular to that of the first one (S_4 perpendicular to S_3). The spectral region transmitted by the first monochromator can be derived from the shape of the region transmitted by the second monochromator. For detailed information on this method, the reader is referred to the literature.

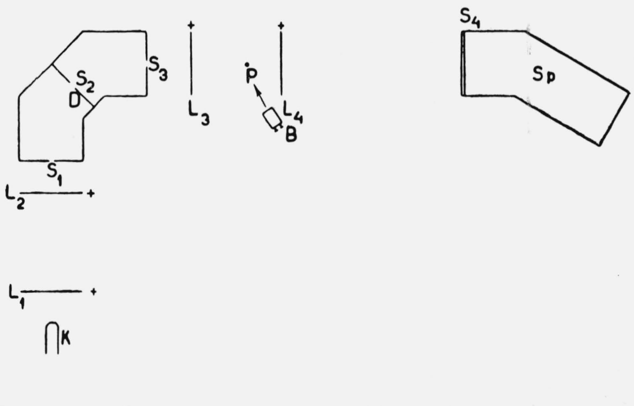

FIGURE 9. Krijgsman's arrangement [32] for the absolute calibration of an arbitrary source K. D, double monochromator with slits S_1, S_2, S_3; P, image of K; Sp, spectrograph with horizontal slit S_4.

B. Calibration of An Arbitrary Receiver

Here, also, the method depends upon the standard available, either a standard source or an absolute receiver. If a standard source is available, one can use either a series of interference filters or a monochromator to separate the radiation into individual wavelengths. In both cases the spectral transmittance of the wavelength-selecting device should be known. If a standard receiver is available, an arbitrary source can be used and the receiver to be calibrated can be compared to the standard receiver in an arrangement similar to that shown in the first part of figure 9 (both receivers in P). If the receiver has a spectral response curve with steep slope (or slopes), it might be necessary to calculate the effective wavelength of the radiation incident upon the receiver.

Factors, like nonlinearity, fatigue effects and area sensitivity of the receiver are not discussed here. But the user should not forget them in the evaluation of his measurements.

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